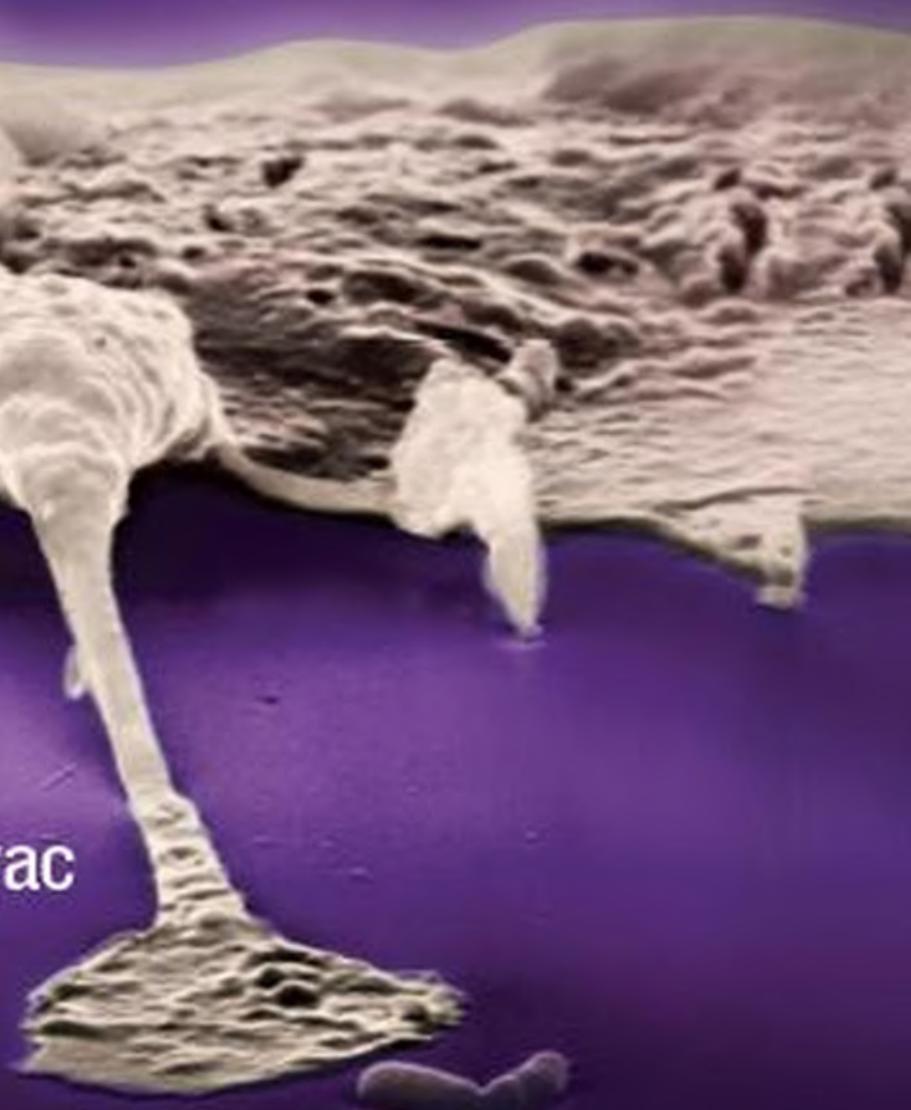


How the Immune System Works

Seventh Edition

Lauren Sompayrac



WILEY Blackwell

How the Immune System Works

I dedicate this book to my sweetheart, my best friend,
and my wife: Vicki Sompayrac.

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SEVENTH EDITION

Lauren Sompayrac, PhD

WILEY Blackwell

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Acknowledgments

I am indebted to my first editor, Chris Davis, who recognized that students did not need another fact-filled immunology textbook. They needed a book that would help them understand how the pieces of this complex system all fit together. That this book is in its seventh edition is a tribute to Chris's wisdom. I also would like to thank my friend Dr. Jim Cook for his many insightful comments, especially on the COVID-19 lecture. I thank the following people, whose

critical comments on earlier editions were most helpful: Drs. Mark Dubin, Linda Clayton, Dan Tenen, Tom Mitchell, Lanny Rosenwasser, and Eric Martz. Diane Lorenz illustrated the first and second editions, and her wonderful artwork can still be found in this book. Finally, I wish to thank Vicki Sompayrac, whose wise suggestions helped make this book more readable, and whose editing was invaluable in preparing the final manuscript.

How to Use This Book

I wrote *How the Immune System Works* because I couldn't find a book that would give my students an overall view of the immune system. Sure, there are as many good, thick textbooks as a person might have money to buy, but these are crammed with every possible detail. There are also lots of "review books" that are great if you want a summary of what you've already learned – but they won't teach you immunology. What was missing was a short book that tells, in simple language, how the immune system fits together – a book that presents the big picture of the immune system, without the jargon and the details.

How the Immune System Works is written in the form of "lectures," because I want to talk to you directly, just as if we were together in a classroom. Although Lecture 1 is a light-hearted overview, meant to give you a running start at the subject, you'll soon discover that this is not "baby immunology." *How the Immune System Works* is a concept-driven analysis of how the immune system players work together to protect us from disease – and, most importantly, why they do it this way.

In Lectures 2 through 10, I focus more closely on the individual players and their roles. These lectures are short, so you probably can read them all in a couple of afternoons. In fact, **I strongly suggest that you begin by reading quickly through Lectures 1–10.** The whole idea is to get an overall view of the subject, and if you read one lecture a week, that won't happen. Don't "study" these ten lectures the first time you read them. Just rip through them. Then, once you have a feel for the immune system, go back and spend a bit more time with these same ten lectures to get a clearer understanding of the "hows and whys."

In Lectures 11–17, I discuss the intestinal immune system, vaccines, allergies, autoimmune disease, HIV-1, cancer, immunotherapy, and COVID-19. These lectures will let you review what you have learned in the earlier lectures by examining real-world examples of the immune system at work. And when you read these final lectures, I think you'll be amazed by how much you now understand about the immune system.

As you read, you will encounter passages highlighted in green, and words that are highlighted in red. These highlights are to alert you to important concepts and terms. They also will help you review a lecture quickly, once you have read it through.

Finally, because most immunology textbooks contain so many facts, it's easy to get the impression that all the important questions about the immune system have already been answered. That's not true. To emphasize this point, at the end of most lectures, I will point out some of the "known unknowns" – important questions which immunologists still aren't able to answer.

In some settings, *How the Immune System Works* will serve as the main text for the immunology section of a larger course. For a semester-long undergraduate or graduate immunology course, your professor may use this book as a companion to a comprehensive textbook. As your course proceeds, reviewing the appropriate lectures in *How the Immune System Works* will help you keep the big picture in focus as the details are filled in. It's really easy to get lost in the details.

No matter how your professor may choose to use this book, you should keep one important point in mind: I didn't write *How the Immune System Works* for your professor. This book is for you!

About the Companion Website

This book is accompanied by a companion website.

www.wiley.com/go/sompayrac/immune7e

This website includes:

- Figures from book

LECTURE 1

An Overview

HEADS UP!

The immune system is a “team effort,” involving many different players. These players can be divided roughly into two groups: those that are members of the innate immune system team and those that are part of the adaptive immune system. Importantly, these two groups work together to provide a powerful defense against invaders.

INTRODUCTION

Immunology is a difficult subject for several reasons. First, there are lots of details, and sometimes these details get in the way of understanding the concepts. To get around this problem, we’re going to concentrate on the big picture. It will be easy for you to find the details somewhere else. Another difficulty in learning immunology is that there is an exception to every rule. Immunologists love these exceptions, because they give clues as to how the immune system functions. But for now, we’re just going to learn the rules. Oh sure, we’ll come upon exceptions from time to time, but we won’t dwell on them. Our goal is to examine the immune system, stripped to its essence.

A third difficulty in studying immunology is that our knowledge of the immune system is still evolving. As you’ll see, there are many unanswered questions, and some of the things that seem true today will be proven false tomorrow. I’ll try to give you a feeling for the way things stand now, and from time to time I’ll discuss what immunologists speculate may be true. But keep in mind that although I’ll try to be straight with you, some of the things I’ll tell you will change in the future – maybe even by the time you read this!

Although these three features make studying immunology difficult, I think the main reason immunology is such a tough subject is that the immune system is a “team effort” which involves many different players interacting with each other. Imagine you’re watching a football game on TV, and the camera is isolated on one player, say, the tight end. You see him run at full speed down the field, and then stop. It doesn’t seem to make any sense. Later, however, you see the same play on the big screen, and now you understand. That tight end took two defenders with him down the field, leaving the running back uncovered to catch the pass and run for a touchdown. The immune system is a lot like a football team. It’s a network of players who cooperate to get things done, and focusing on a single player doesn’t make much sense. You need an overall view. That’s the purpose of this first lecture, which you might call “turbo immunology.” Here, I’m going to take you on a quick tour of the immune system, so you can get a feeling for how it all fits together. Then in the next lectures, we’ll go back and take a closer look at the individual players and their interactions.

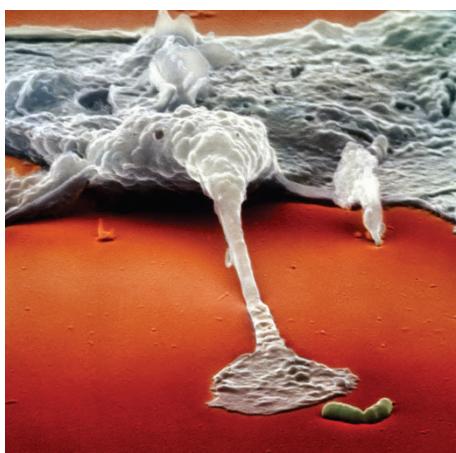
PHYSICAL BARRIERS

Our first line of defense against invaders consists of physical barriers, and to cause real trouble, viruses, bacteria, parasites, and fungi must penetrate these shields. Although we tend to think of our skin as the main barrier, the area covered by our skin is only about two square meters. In contrast, the area covered by the mucous membranes that line our digestive, respiratory, and reproductive tracts measures about 400 square meters – an area about as big as two tennis courts. The main point here is that there is a large perimeter which must be defended.

THE INNATE IMMUNE SYSTEM

Any invader that breaches the physical barrier of skin or mucosa is greeted by the **innate immune system** – our second line of defense. Immunologists call this system “innate” because it is a defense that all animals just naturally seem to have. Indeed, some of the weapons of the innate immune system have been around for more than 500 million years. Let me give you an example of how this amazing innate system works.

Imagine you are getting out of your hot tub, and as you step onto the deck, you get a large **splinter** in your big toe. On that splinter are many bacteria, and within a few hours you’ll notice (unless you had a lot to drink in that hot tub!) that the area around where the splinter entered is red and **swollen**. These are indications that **your innate immune system has kicked in**. Your tissues are home to roving bands of white blood cells that defend you against attack. To us, tissue looks pretty solid, but that’s because we’re so big. To a cell, tissue looks somewhat like a sponge with holes through which individual cells can move rather freely. One of the defender cells that is stationed in your tissues is the most famous innate immune system player of them all: the **macrophage**. If you’re a bacterium, a macrophage is the last cell you want to meet after your ride on that splinter! Here is an electron micrograph showing a macrophage about to devour a bacterium.

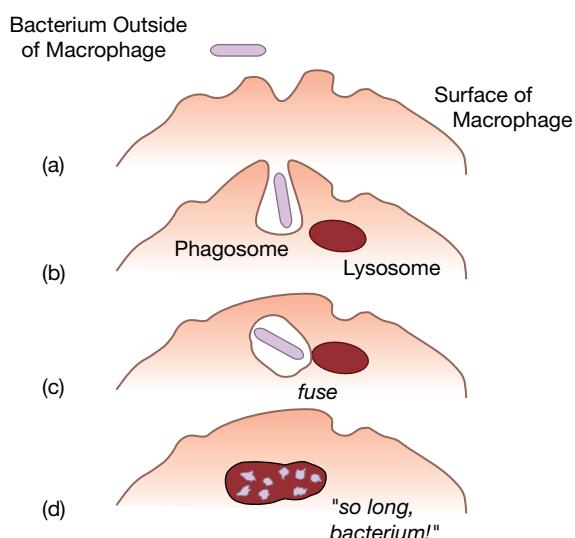


Credit: Lennart Nilsson/Boehringer Ingelheim/TT/Science Photo Library.

You will notice that this macrophage isn’t just waiting until it bumps into the bacterium purely by chance. No, this macrophage has actually sensed the presence of the bacterium and is reaching out a “foot” to grab it. But how does a macrophage know that a bacterium is out there? The answer is that macrophages have antennae (receptors) on their surface which are tuned to recognize “danger molecules”

characteristic of common microbial invaders. For example, the membranes that surround bacteria are made up of certain fats and carbohydrates that are not normally found in the human body. Some of these foreign molecules represent “find me and eat me” signals for macrophages. And when macrophages detect danger molecules, they begin to crawl toward the microbe which is emitting these molecules.

When it encounters a bacterium, a macrophage first engulfs it in a pouch (vesicle) called a **phagosome**. The vesicle containing the bacterium is then taken inside the macrophage, where it fuses with another vesicle termed a **lysosome**. Lysosomes contain powerful chemicals and enzymes which can destroy bacteria. In fact, these agents are so destructive that they would kill the macrophage itself if they were released inside it. That’s why they are confined within vesicles. Using this clever strategy, the macrophage can destroy an invader without committing suicide. This whole process is called **phagocytosis**, and this series of snapshots shows how it happens.

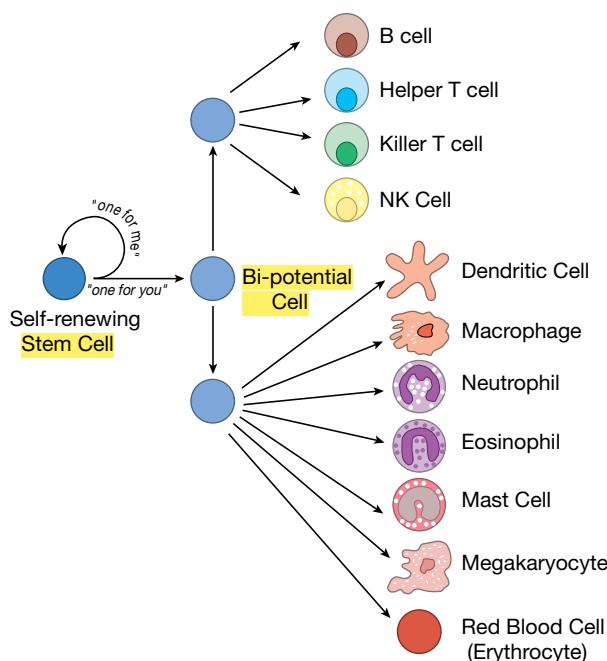


Macrophages have been around for a very long time. In fact, the ingestion technique macrophages employ is a refinement of the strategy that amoebas use to feed themselves – and amoebas have roamed the Earth for about 2.5 billion years. So why is this creature called a macrophage? “Macro,” of course, means large – and a macrophage is a large cell. Phage comes from a Greek word meaning “to eat.” So a macrophage is a **big eater**. In fact, in addition to defending against invaders, the macrophage also functions as a **garbage collector**. It will eat almost anything. Immunologists can take advantage of this appetite by feeding macrophages iron filings. Then, using a small magnet, they can separate macrophages from other cells in a cell mixture. Really!

Where do macrophages come from? Macrophages and all the other blood cells in your body are the descendants

of self-renewing **blood stem cells** – the cells from which all the blood cells “stem.” By self-renewing, I mean that when a stem cell grows and divides into two daughter cells, it does a “one for me, one for you” thing in which some of the daughter cells go back to being stem cells, and some of the daughters go on to become mature blood cells. This strategy of continual self-renewal insures that there will always be blood stem cells in reserve to carry on the process of making mature blood cells.

Macrophages are so important to our defense that they actually take up their sentinel positions in the tissues well before we are born. After birth, blood stem cells, which reside in the bone marrow, can replenish the supply of macrophages and all the other blood cells as they are needed. As the daughters of blood stem cells mature, they must make choices that determine which type of blood cell they will become when they grow up. As you can imagine, these choices are not random, but are carefully controlled to make sure you have enough of each kind of blood cell. For example, some daughter cells become red blood cells, which capture oxygen in the lungs, and transport it to all parts of the body. Our stem cell “factories” must turn out more than two million new red blood cells each second to replace those lost due to normal wear and tear. Other descendants of a blood stem cell may become macrophages, neutrophils, or other types of “white” blood cells. And just as white wine isn’t really white, these cells aren’t white either. They are colorless, but biologists use the term “white” to indicate that they lack hemoglobin, and therefore are not red. White blood cells also are called **leukocytes**. Here is a figure showing some of the many different kinds of blood cells a stem cell can become.



When the cells that can mature into macrophages first exit the bone marrow and enter the blood stream, they are called **monocytes**. All in all, you have about two billion of these cells circulating in your blood at any one time. This may seem a little creepy, but you can be very glad they are there. Without them, you’d be in deep trouble. Monocytes remain in the blood for an average of about three days. During this time they travel to the capillaries – which represent the “end of the line” for blood vessels – looking for a crack between the endothelial cells that line the inside of the capillaries. These endothelial cells are shaped like shingles, and by sticking a foot between them, a monocyte can leave the blood, enter the tissues, and mature into a macrophage. In the tissues, most macrophages just hang out, do their garbage collecting thing, and wait for you to get that splinter so they can do some real work.

When macrophages eat the bacteria on that splinter in your foot, they give off chemicals which increase the flow of blood to the vicinity of the wound. The buildup of blood in this area is what makes your toe with the splinter red. Some of these chemicals also cause the cells that line the blood vessels to contract, leaving spaces between them so that fluid from the capillaries can leak out into the tissues. It is this fluid which causes the swelling. In addition, chemicals released by macrophages can stimulate nerves in the tissues that surround the splinter, sending pain signals to your brain to alert you that something isn’t quite right in the area of your big toe.

During their battle with bacteria, macrophages produce and give off (secrete) proteins called **cytokines**. These are hormone-like messengers which facilitate communication between cells of the immune system. Some of these cytokines alert monocytes and other immune system cells traveling in nearby capillaries that the battle is on, and encourage these cells to exit the blood to help fight the rapidly multiplying bacteria. Pretty soon, you have a vigorous **inflammatory response** going on in your toe, as the innate immune system battles to eliminate the invaders.

So here’s the strategy: You have a large perimeter to defend, so you station sentinels (macrophages) to check for invaders. When these sentinels encounter the enemy, they send out signals (cytokines) that recruit more defenders to the site of the battle. The macrophages then do their best to hold off the invaders until reinforcements arrive. Because the innate response involves warriors such as macrophages, which are programmed to recognize many common invaders, your innate immune system usually responds so quickly that the battle is over in just a few days.

There are other players on the innate team. For example, in addition to the **professional phagocytes** such as macrophages, which make it their business to eat

invaders, the innate system also includes the complement proteins that can punch holes in bacteria, and natural killer cells which are able to destroy bacteria, parasites, virus-infected cells, and some cancer cells. We will talk more about the macrophage's innate system teammates in the next lecture.

THE ADAPTIVE IMMUNE SYSTEM

About 99% of all animals get along just fine with only natural barriers and the innate immune system to protect them. However, vertebrates like us have a third level of defense: the **adaptive immune system**. This is a defense system which actually can adapt to protect us against almost any invader. One of the first clues that the adaptive immune system existed came back in the 1790s when Edward Jenner began vaccinating the English against smallpox virus. In those days, smallpox was a major health problem. Hundreds of thousands of people died from this disease, and many more were horribly disfigured. What Jenner observed was that milkmaids frequently contracted a disease called cowpox, which caused lesions on their hands that looked similar to the sores caused by the smallpox virus. Jenner also noted that milkmaids who had contracted cowpox almost never got smallpox (which, it turns out, is caused by a close relative of the cowpox virus).

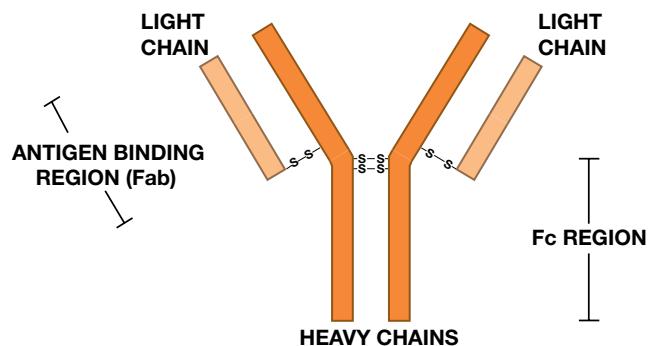
So Jenner decided to conduct a daring experiment. He collected pus from the sores of a milkmaid who had cowpox, and used it to inoculate a little boy named James Phipps. Later, when Phipps was re-inoculated with pus from the sores of a person infected with smallpox, he did not contract that disease. In Latin, the word for cow is *vacca* – which explains where we get the word vaccine. History makes out the hero in this affair to be Edward Jenner, but I think the real hero that day was the young boy. Imagine having this big man approach you with a large needle and a tube full of pus! Although this isn't the sort of thing that could be done today, we can be thankful that Jenner's experiment was a success, because it paved the way for vaccinations that have saved countless lives.

Smallpox virus was not something humans encountered regularly. So Jenner's experiment showed that if the human immune system was given time to prepare, it could produce weapons that could provide protection against an intruder it had never seen before. Importantly, the smallpox vaccination only protected against smallpox or closely related viruses such as cowpox. Phipps was still able to get mumps, measles, and the rest. This is one of

the hallmarks of the adaptive immune system: It adapts to defend against specific invaders.

Antibodies and B cells

Eventually, immunologists determined that immunity to smallpox was conferred by special proteins that circulated in the blood of immunized individuals. These proteins were named **antibodies**, and the agent that caused the antibodies to be made was called an **antigen** – in this case, the cowpox virus. Here's a sketch that shows the prototype antibody, **immunoglobulin G (IgG)**.



As you can see, an IgG antibody molecule is made up of two pairs of two different proteins, the **heavy chain (Hc)** and the **light chain (Lc)**. Because of this structure, each molecule has two identical "hands" (**Fab regions**) that can bind to antigens. Proteins are the ideal molecules to use for constructing antibodies that can grasp attackers, because different proteins can fold up into a myriad of complex shapes.

IgG makes up about 75% of the antibodies in the blood, but there are four other **classes** of antibodies: **IgA, IgD, IgE, and IgM**. All these classes of antibody are produced by **B cells** – white blood cells that are born in the bone marrow and can mature to become antibody factories called **plasma B cells**.

In addition to having hands that can bind to an antigen, an antibody molecule also has a **constant region (Fc)** "tail" which can bind to receptors (**Fc receptors**) on the surface of cells such as macrophages. In fact, it is the special structure of the antibody Fc region that determines its class (e.g., IgG vs. IgA), which immune system cells it will bind to, and how it will function.

The hands of each antibody bind to a specific antigen (e.g., a protein on the surface of the smallpox virus), so in order to have antibodies available that can bind to many different antigens, many different antibody molecules are required. Now, if we want antibodies to protect us from every possible invader (and we do!), how many different antibodies would we need? Well, immunologists estimate

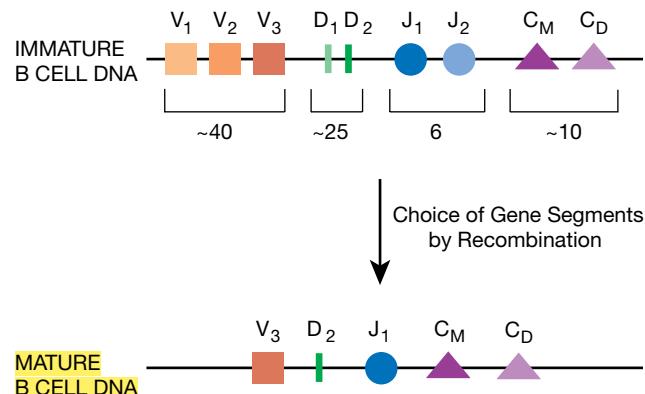
that about 100 million should do the trick. Since each antigen-binding region of an antibody is composed of a heavy chain and a light chain, we could mix and match about 10,000 different heavy chains with 10,000 different light chains to get the 100 million different antibodies we need. However, human cells only have about 25,000 genes in all, so if each heavy or light chain protein were encoded by a different gene, most of a human's genetic information would be used up just to make antibodies. You see the problem.

Generating antibody diversity by modular design

The riddle of how B cells could produce the 100 million different antibodies required to protect us was solved in 1977 by Susumu Tonegawa, who received the Nobel Prize for his discovery. When Tonegawa started working on this problem, the dogma was that the DNA in every cell in the body was the same. This made perfect sense, because after an egg is fertilized, the DNA in the egg is copied. These copies are then passed down to the daughter cells, where they are copied again, and passed down to their daughters – and so on. Therefore, barring errors in copying, each of our cells should end up with the same DNA as the original, fertilized egg. Tonegawa, however, hypothesized that although this is probably true in general, there might be exceptions. His idea was that all of our B cells might start out with the same DNA, but that as these cells mature, the DNA that makes up the antibody genes might change – and these changes might be enough to generate the 100 million different antibodies we need.

Tonegawa decided to test this hypothesis by comparing the DNA sequence of the light chain from a mature B cell with the DNA sequence of the light chain from an immature B cell. Sure enough, he found that they were different, and that they were different in a very interesting way. What Tonegawa and others discovered was that mature antibody genes are made by modular design.

In every B cell, on the chromosomes that encode the antibody heavy chain, there are multiple copies of four types of DNA modules (**gene segments**) called V, D, J, and C. Each copy of a given module is slightly different from the other copies of that module. For example, in humans there are about forty different V segments, about twenty-five different D segments, six different J segments, and so on. To assemble a mature heavy chain gene, each B cell chooses (more or less at random) one of each kind of gene segment, and pastes them together like this.



You have seen this kind of mix-and-match strategy used before to create diversity. For example, twenty different amino acids are mixed and matched to create the huge number of different proteins that our cells produce. And to create genetic diversity, the chromosomes you inherited from your mother and father are mixed and matched to make the set of chromosomes that goes into your egg or sperm cells. Once Mother Nature gets a good idea, she uses it over and over – and modular design is one of her very best ideas.

The DNA that encodes the light chain of the antibody molecule is also assembled by picking gene segments and pasting them together. Because there are so many different gene segments that can be mixed and matched, this scheme can be used to create about 10 million different antibodies – not quite enough. So, to make things even more diverse, when the gene segments are joined together, additional DNA bases are added or deleted. When this **junctional diversity** is included, there is no problem creating 100 million B cells, each with the ability to make a different antibody. The magic of this scheme is that by using modular design and junctional diversity, only a small amount of genetic information is required to create incredible antibody diversity.

Clonal selection

In the human blood stream, there are about three billion B cells. This seems like a lot, but if there are 100 million different kinds of B cells (to produce the 100 million different kinds of antibodies we need for protection), this means that, on average, there will only be about thirty B cells in the blood that can produce an antibody which will bind to a given antigen (e.g., a protein on the surface of a virus). The point here is that, although we have B cells in our arsenal that can deal with essentially any invader, we don't have a lot of any one kind of B cell. As a result, when we are attacked, more of the appropriate B cells must be made. Indeed, B cells are made "on demand." But how

does the immune system know which B cells to make more of? The solution to this problem is one of the most elegant in all of immunology: the principle of **clonal selection**.

After B cells do their mix-and-match thing and paste together the modules required to form the “recipes” for their heavy and light chain antibody proteins, a relatively small number of these proteins is made – a “test batch” of antibody molecules, if you will. These tester antibodies, called **B cell receptors (BCRs)**, are transported to the surface of the B cell and are tethered there with their antigen-binding regions facing out. Each B cell has roughly 100,000 BCRs anchored on its surface, and all the BCRs on a given B cell recognize the same antigen.

The B cell receptors on the surface of a B cell act like “bait.” What they are “fishing for” is the molecule which their Fab regions have the right shape to grasp – their **cognate antigen**. Sadly, the vast majority of B cells fish in vain. For example, most of us will never be infected with polio virus or HIV-1. Consequently, those B cells in our body which could make antibodies that recognize these viruses never will find their match. It must be very frustrating for most B cells. They fish all their lives, and never catch anything!

On occasion, however, a B cell does make a catch. And when a B cell’s receptors bind to its cognate antigen, that B cell is triggered to double in size and divide into two daughter cells – a process immunologists call **proliferation**. Both daughter cells then double in size and divide to produce a total of four cells, and so forth. Each cycle of cell growth and division takes about twelve hours to complete, and this period of proliferation usually lasts about a week. At the end of this time, a “clone” of roughly 20,000 identical B cells will have been produced, all of which have receptors on their surface that can recognize the same antigen. Now there are enough B cells to mount a real defense!

After the selected B cells proliferate to form this large clone, most of them begin to make antibodies in earnest. The antibodies produced by these selected B cells are slightly different from the antibody molecules displayed on their surface in that there is no “anchor” to attach them to the B cell’s surface. As a result, these antibodies are transported out of the B cell and into the blood stream. One B cell, working at full capacity, can pump out about 2,000 antibody molecules per second! After making this heroic effort, most of these B cells die, having worked for only about a week as antibody factories.

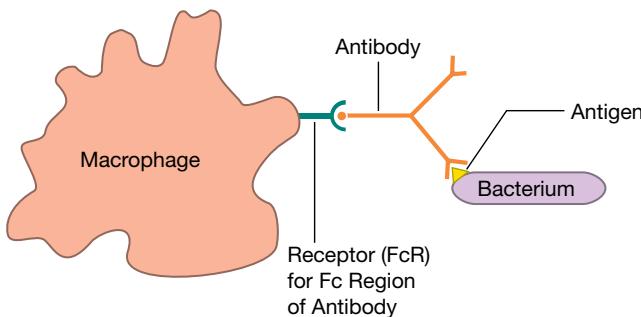
When you think about it, this is a marvelous strategy. First, because they employ modular design, B cells use relatively few genes to create enough different antibody

molecules to recognize any possible invader. Second, B cells are made on demand. So instead of filling up our bodies with a huge number of B cells which may never be used, we begin with a relatively small number of B cells of each kind, and then select the particular B cells that will be useful against the invader *du jour*. Once selected, the B cells proliferate rapidly to produce a large clone of B cells whose antibodies are guaranteed to be useful against the invader. Third, after the clone of B cells has grown sufficiently large, most of these cells become antibody factories which manufacture huge quantities of the very antibodies that are right to defend against the invader. Finally, when the intruder has been conquered, most of the B cells die. As a result, we don’t fill up with B cells that are appropriate to defend against yesterday’s invader, but which would be useless against the enemy that attacks us tomorrow. I love this system!

What antibodies do

Interestingly, although antibodies are very important in the defense against invaders, they don’t really kill anything. Their job is to plant the “kiss of death” on an invader – to tag it for destruction. If you go to a fancy wedding, you’ll usually pass through a receiving line before you are allowed to enjoy the champagne and cake. Of course, one of the functions of this receiving line is to introduce everyone to the bride and groom. But the other function is to be sure no outsiders are admitted to the celebration. As you pass through the line, you will be screened by someone who is familiar with all the invited guests. If she finds that you don’t belong there, she will call the bouncer and have you removed. She doesn’t do it herself – certainly not. Her role is to identify undesirables, not to show them to the door. And it’s the same with antibodies: They identify invaders, and let other players do the dirty work.

In developed countries, the invaders we encounter most frequently are bacteria and viruses. Antibodies can bind to both types of invaders and tag them for destruction. Immunologists like to say that antibodies can **opsonize** these invaders. This term comes from a German word that means “to prepare for eating.” I like to equate opsonize with “decorate,” because I picture these bacteria and viruses with antibodies hanging all over them, decorating their surfaces. Anyway, when antibodies opsonize bacteria or viruses, they do so by binding to the invader with their Fab regions, leaving their Fc tails available to bind to Fc receptors on the surface of cells such as macrophages. Using this strategy, antibodies can form a bridge between the invader and the phagocyte, bringing the invader in close, and preparing it for phagocytosis.



In fact, it's even better than this. When a phagocyte's Fc receptors bind to antibodies that are opsonizing an invader, the appetite of the phagocyte increases, making it even more phagocytic. Macrophages have proteins on their surface that can bind directly to many common invaders. However, the ability of antibodies to form a bridge between a macrophage and an invader allows a macrophage to increase its catalog of enemies to include any invader to which an antibody can bind, common or uncommon. In effect, antibodies focus a macrophage's attention on invaders, some of which (the uncommon ones) a macrophage would otherwise ignore.

During a viral attack, antibodies can do something else that is very important. Viruses enter our cells by binding to certain receptor molecules on a cell's surface. Of course these receptors are not placed there for the convenience of the virus. They are normal receptors, such as the Fc receptor, that have quite legitimate functions, but which the virus has learned to use to its own advantage. Once it has bound to these receptors and entered a cell, a virus then uses the cell's machinery to make many copies of itself. These newly made viruses burst out of the cell, sometimes killing it, and go on to infect neighboring cells. Now for the neat part: Antibodies can actually bind to a virus while it is still outside of a cell, and can keep the virus either from entering the cell or from reproducing once it has entered. For example, some antibodies can attach to the part of the virus that normally would plug into its cellular receptor and prevent the virus from "docking" on the surface of a cell. Antibodies with these special properties are called **neutralizing antibodies**.

T cells

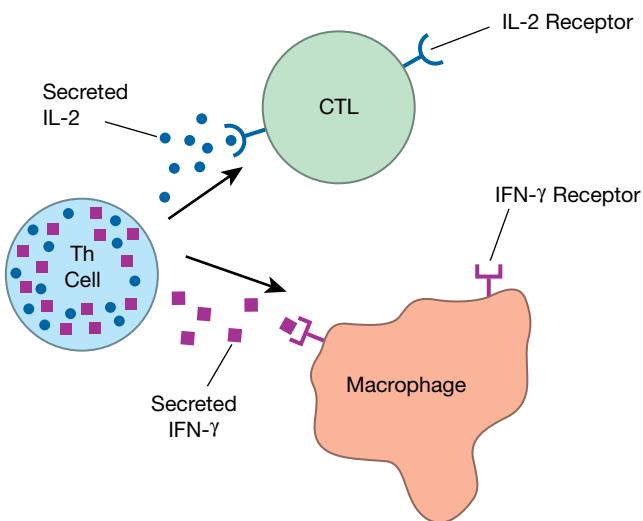
Although antibodies can tag viruses for phagocytic ingestion and can help keep viruses from infecting cells, there is a weakness in the antibody defense against viruses: Once a virus gets into a cell, antibodies can't get to it, so the virus is safe to make thousands of copies of itself. To deal with this potential problem, the immune system evolved to include another weapon: the **T cell** – an additional member of the adaptive immune system team.

The importance of T cells is suggested by the fact that an adult human has about 300 billion of them. T cells are very similar to B cells in appearance. In fact, under an ordinary microscope, an immunologist can't tell them apart. Like B cells, T cells are produced in the bone marrow, and on their surface they display antibody-like molecules called **T cell receptors (TCRs)**. Like the B cell's receptors (the antibody molecules attached to its surface), TCRs are made by a mix-and-match, modular design strategy. As a result, TCRs are about as diverse as BCRs. T cells also employ the principle of clonal selection: When a T cell's receptors bind to their cognate antigen, the T cell proliferates to build up a clone of T cells with the same specificity. This proliferation stage takes about a week, so like the antibody response, the T cell response is slow and specific.

Although they are similar in many ways, there are also important differences between B cells and T cells. B cells mature in the bone marrow, whereas T cells mature in the thymus (that's why they're called "T" cells). B cells make antibodies that can recognize any organic molecule, but T cells specialize in recognizing protein antigens. Although a B cell can secrete its receptors in the form of antibodies, a T cell's receptors remain tightly glued to its surface. Perhaps most importantly, a B cell can recognize an antigen "by itself," whereas a T cell will only recognize an antigen if it is "properly presented" by another cell. I'll explain what that means in a bit.

There are actually three main types of T cells: **killer T cells** (frequently called **cytotoxic lymphocytes or CTLs**), **helper T cells**, and **regulatory T cells**. The killer T cell is a potent weapon that can destroy virus-infected cells. Indeed, by recognizing and killing these cells, the CTL solves the "hiding virus" problem – the weakness I mentioned in the antibody defense against viruses. The way a killer T cell destroys virus-infected cells is by making contact with its target and then triggering the cell to commit suicide! This "assisted suicide" is a great way to deal with viruses that have infected cells – because when a virus-infected cell dies, the viruses within the cell die also.

The second type of T cell is the **helper T cell (Th cell)**. As you will see, this cell serves as the quarterback of the immune system team. It directs the action by secreting chemical messengers (cytokines) that have dramatic effects on other immune system cells. These cytokines have names like **interleukin 2 (IL-2)** and **interferon gamma (IFN- γ)**, and we will discuss what they do in later lectures. For now, it is only important to realize that helper T cells are basically cytokine factories.



The third type of T cell is the **regulatory T cell**. The role of this type of T cell is to **keep the immune system from over-reacting or from reacting inappropriately**. Immunologists are still working to understand how T cells become regulatory T cells and exactly how they perform these important functions. I'll tell you more about regulatory T cells in later lectures.

Antigen presentation

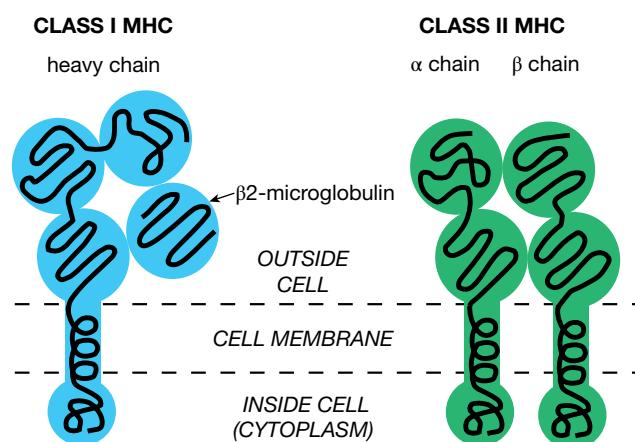
One thing I need to clear up is **exactly how antigen is presented to T cells**. It turns out that special proteins called **major histocompatibility complex (MHC)** proteins do the "presenting," and that T cells use their receptors to "view" this presented antigen. As you may know, "histo" means tissue, and these major histocompatibility proteins, in addition to being presentation molecules, also are involved in the rejection of transplanted organs. In fact, when you hear that someone is waiting for a "matched" kidney, it's the MHC molecules of the donor and the recipient that the transplant surgeon is trying to match.

There are two types of MHC molecules, called class I and class II. **Class I MHC molecules** are found in varying amounts on the surface of most cells in the body. Class I MHC molecules function as "billboards," which inform killer T cells about what is going on inside these cells. For example, when a human cell is infected by a virus, fragments of viral proteins called **peptides** are loaded onto class I MHC molecules and transported to the surface of the infected cell. By inspecting these protein fragments displayed by class I MHC molecules, killer T cells can use their receptors to "look into" the cell to discover that it has been infected and that it should be destroyed.

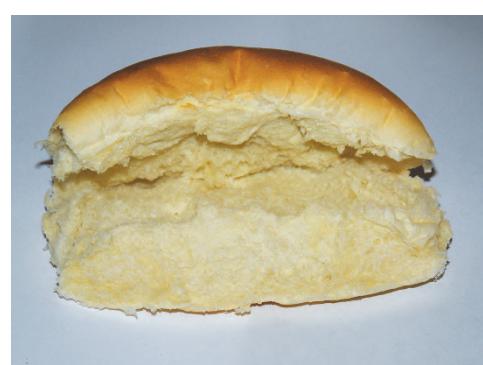
Class II MHC molecules also function as billboards, but **this display is intended for the enlightenment of helper T cells**. Only certain cells in the body make class II

MHC molecules, and these are called **antigen presenting cells (APCs)**. Macrophages, for example, are excellent antigen presenting cells. During a bacterial infection, a macrophage will "eat" bacteria, and will load fragments of ingested bacterial proteins onto class II MHC molecules for display on the surface of the macrophage. Then, using their T cell receptors, helper T cells can scan the macrophage's class II MHC billboards for news of the bacterial infection. So class I MHC molecules alert killer T cells when something isn't right inside a cell, and class II MHC molecules displayed on APCs inform helper T cells that problems exist outside of cells.

Although a class I MHC molecule is made up of one long chain (the heavy chain) plus a short chain (**$\beta 2$ -microglobulin**), and a class II MHC molecule has two long chains (α and β), you'll notice that these molecules are rather similar in appearance.



Okay, I know it's hard to visualize the real shapes of molecules from drawings like this, so I thought I'd show you a few pictures that may make this more real. Here's what an empty MHC molecule might look like from the viewpoint of the T cell receptor. Right away you see the groove into which the protein fragment would fit.



Next, let's look at a fully-loaded class I molecule.



I can tell it's a class I MHC molecule because the peptide is contained nicely within the groove. It turns out that the ends of the groove of a class I molecule are closed, so a protein fragment must be about nine amino acids in length to fit in properly. Class II MHC molecules are slightly different.



Here you see that the peptide overflows the groove. This works fine for class II, because the ends of the groove are open, so protein fragments as large as about twenty amino acids fit nicely.

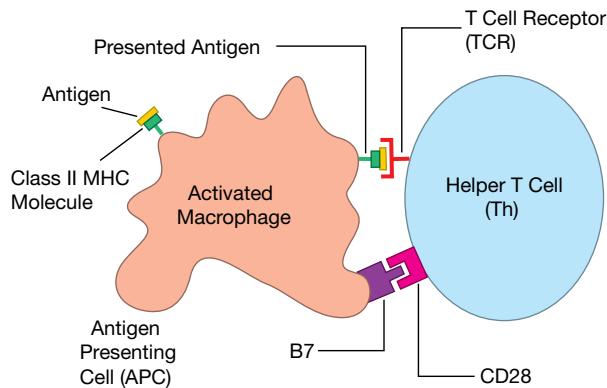
So MHC molecules resemble buns, and the protein fragments they present resemble wieners. And if you imagine that the cells in our bodies have hot dogs on their surfaces, you won't be far wrong about antigen presentation. That's certainly the way I picture it!

Activation of the adaptive immune system

Because B and T cells are such potent weapons, there is a requirement that cells of the adaptive immune system must be activated before they can function. B and T cells are called **lymphocytes**, and how they are activated is one of the key issues in immunology. To introduce this concept, I will sketch how helper T cells are activated.

The first step in the activation of a helper T cell is recognition of its cognate antigen (e.g., a fragment of a bacterial protein) displayed by class II MHC molecules on the surface of an antigen presenting cell. However, seeing its cognate antigen on that billboard isn't enough – a second

signal or "key" also is required for activation. This second signal is nonspecific (it's the same for any antigen), and it involves a protein (B7 in this drawing) on the surface of an antigen presenting cell that plugs into its receptor (CD28) on the surface of the helper T cell.



You see an example of this kind of two-key system when you visit your safe deposit box. You bring with you a key that is specific for your box – it won't fit any other. The bank teller provides a second, nonspecific key that will fit all the boxes. Only when both keys are inserted into the locks on your box can it be opened. Your specific key alone won't do it, and the teller's nonspecific key alone won't either. You need both. Now, why do you suppose helper T cells and other cells of the adaptive immune system require two keys for activation? For safety, of course – just like your bank box. These cells are powerful weapons that must only be activated at the appropriate time and place.

Once a helper T cell has been activated by this two-key system, it proliferates to build up a clone composed of many helper T cells whose receptors recognize the same antigen. These helper cells then mature into cells that can produce the cytokines needed to direct the activities of the immune system. B cells and killer T cells also require two-key systems for their activation, and we'll talk about them in another lecture.

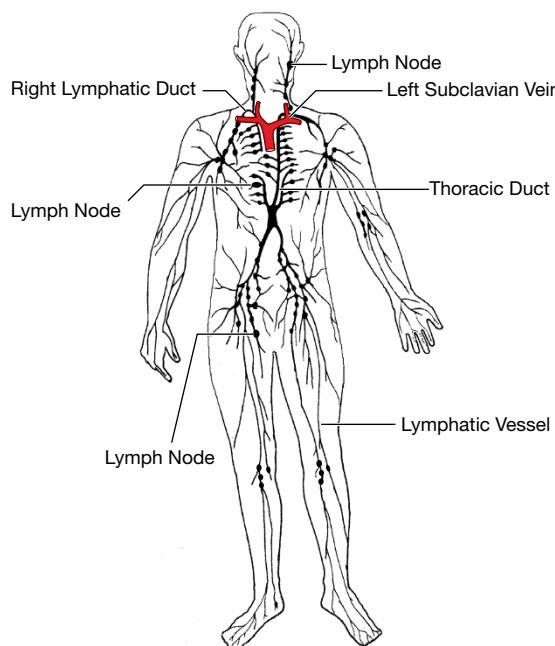
The secondary lymphoid organs

If you've been thinking about how the adaptive immune system might get turned on during an attack, you've probably begun to wonder whether this could ever happen. After all, there are only between 100 and 1,000 T cells that will have TCRs specific for a given invader, and for these T cells to be activated, they must come in contact with an antigen presenting cell that has "seen" that invader. Given that these T cells and APCs are spread throughout the body, it would seem very unlikely that this would happen before an invasion got completely out of hand. Fortunately, to make this work with reasonable probability, the immune system includes "meeting

places" – the **secondary lymphoid organs**. The best known secondary lymphoid organ is the **lymph node**.

You may not be familiar with the **lymphatic system**, so I'd better say a few words about it. In your home, you have two plumbing systems. The first supplies the water that comes out of your faucets. This is a pressurized system, with the pressure being provided by a pump. You have another plumbing system that includes the drains in your sinks, showers, and toilets. This second system is not under pressure – the water just flows down the drain and out into the sewer. The two systems are connected in the sense that eventually the wastewater is recycled and used again.

The plumbing in a human is very much like this. We have a pressurized system (the cardiovascular system) in which blood is pumped around the body by the heart. Everybody knows about this one. But we also have **another plumbing system: the lymphatic system**. This system is not under pressure, and it **drains the fluid (lymph) that leaks out of our blood vessels into our tissues**. Without this system, our tissues would fill up with fluid and we'd blow up like a balloon! Lymph is collected from the tissues of our lower body into lymphatic vessels, and is transported by these vessels, under the influence of muscular contraction, through a series of one-way valves to the upper torso. This lymph, plus lymph from the left side of the upper torso, is collected into the thoracic duct and emptied into the left subclavian vein to be recycled back into the blood. Likewise, lymph from the right side of the upper body is collected into the right lymphatic duct and is emptied into the right subclavian vein. **Importantly, on its way back to be reunited with the blood, the lymph passes through a series of way stations – the lymph nodes.**



In a human, there are about 500 lymph nodes that range in size from very small to almost as big as a Brussels sprout. Most are arrayed in "chains" that are connected by lymphatic vessels. **Invaders such as bacteria and viruses are carried by the lymph to nearby nodes, and antigen presenting cells that have picked up foreign antigens in the tissues travel to lymph nodes to present their cargo.** Meanwhile, B cells and T cells circulate from node to node, looking for the antigens for which they are "fated." **So lymph nodes really function as "dating bars" – places where T cells, B cells, APCs, and antigens all gather for the purpose of communication and activation.** Bringing these cells and antigens together within the small volume of a lymph node greatly increases the probability that they will interact and efficiently activate the adaptive immune system.

Immunological memory

After B and T cells have been activated, have proliferated to build up clones of cells with identical antigen specificities, and have vanquished the enemy, **most of them die off**. This is **a good thing, because we wouldn't want our immune system to fill up with old B and T cells**. On the other hand, it would be nice if some of these experienced B and T cells would stick around, just in case we are exposed to the same invaders again. That way, the adaptive immune system wouldn't have to start from scratch. And that's just the way it works. **These leftover B and T cells are called **memory cells**.** In addition to being more numerous than the original, inexperienced B and T cells, memory cells are easier to activate. As a result of this immunological memory, during a second attack, the adaptive system can usually spring into action so quickly that you never even experience any symptoms.

Tolerance of self

As I mentioned earlier, B cell receptors and T cell receptors are so diverse that they should be able to recognize any invader. However, this diversity poses a potential problem: If B and T cell receptors are this diverse, many of them are certain to recognize our own "self" molecules (e.g., the molecules that make up our cells, or proteins like insulin that circulate in our blood). If this were to happen, our adaptive immune system might attack our own bodies, and we could die from autoimmune disease. Fortunately, B cells and T cells are "screened" to avoid autoimmunity, and this testing is sufficiently rigorous that autoimmune disease is relatively rare.

A COMPARISON OF THE INNATE AND ADAPTIVE IMMUNE SYSTEMS

Now that you have met some of the main players, I want to emphasize the differences between the innate and adaptive

immune system teams. Understanding how they differ is crucial to understanding how the immune system works.

Imagine that you are in the middle of town and someone steals your shoes. You look around for a store where you can buy another pair, and the first store you see is called Charlie's Custom Shoes. This store has shoes of every style, color, and size, and the salesperson is able to fit you in exactly the shoes you need. However, when it comes time to pay, you are told that you must wait a week or two to get your shoes – they will have to be custom-made for you, and that will take a while. But you need shoes right now! So they send you across the street to Freddie's Fast Fit – a store that only carries a few styles and sizes. Freddie's wouldn't be able to fit Shaquille O'Neal, but this store does stock shoes in the common sizes that fit most people. Consequently, you can buy a pair of shoes from Freddie's that will tide you over while your custom shoes are being made for you.

This is very similar to the way the innate and adaptive immune systems work. The players of the innate system (such as the macrophage) are already in place, and are ready to defend against a relatively small attack by invaders we are likely to meet on a day-to-day basis. Indeed, in many instances, the innate system is so effective and so fast that the adaptive immune system never even kicks in. In other cases, the innate system may be insufficient to deal with an invasion, and the adaptive system will need to be mobilized. This takes time, however, because the B and T cells of the adaptive system must be custom-made through the process of clonal selection and proliferation. Consequently, while these "designer cells" are being produced, the innate immune system must do its best to hold the invaders at bay.

THE INNATE SYSTEM RULES!

Immunologists used to believe that the only function of the innate system was to provide a rapid defense which would deal with invaders while the adaptive immune system was getting cranked up. However, it is now clear that the innate system does much more than that.

The adaptive immune system's antigen receptors (BCRs and TCRs) are so diverse that they can probably recognize any protein molecule in the universe. However, the adaptive system is clueless as to which of these molecules is dangerous and which is not. So how does the adaptive system distinguish friend from foe? The answer is that it relies on the judgment of the innate system.

The receptors of the innate system are precisely tuned to detect the presence of the common pathogens (disease-causing agents) we encounter in daily life – viruses, bacteria, fungi, and parasites. In addition, the innate system has receptors which can detect when even "uncommon" pathogens kill human cells. Consequently, it is the innate system which is responsible for evaluating the danger and for activating the adaptive immune system. In a real sense, the innate system does "risk assessment" and gives "permission" to the adaptive system to respond to an invasion. But it's even better than that, because the innate system does more than just turn the adaptive system on. The innate system actually integrates all the information it collects about an invader, and formulates a plan of action. This "game plan," which the innate system delivers to the adaptive immune system, tells which weapons must be mobilized (e.g., B cells or killer T cells) and where in the body these weapons should be deployed. So if we think of the helper T cell as the quarterback of the adaptive immune system team, we should consider the innate immune system to be the "coach" – for it is the innate system which "scouts" the opponents, designs the game plan, and sends in the plays for the quarterback to call.

EPILOGUE

We have come to the end of our turbo-charged overview of the immune system, and by now you should have a rough idea of how the system works. In the next nine lectures, we will focus more sharply on the individual players of the innate and adaptive system teams, paying special attention to how and where these players interact with each other to make the system function efficiently.

The Innate Immune System

HEADS UP!

The innate immune system is a “hard-wired” defense that has evolved over millions of years to recognize pathogens that commonly infect humans. The innate system team includes the complement system of proteins, the professional phagocytes, and natural killer cells. Before they can fight, these warriors must be activated. Cooperation between innate system players is critical to insure a fast and effective response against everyday invaders.

INTRODUCTION

For years, immunologists didn’t pay much attention to the innate system – because the adaptive system seemed more interesting. However, studies of the adaptive immune system have led to a new appreciation of the role that the innate system plays, not only as a lightning-fast second line of defense (if we count physical barriers as our first defense), but also as an activator and a controller of the adaptive immune system.

It’s easy to understand the importance of the innate system’s quick response to common invaders if you think about what could happen in an uncontrolled bacterial infection. Imagine that the splinter from your hot tub deck introduced just one bacterium into your tissues. As you know, bacteria multiply very quickly. In fact, a single bacterium doubling in number every thirty minutes could give rise to roughly 100 trillion bacteria in one day. If you’ve ever worked with bacterial cultures, you know that a one liter culture containing one trillion bacteria is so dense you can’t see through it. So, a single bacterium proliferating for one day could yield a dense culture of about

100 liters. Now remember that your total blood volume is only about five liters, and you can appreciate what an unchecked bacterial infection could do to a human! Without the quick-acting innate immune system to defend us, we would clearly be in big trouble.

THE COMPLEMENT SYSTEM

The complement system is composed of about twenty different proteins that work together to destroy invaders and to signal other immune system players that the attack is on. The complement system is very old. Even sea urchins, which evolved about 700 million years ago, have a complement system. In humans, complement proteins start being made during the first trimester of fetal development, so this important system is ready to go well before a child is born. Indeed, those rare humans born with a defect in one of the major complement proteins usually do not live long before succumbing to infection.

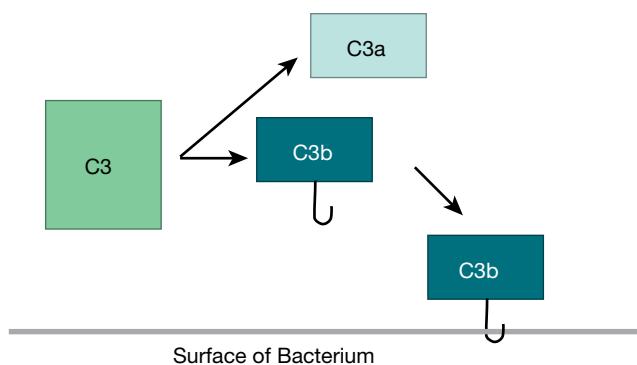
When I first read about the complement system, I thought it was way too complicated to even bother understanding. But as I studied it further, I began to realize that it is really quite simple and elegant. As with just about everything else in the immune defense, the complement system must be activated before it can function, and there are three ways this can happen. The first, the so-called “classical” pathway, depends on antibodies for activation, so we’ll save that for a later lecture. Because the way the complement system functions is independent of how it is activated, you won’t miss much by waiting to hear about the antibody-dependent pathway of activation.

The alternative pathway

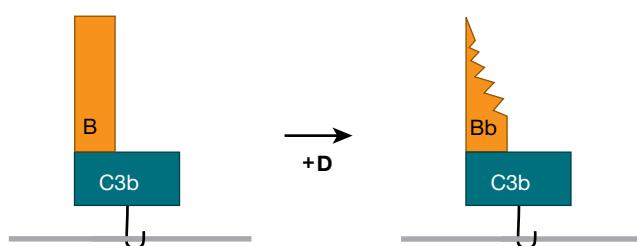
The second way the complement system can be activated is called the alternative pathway – although the alternative pathway certainly evolved before the classical

pathway. Immunologists call antibody-dependent activation “classical,” simply because it happened to have been discovered first.

The proteins that make up the complement system are produced mainly by the liver, and are present at high concentrations in blood and tissues. The most abundant complement protein is called C3, and in the human body, C3 molecules are continually being broken into two smaller proteins. One of the protein fragments created by this “spontaneous” cleavage, C3b, is very reactive, and can bind to either of two common chemical groups (amino or hydroxyl groups). Because many of the proteins and carbohydrates that make up the surfaces of invaders (e.g., bacterial cells) have amino or hydroxyl groups, there are lots of targets for these little C3b “grenades.”

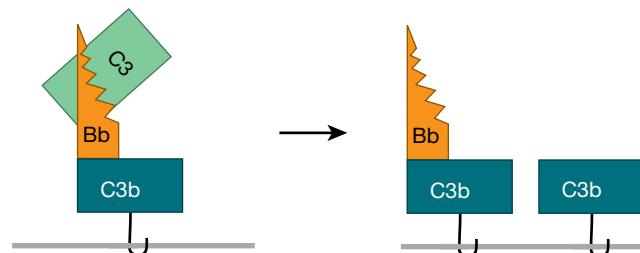


If C3b doesn't find one of these chemical groups to react with within about sixty microseconds, it is neutralized by binding to a water molecule, and the game is over. This means that the spontaneously clipped C3 molecule has to be right up close to the surface of the invading cell in order for the complement cascade to continue. Once C3b is stabilized by reacting with a molecule on the cell surface, another complement protein, B, binds to C3b, and complement protein D comes along and clips off part of B to yield C3bBb.

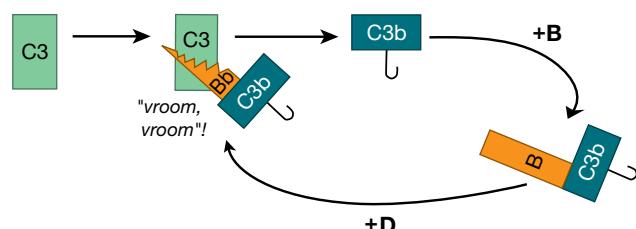


Once a bacterium has this C3bBb molecule glued to its surface, the fun really begins, because C3bBb acts like a “chain saw” that can cut other C3 proteins and convert them to C3b. Consequently, C3 molecules that are in the

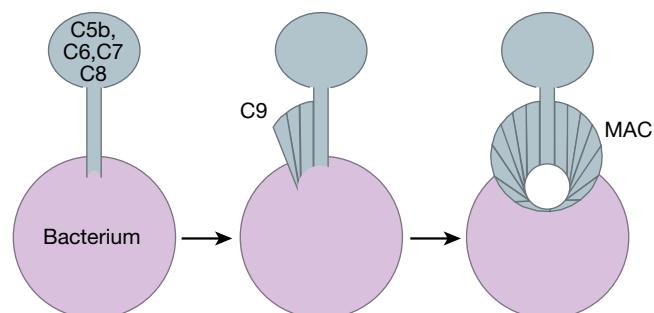
neighborhood don't have to wait for spontaneous clipping – the C3bBb molecule (called a **convertase**) can do the job very efficiently. And once another C3 molecule has been clipped, it too can bind to an amino or hydroxyl group on the surface of the bacterium.



This process can continue, and pretty soon there will be lots of C3b molecules attached to the surface of the target bacterium – and each of them can form a C3bBb convertase – which can then cut even more C3 molecules. All this attaching and cutting sets up a positive feedback loop and the whole process just snowballs.



Once C3b is bound to the surface of a bacterium, the complement cascade can proceed further. The C3bBb chain saw can bind to another molecule of C3b, and together they can clip a complement protein called C5 into two pieces. One of these pieces, C5b, can then combine with other complement proteins (C6, C7, C8, and C9) to make a **membrane attack complex (MAC)**. To form this structure, C5b, C6, C7, and C8 form a “stalk” that anchors the complex in the bacterial cell membrane. Then C9 proteins are added to make a channel that opens up a hole in the surface of the bacterium. And once a bacterium has a hole in its surface, it's toast!



I have used a bacterium as our model pathogen, but the complement system also can defend against other invaders such as parasites and even some viruses. For example, complement proteins can poke holes in enveloped viruses (e.g., HIV-1) by constructing membrane attack complexes on the surface of the virus.

Now, you may be thinking: With these grenades going off all over the place, why doesn't the complement system form membrane attack complexes on the surface of our own cells? The answer is that human cells are equipped with many safeguards that keep this from happening. In fact, there are about as many proteins devoted to controlling the complement system as there are proteins in the system itself! For instance, the complement fragment C3b can be clipped to an inactive form by proteins in the blood, and this clipping is accelerated by an enzyme (MCP) that is present on the surface of human cells. There is also a protein on human cells called decay accelerating factor (DAF), which accelerates the destruction of the convertase C3bBb by other blood proteins. This can keep the positive feedback loop from getting started. And yet another human cell-surface protein, CD59 (also called protectin), prevents the incorporation of C9 molecules into nascent MACs.

An interesting story illustrates why these safeguards are so important. Transplant surgeons don't have enough human organs to satisfy the demand for transplantation, so they are considering using organs from animals. One of the hot candidates for an organ donor is the pig, because pigs are cheap to raise and some of their organs are about the same size as those of humans. As a warm-up for human transplantation, surgeons decided to transplant a pig organ into a baboon. This experiment was not a big success! Almost immediately, the baboon's immune system began to attack the organ, and within minutes the transplanted organ was a bloody pulp. The culprit? The complement system. It turns out that the pig versions of DAF and CD59 don't work to control primate complement, so the unprotected pig organ was vulnerable to attack by the baboon's complement system.

This story highlights two important features of the complement system. First, **the complement system works very fast**. Complement proteins are present at high concentrations in blood and in tissues, and they are ready to go against any invader that has a surface with a spare hydroxyl or amino group. A second characteristic of this system is that **if a cell surface is not protected, it will be attacked by complement. In fact, the picture you should have is that the complement system is continually dropping these little grenades, and any unprotected surface will be a target. In this system, the default option is death!**

The lectin activation pathway

In addition to the classical (antibody-dependent) and alternative (antibody-independent) pathways of complement activation, there is a third pathway that may be the most important activation pathway of all: the **lectin activation pathway**. The central player in this pathway is a protein that is produced mainly in the liver, and which is present in moderate concentrations in the blood and tissues. This protein is called **mannose-binding lectin (MBL)**. A lectin is a protein that is able to bind to a carbohydrate molecule, and mannose is a carbohydrate molecule found on the surface of many common pathogens. For example, MBL has been shown to bind to yeasts such as *Candida albicans*; to viruses such as HIV-1 and influenza A; to many bacteria, including *Salmonella* and *Streptococcus*; and to parasites such as *Leishmania*. In contrast, mannose-binding lectin does not bind to the carbohydrates found on healthy human cells and tissues. This is an example of an important strategy employed by the innate system: **The innate system mainly focuses on patterns of carbohydrates and fats that are found on the surface of common pathogens, but not on the surface of human cells.**

The way mannose-binding lectin works to activate the complement system is very simple. In the blood, MBL binds to another protein called MASP. Then, when the mannose-binding lectin grabs its target (mannose on the surface of a bacterium, for example), the MASP protein functions like a convertase to clip C3 complement proteins to make C3b. Because C3 is so abundant in the blood, this happens very efficiently. The C3b fragments can then bind to the surface of the bacterium, and the complement chain reaction we just discussed will be off and running. So, **whereas the alternative activation pathway is spontaneous, and can be visualized as complement grenades going off randomly here and there to destroy any unprotected surface, lectin activation can be thought of as complement "smart bombs" that are targeted by mannose-binding lectins.**

Other complement system functions

In addition to building membrane attack complexes, the complement system has two other important functions. When C3b has attached itself to the surface of an invader, it can be clipped by a serum protein to produce a smaller fragment, iC3b. The "i" prefix denotes that this cleaved protein is now **inactive** for making MACs. However, it is still glued to the invader, and it can prepare the invader for phagocytosis (i.e., can opsonize it) in much the same way that invaders can be opsonized by antibodies. On the surface of phagocytes (e.g., macrophages) are receptors that can bind to iC3b, and the binding of iC3b-opsonized

invaders facilitates phagocytosis. Many invaders have surfaces that are rather “slimy,” making them difficult for macrophages to grasp. However, when these slippery invaders are coated with complement fragments, phagocytes can get a better grip. Thus, **a second function of complement is to decorate the surfaces of invaders, thereby acting like a “poor man’s antibody” in opsonization.**

The complement system has a third important function: **Fragments of complement proteins can serve as chemoattractants – chemicals that recruit other immune system players to the battle site.** For example, **C3a** and **C5a** are the pieces of C3 and C5 that are clipped off when C3b and C5b are made (let nothing be wasted!). These fragments don’t bind to the surface of invaders. Rather, they are set free in the tissues where they function as chemoattractants. C5a is an especially powerful chemoattractant for macrophages, and can activate them so that they become more potent killers. Interestingly, these fragments, C3a and C5a, are called **anaphylatoxins**, because they can contribute to anaphylactic shock – something we will talk about in another lecture.

So **the complement system is quite multifunctional: It can destroy invaders by building membrane attack complexes; it can tag intruders for destruction by phagocytes; it can alert other cells that we are being attacked and direct them to the battle scene; and it can help activate them. Most importantly, it can do all these things very fast.**

THE PROFESSIONAL PHAGOCYTES

Professional phagocytes comprise **the second arm of the innate system**. These cells are called “professional” because they make their living mainly by eating (phagocytosis). The most important professional phagocytes are the **macrophages and the neutrophils**.

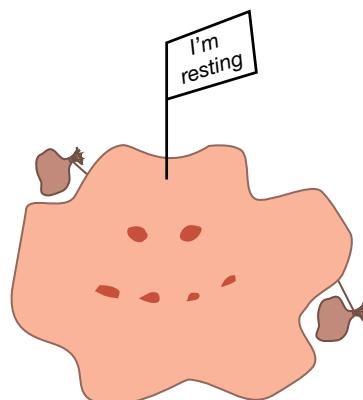
Macrophages – immune system sentinels

Macrophages are found **under your skin**, where they provide protection against invaders which penetrate this barrier and gain entry into your tissues (e.g., as the result of a wound or a burn). Macrophages also are present in your lungs, where they defend against inhaled microbes. Still other macrophages reside in the tissues that surround your intestines. There they lie in wait for microbial invaders you have ingested, which have escaped the confines of your intestines, and which have entered your tissues. Indeed, **macrophages are sentinel cells that can be found just below the surface in all areas of your body which are exposed to the outside world** – areas that are prime targets for microbial infection. Macrophages are present in most tissues before birth, so they are already on duty when a baby is

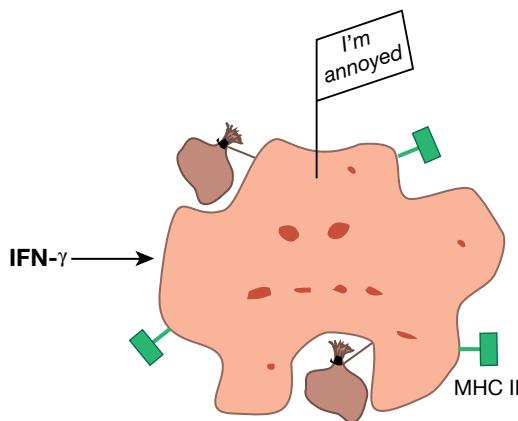
born. Later, in response to an infection, monocytes can be recruited from the bone marrow and can enter infected tissues. **There they mature into macrophages and can help the tissue-resident macrophages deal with the invader.**

Macrophages can exist in three stages of readiness. In tissues, they usually are found just lounging and slowly proliferating. In this “resting” state, they function primarily as **garbage collectors**, taking sips of whatever is around them, and keeping our tissues free of debris. About one million cells die per second in an adult human, so macrophages have a lot of tidying up to do. **Dying cells** give off “find me” signals that attract macrophages, bringing them close enough to recognize “eat me” signals displayed on the surface of these cells. Healthy cells, on the other hand, display “don’t eat me” signals on their surface to protect them from macrophage ingestion.

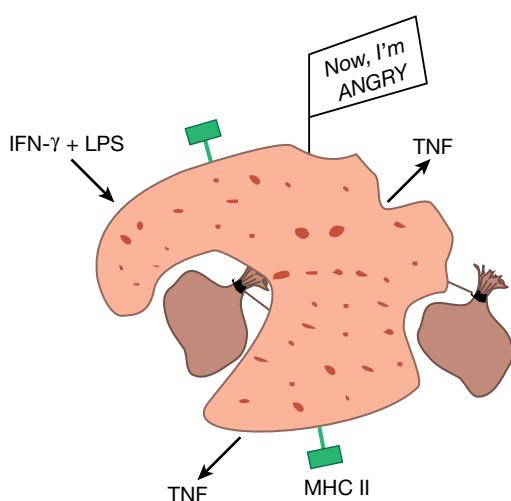
Resting macrophages **express very few class II MHC molecules on their surface**, so they aren’t much good at presenting antigen to helper T cells. This makes sense. Why would they want to present garbage anyway? For the average macrophage, life is pretty boring. They live for months in tissues and just collect garbage.



Every once in a while, however, some of these resting macrophages receive signals which alert them that the barrier defense has been penetrated and that there are **intruders in the area**. When this happens, they become activated (or “primed,” as immunologists usually say). In this state, macrophages take larger gulps and **upregulate expression of class II MHC molecules**. Now a macrophage can **function as an antigen presenting cell**, and when it **engulfs invaders**, it can use its class II MHC molecules to **display fragments of the invaders’ proteins for helper T cells to see**. Although a number of different signals can prime a resting macrophage, the best studied is an intercellular communication molecule (cytokine) called **interferon gamma (IFN-γ)**. This cytokine is produced mainly by helper T cells and natural killer cells.



In the primed state, macrophages are good antigen presenters and reasonably good killers. However, there is an even higher state of readiness, "hyperactivation," which they can attain if they receive a direct signal from an invader. Such a signal can be conveyed, for example, by a molecule called **lipopolysaccharide (LPS)**. LPS, a component of the outer cell membrane of Gram-negative bacteria such as *Escherichia coli*, can be shed by these bacteria, and can activate receptors on the surface of primed macrophages. Macrophages also have receptors for mannose. When receptors on the surface of a macrophage detect "danger signals" such as LPS or mannose, the macrophage knows for sure that there has been an invasion. Faced with this realization, the macrophage stops proliferating, and focuses its attention on killing. In the hyperactive state, macrophages grow larger and increase their rate of phagocytosis. In fact, they become so large and phagocytic that they can ingest invaders that are as big as unicellular parasites. Hyperactivated macrophages also produce and secrete another cytokine, **tumor necrosis factor (TNF)**. This cytokine can kill tumor cells and virus-infected cells, and can help activate other immune system warriors.



Inside a hyperactivated macrophage, the number of lysosomes increases, so that the destruction of ingested invaders becomes more efficient. In addition, hyperactivated macrophages increase production of reactive oxygen molecules such as hydrogen peroxide. You know what peroxide can do to hair, so you can imagine what it might do to a bacterium! Finally, when hyperactivated, a macrophage can dump the contents of its lysosomes onto multicellular parasites, enabling it to destroy invaders that are too large for it to "eat." Yes, a hyperactivated macrophage is a killing machine!

So a macrophage is a versatile cell. It can function as a garbage collector, as an antigen presenting cell, or as a vicious killer—depending on its activation level. However, you shouldn't get the impression that macrophages have three "gears." Nothing in immunology has gears, and the activation state of a macrophage is a continuum that really depends on the type and the strength of the activation signals it receives.

Usually, macrophages are able to deal with small attacks. However, when invaders are numerous, macrophages risk being overpowered, and in those cases, macrophages call for backup. The most common reinforcement for battling macrophages is a cell called a **neutrophil**. Indeed, although the macrophage is unmatched in versatility, the most important of the professional phagocytes is probably the neutrophil.

Neutrophils – the immune system's foot soldiers

All of our cells receive their nutrients from the blood, and consequently no cell is more than about the thickness of a fingernail from a blood vessel. If a cell is farther away than that, it will die of starvation. Because our tissues are laced with blood vessels, blood is the perfect vehicle for bringing reinforcements to parts of the body that are under attack. And circulating through our veins and arteries are about twenty billion neutrophils. In contrast to macrophages, which can be thought of as sentinels, neutrophils are more like "foot soldiers." Their job is to "kill things and break stuff," and they are really good at this.

Neutrophils live a very short time. In fact, they come out of the bone marrow programmed to die in an average of about five days. In contrast to macrophages, **neutrophils are not antigen presenting cells. They are professional killers which are on call from the blood.**

Once they have been summoned, it only takes neutrophils about half an hour to exit the blood and become fully activated. In this state, neutrophils are incredibly phagocytic, and once their prey has been taken inside, a whole battery of powerful chemicals awaits the unlucky

guest. Neutrophils also produce battle cytokines (e.g., TNF) that can alert other immune system cells. And most importantly, activated neutrophils give off destructive chemicals which are pre-made and stored inside the neutrophil until needed. These chemicals can turn tissues into a toxic soup that is lethal to invading microbes. Indeed, neutrophils are unique in that they are the only immune system cells that are “licensed” to liquify both cells and connective tissue.

My friend Dan Tenen studies neutrophils. Another friend, Linda Clayton, who experiments with T cells, likes to kid him by asking, “Why do you bother studying neutrophils, Dan? All they do is dive into pus and die!” She’s right, of course. Pus is mainly dead neutrophils. However, Dan reminds her that humans can live for long periods without her fancy T cells, but without his neutrophils they will succumb to infection and die within a matter of days.

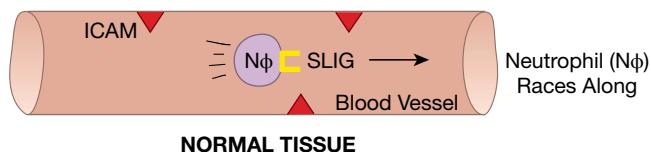
Now, why do you think things are set up so that macrophages are very long-lived, yet neutrophils live only a few days? Doesn’t that seem wasteful? Why not let neutrophils enjoy a long life, just like macrophages? That’s right! It would be too dangerous. Neutrophils come out of blood vessels ready to kill, and in the course of this killing, there is always damage to normal tissues. So to limit collateral damage, neutrophils are programmed to be short-lived. If the battle requires additional neutrophils, more can be recruited from the blood – there are plenty of them there. Indeed, neutrophils represent about 70% of the circulating white blood cells. In contrast, because macrophages act as sentinels that watch for invaders and signal an attack, it makes sense that macrophages should have a long life out in the tissues.

It has been known for a long time that neutrophils are voracious phagocytes, and that they can give off chemicals that destroy both invaders and tissues. Recently, however, it was discovered that under certain conditions, some dying neutrophils can release web-like structures called **neutrophil extracellular traps (NETs)**. These NETs are composed of cellular DNA that is coated with proteins derived from the granules in which neutrophils store the chemicals they use to do their destructive work. In the laboratory, NETs can trap or kill bacteria, viruses, fungi, and parasites. Nevertheless, it is not yet clear what triggers neutrophils to release these NETs, or how important NETs are for the immune defense. Although it is possible that NETs play a role in protecting us against certain invaders, neutrophil function is usually tightly controlled to limit unwanted tissue damage. Consequently, it seems counterintuitive that the inflammation and tissue damage caused by NETs would be a good thing. Indeed, much of the research on neutrophil extracellular traps centers on

discovering the possible role NETs might have in causing disease.

How neutrophils exit the blood

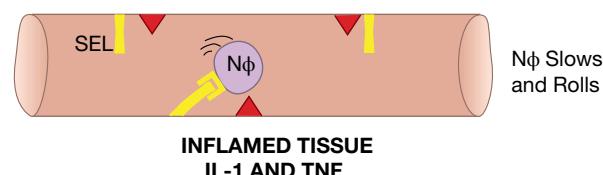
You may be wondering: If neutrophils are all that dangerous, how do they know when to leave the blood stream and where to go? It certainly wouldn’t do to have neutrophils leave the blood and become activated just any old place. No indeed, and the way this works is very clever. Inside blood vessels, neutrophils exist in an inactive state, and they are swept along by the blood at high speed – about 1,000 microns per second. If you’re the size of a neutrophil, that’s really fast.



NORMAL TISSUE

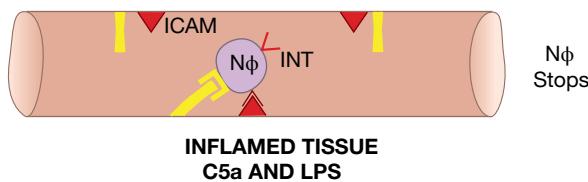
In this sketch, you will notice that there is a protein, intercellular adhesion molecule (ICAM), which is expressed on the surface of the endothelial cells that line blood vessels. There is also another adhesion molecule called selectin ligand (SLIG) that is expressed on the surface of neutrophils. As you can see, however, these two adhesion molecules are not “partners,” so they don’t bind to each other, and the neutrophil is free to zip along with the flowing blood.

Now imagine that you get a splinter in your big toe, and that the bacteria on the splinter activate macrophages which are standing guard in the tissues of your foot. These activated macrophages give off cytokines – interleukin 1 (IL-1) and TNF – which signal that an invasion has begun. When endothelial cells that line nearby blood vessels receive these alarm signals, they begin to express a new protein on their surfaces called selectin (SEL). It normally takes about six hours for this protein to be made and transported to the surface of endothelial cells. Selectin is the adhesion partner for selectin ligand, so when selectin is expressed on the endothelial cell surface, it functions like Velcro to grab neutrophils as they fly by. However, this interaction between selectin and its ligand is only strong enough to cause neutrophils to slow down and roll along the inner surface of the blood vessel.

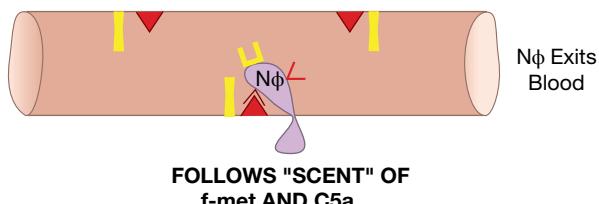
INFLAMED TISSUE
IL-1 AND TNF

As a neutrophil rolls, it “sniffs.” What it’s sniffing for is a signal that there is a battle (an inflammatory reaction) going on in the tissues. Complement fragment C5a and LPS are two of the inflammatory signals that a neutrophil recognizes. When it receives such signals, the neutrophil rushes a new protein called integrin (INT) to its surface. To make rapid surface expression of integrin possible, a lot of this protein is made in advance by the neutrophil and is stored inside the cell until needed. This quick reaction is important, because the neutrophil hasn’t stopped – it’s still rolling along. If it rolls too far, it will leave the region where selectin is expressed, and will then start to zoom along again at blood speed.

When integrin appears on the neutrophil’s surface, it interacts with its binding partner, ICAM, which always is expressed on the surface of endothelial cells. This interaction is very strong and it causes the neutrophil to stop rolling.



Once a neutrophil has stopped, it can be encouraged by chemoattractants to pry apart the endothelial cells that line the blood vessels, exit into the tissues, and migrate to the site of inflammation. These chemoattractants include the complement fragment C5a and fragments of bacterial proteins called **f-met peptides**. Bacterial proteins begin with a special initiator amino acid called formyl methionine (f-met). In human cells, only mitochondria produce proteins with this initiator, so less than 0.1% of all human proteins contain this amino acid. Bacteria secrete f-met peptides, and macrophages burp up these protein fragments when they ingest bacteria. Consequently, C5a and f-met peptides function as “find me” signals to help phagocytes such as neutrophils locate invaders which have been identified as dangerous by the innate system. And as they travel through the tissues, neutrophils can be activated by cytokines such as TNF. As a result, they arrive at the battle scene ready to kill.



Neutrophil logic

So **neutrophils use a stepwise mechanism to exit the blood**. This system – which involves selectin-selectin ligand binding to make the neutrophil roll, integrin-ICAM interactions to stop the neutrophil, and chemoattractants and their receptors to encourage the neutrophil to exit from the blood – may seem overly complicated. Wouldn’t it be simpler just to have one pair of adhesion molecules (say, selectin and its ligand) do all three things? Yes, it would be simpler, but it would also be very dangerous. In a human there are about 100 billion endothelial cells. Suppose one of them gets a little crazy, and begins to express a lot of selectin on its surface. If selectin binding were the only requirement, neutrophils could empty out of the blood into normal tissues where they could do terrible damage. **Having three types of molecules which must be expressed before neutrophils can exit the blood and spring into action helps make the system fail-safe.**

You remember I mentioned that to completely upregulate expression of that first cellular adhesion molecule, selectin, takes about six hours. Doesn’t this seem a bit too leisurely? **Wouldn’t it be better to begin recruiting neutrophils from the blood just as soon as a macrophage senses danger?** Not really. Before you start to recruit reinforcements, **you want to be sure that the attack is serious**. If a macrophage encounters only a few invaders, it can usually handle the situation without help in a short time. Summoning neutrophils would only lead to unnecessary tissue damage. In contrast, a major invasion involving many macrophages can go on for days. The sustained expression of alarm cytokines from many macrophages engaged in battle is required to upregulate selectin expression, and this insures that more troops will be summoned only when they are really needed.

Neutrophils are not the only blood cells that need to exit the blood and enter tissues. For example, mast cells, which are involved in protection against parasites, must exit the blood at the site of a parasitic infection. Monocytes, which can mature into tissue macrophages, need to leave the blood stream at appropriate places. And activated B cells and T cells must be dispatched to sites of infection. **This whole business is like a postal system in which there are trillions of packages (immune system cells) that must be delivered to the correct destinations.** This delivery problem is solved by using the same basic strategy that works so well for neutrophils. **The key feature of the immune system’s “postal service” is that the Velcro-like molecules which cause the cells to roll and stop are different from cell type to cell type and destination to destination.** As a result, these cellular adhesion molecules actually serve as “zip codes” to insure that cells are delivered to the appropriate

locations. Indeed, the selectins and their ligands are really families of molecules, and only certain members of the selectin family will pair up with certain members of the selectin ligand family. The same is true of the integrins and their ligands. Because of this two-digit zip code (type of selectin, type of integrin), there are enough “addresses” available to send the many different immune system cells to all the right places. **Because immune system cells are equipped with particular adhesion molecules, and their intended destinations express the corresponding adhesion partners, the different types of immune system cells will roll, stop, and exit the blood exactly where they are needed.**

HOW IMMUNE SYSTEM SENTINELS RECOGNIZE INVADERS

Before immune system cells such as macrophages can spring into action, **they must first recognize that there has been an invasion.** But how do they do this? The answer is that immune system cells come equipped with **an array of pattern-recognition receptors (PRRs)** which are designed to recognize danger signals associated with a microbial attack. Altogether, there are more than twenty different PRRs that are expressed by various types of immune system cells. **When their pattern-recognition receptors detect invaders, warrior cells such as macrophages are activated,** and battle cytokines are produced which alert and activate other immune system cells.

Some pattern-recognition receptors detect **pathogen-associated molecular patterns (PAMPs)** that are characteristic of broad classes of invaders. The PRRs about which most is known are the **Toll-like receptors (TLRs).** So far, ten human TLRs have been discovered, and different cells express different combinations of these TLRs. **Some TLRs are displayed on the cell surface, where they respond to invaders that are outside the cell.** For example, **TLR4** is used by macrophages to sense the presence of LPS. TLR4 is anchored in the macrophage's plasma membrane and points outward to sense bacterial invaders in the external environment.

Other PRRs are found inside cells. These intracellular pattern-recognition receptors can detect RNA and DNA in compartments within a cell where they should not be found in a healthy cell. **For instance, when invaders are phagocytosed, they end up in phago-lysosomes, where they are eventually destroyed.** During this destruction, their “coats” are stripped off to reveal what’s inside them. Some Toll-like receptors (e.g., **TLR7** and **TLR9**) are located in the membranes of phago-lysosomes. These

pattern-recognition receptors point inward into the phago-lysosome so that they can alert the cell to the presence of viruses or bacteria that have been phagocytosed. TLR7 detects the single-stranded RNA of viruses such as influenza and HIV-1, whereas TLR9 recognizes the double-stranded DNA of bacteria and herpes simplex virus.

These pattern-recognition receptors recognize general characteristics of classes of invaders – not just a single invader. For example, LPS is a common component of bacterial cell walls, and single-stranded RNA is found in many viruses. Consequently, TLR4 can detect invasions by many different types of bacteria (those with LPS in their cell wall), and TLR7 can alert cells to attacks by many different viruses (those which carry their genetic information in the form of single-stranded RNA). So in contrast to B cell receptors and T cell receptors, which are specific for each invader, pattern-recognition receptors are “economical” in the sense that each one can identify many different pathogens.

There is a second important characteristic of these PRRs: The patterns they recognize represent structural features which are so important to the pathogen that they cannot easily be altered by mutation to avoid detection. For instance, the region of the LPS molecule which TLR4 recognizes is indispensable for constructing bacterial cell walls. Consequently, a bacterium would be in big trouble if that part of the LPS molecule were mutated to try to evade detection by TLR4.

There are other PRRs which are tuned to recognize **damage-associated molecular patterns (DAMPs).** Molecules that function as DAMPs are normally intracellular, but are released by dying cells (e.g., cells killed by viruses). Consequently, **DAMPs can alert the immune system to widespread cellular death associated with an infection.** DAMPs are important because they allow immune system cells to respond to the damage caused by pathogens for which there is no specific PRR, including new pathogens that have not been encountered before.

HOW THE INNATE IMMUNE SYSTEM DEALS WITH VIRUSES

When a **virus infects a human cell it takes over the cell's machinery and uses it to produce many more copies of the virus.** Eventually, the newly made viruses burst out of the infected cell, and go on to infect other cells in the neighborhood. We have already discussed some of the

weapons the innate system can use to defend against viruses while they are **outside of cells**. For example, proteins of the complement system can **opsonize viruses for phagocytosis by macrophages and neutrophils**, and complement proteins can puncture the envelopes of some viruses. However, once a virus has entered a cell to begin its reproductive cycle, these weapons are ineffective.

The interferon system

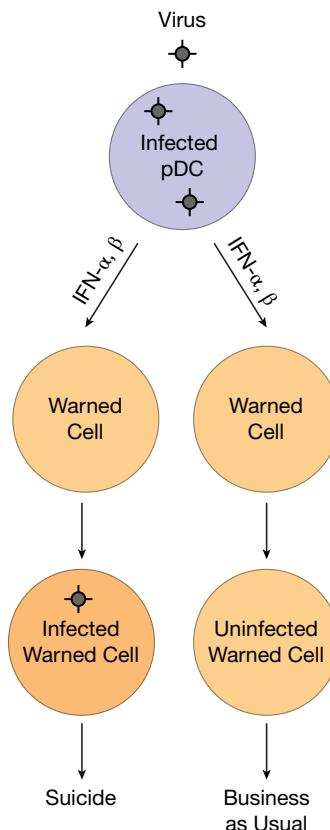
Fortunately, there are other innate system weapons which are useful against virus-infected cells. Indeed, the innate system weapon that viruses fear most is the **interferon system**. This defense is so potent that most viruses have evolved ways to try to fend off the interferon system – at least long enough for the virus to reproduce and spread to a new host.

When their pattern-recognition receptors detect a virus attack, cells can produce proteins called interferon alpha (IFN- α) and interferon beta (IFN- β), proteins that can “interfere” with viral reproduction.

IFN- α and IFN- β are called **type I interferons** to distinguish them from IFN- γ , mentioned earlier, which is a type II interferon. Most human cells quickly produce type I interferons when they are attacked by a virus, and most have receptors on their surface for these interferon proteins. **Consequently, the interferon produced by a virus-infected cell can actually bind to receptors on the infected cell itself.** This binding causes the infected cell to produce several hundred antiviral proteins that act to reduce the amount of virus produced by the infected cell. Type I interferons also can function as “warning proteins.” When IFN- α and IFN- β produced by virus-infected cells bind to interferon receptors on nearby cells, those cells are warned that there are viruses in the area, and that they may soon be attacked. As a result of this early warning, the alerted cells turn on expression of antiviral genes and prepare to commit suicide if the virus does infect them.

The elegant part of the interferon warning system is that **although the binding of interferon to its receptors prepares an uninfected cell for a viral attack, that cell continues to do business as usual unless an attack actually occurs.** The alerted cell will only commit suicide if it is infected by a virus. Moreover, if the attack does not come, the warned cell eventually “stands down” from its state of readiness.

For the infected cell, suicide is an altruistic act, because both the cell and the virus within it die together. But this “beneficial suicide” prevents the virus from reproducing and infecting other cells.



Although many cell types can produce type I interferons, the “King of Interferon” by far is a white blood cell called a **plasmacytoid dendritic cell (pDC)**. Human pDCs use TLR7 and TLR9 to detect viral RNA and DNA, respectively, and when either of these PRRs is engaged, a pDC dedicates more than half of its protein-making capacity to making interferon. As a result, **a plasmacytoid dendritic cell can make up to 1,000 times as much type I interferon per day as any other cell type!** And not only do pDCs make a lot of interferon, they make it really quickly – usually within **about four hours of a viral infection**. Interestingly, pDCs lack Toll-like receptors which can detect bacterial infections. So **pDCs are special weapons designed to deal with viral infections**. These “interferon factories” can play a critical role in the innate system’s defense against viruses, especially early in a viral infection.

Natural killer cells

There is another important player on the innate immune system team that can help defend against a viral infection: the **natural killer (NK) cell**. Indeed, humans with genetic defects which make them deficient in NK cell function have great difficulty controlling herpes virus and human papillomavirus infections.

Natural killer cells mature in the bone marrow, and when they are not responding to an infection, NK cells

are short-lived, with a half-life of only about a week. NK cells are usually found in the blood or in the spleen and liver (two organs that store blood), and relatively few NK cells reside in tissues that are not under attack. So like neutrophils, natural killer cells are mostly on call. NK cells use the “roll, stop, exit” strategy to leave the blood and enter tissues at sites of infection – and once in the tissues, they proliferate rapidly to build up their numbers.

When they reach the battleground, natural killer cells can play two roles in defending us against infections: They can give off cytokines such as IFN- γ that help with the defense and they can destroy virus-infected cells, bacteria, and some cancer cells by forcing them to commit suicide. In some cases, NK cells employ an injection system that uses perforin proteins to help deliver “suicide” enzymes (e.g., granzyme B) into a target cell. In other situations, a protein called Fas ligand on the NK cell surface interacts with a protein called Fas on the surface of its target, signaling the target cell to self-destruct.

Like macrophages, NK cells can be hyperactivated. When they first enter tissues, NK cells produce some cytokines and can kill, but they produce larger quantities of cytokines and can kill more efficiently if they are hyperactivated. Several signals have been identified that can hyperactivate natural killer cells; these signals are generated only when the body is under attack. For example, during a viral attack, NK cells can be hyperactivated by IFN- α or IFN- β given off by virus-infected cells. Or if bacteria invade, NK cells can be hyperactivated when their surface receptors detect LPS.

The method NK cells use to identify their targets is quite different from that of killer T cells. Natural killer cells do not have T cell receptors – the receptors that are constructed by mixing and matching gene segments. The surface receptors that NK cells use for target recognition are of two types: activating receptors which, when engaged, motivate the NK cell to kill, and inhibitory receptors which, when engaged, encourage it not to kill.

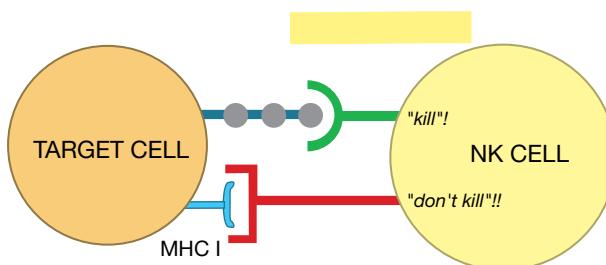
The “don’t kill” signal is conveyed by inhibitory receptors that recognize class I MHC molecules on the surface of a potential target cell. Class I MHC molecules are found in varying amounts on the surface of most healthy cells in our bodies. Consequently, the presence of this surface molecule is an indication that a cell is doing okay. In contrast, “kill” signals involve interactions between the activating receptors on the surface of an NK cell and unusual carbohydrates or proteins on the surface of a target cell. These peculiar surface molecules act as flags which indicate that the target cell has been stressed, usually because it has been infected by a virus or is becoming cancerous. Natural killer cells “measure” the relative strengths of the “kill” and the “don’t kill” signals to evaluate the health of a cell, and to determine whether that cell should be destroyed.

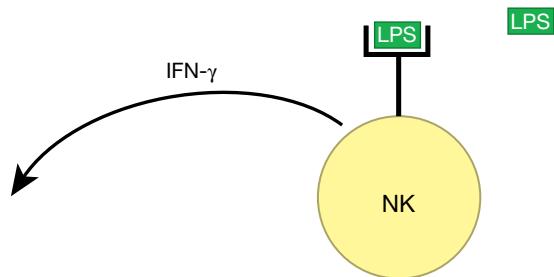
Now, why do you think it would be a good idea to have NK cells destroy cells that do not express class I MHC molecules? You remember that by examining peptides displayed by class I MHC proteins, killer T cells are able to “look inside” cells to see if anything is wrong. But what if some clever virus were to turn off expression of MHC molecules in the cells it infects? Wouldn’t those virus-infected cells then be “invisible” to killer T cells? Indeed they would be. So, in those cases, it would be great to have another weapon that could kill the virus-infected cells which don’t display MHC molecules on their surface. And that’s just what natural killer cells can do.

THE INNATE IMMUNE SYSTEM – A COOPERATIVE EFFORT

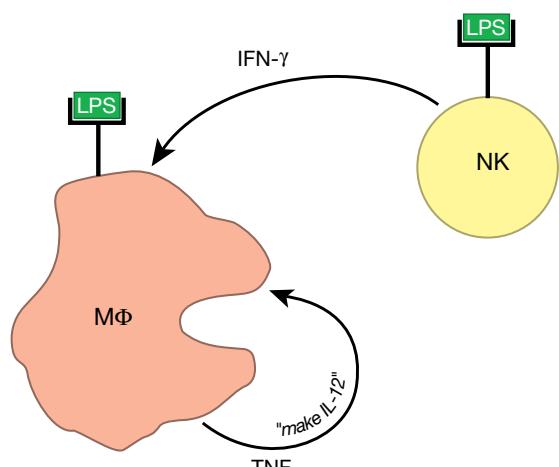
To make the innate system work efficiently, there must be cooperation between players. Neutrophils are on call from the blood. And who does the calling? The sentinel cell – the macrophage. So here we have a defense strategy in which garbage collectors alert the hired guns when their help is needed. Indeed, cooperation between macrophages and neutrophils is essential for mounting an effective defense against invading microbes. Without macrophages to summon them to sites of attack, neutrophils would just go around and around in the blood. And without neutrophils to help them, macrophages would be hard pressed to deal with sizable infections.

Also, during a bacterial infection, molecules such as LPS activate receptors on the surface of natural killer cells, signaling that an attack is on. NK cells then respond by producing significant amounts of IFN- γ .

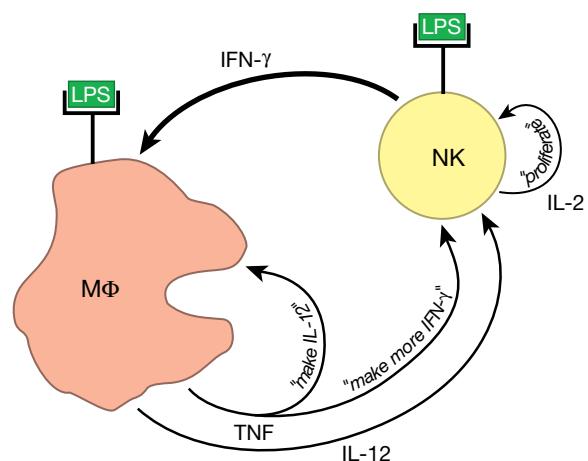




The IFN- γ produced by NK cells can prime macrophages (MΦ), which can then be hyperactivated when their receptors also bind to LPS.



When a macrophage is hyperactivated, it produces lots of TNF. Importantly, a macrophage has receptors on its surface to which this cytokine can bind, so a macrophage can respond to the TNF it produces. And when TNF binds to these receptors, the macrophage begins to secrete IL-12. Together, TNF and IL-12 influence NK cells to increase the amount of IFN- γ they produce. And when there is more IFN- γ around, more macrophages can be primed.



There is something else interesting going on here. **IL-2** is a growth factor that is produced by NK cells. Normally, NK cells don't express the receptor for IL-2, so they don't proliferate in response to this cytokine – even though they are making it. During an infection, however, the TNF produced by macrophages upregulates the expression of IL-2 receptors on the surface of NK cells. Consequently, NK cells can now react to the IL-2 they make and begin to proliferate. As a result of this proliferation, there will soon be many more NK cells to defend against an invasion – and to help activate more macrophages. So **macrophages and NK cells cooperate in several different ways to strengthen the response of the innate system to an attack.**

Professional phagocytes and the complement system also work together. As we discussed, complement protein fragments such as iC3b can tag invaders for phagocyte ingestion. But complement opsonization also can play a role in activating macrophages. When C3 fragments that are decorating an invader bind to receptors on the surface of a macrophage, this provides an activation signal for the macrophage which is similar to that supplied by LPS. This is a good idea because there are many invaders that can be opsonized by complement but which do not make LPS.

Cooperation between the complement system and the phagocytes is not a one-way street. Activated macrophages actually produce several of the most important complement proteins: C3, factor B, and factor D. So in the heat of battle, when complement proteins may be depleted out in the tissues, macrophages can help resupply the complement system. In addition, during an infection, macrophages secrete chemicals that increase the permeability of nearby blood vessels. And when these vessels become leaky, more complement proteins are released into the tissues.

These interactions between phagocytes, NK cells, and the complement proteins are examples of the many ways in which innate system players work together. **Only by cooperating with each other can the players on the innate system team respond quickly and strongly to an invasion.**

A PROPORTIONAL RESPONSE

In reacting to an attack, our military tries to mount a response which is proportional to the threat. Such a proportional response insures that, on the one hand, resources will not be wasted by overreacting and, on the other hand, that the reaction will be strong enough to get the job done.

The immune system is also set up to provide a proportional response to microbial invasions. For example, the number of macrophages engaged in battle depends on the size of the attack, and the amount of chemicals given off by macrophages to summon neutrophils or activate NK cells depends on how many macrophages are fighting. Consequently, the more serious the invasion, the more macrophages will be involved, and the more

neutrophils and NK cells will be mobilized. Likewise, the larger a bacterial invasion is, the more danger molecules such as LPS will be present at the battle scene. And the more LPS there is, the more NK cells will be activated to produce battle cytokines such as IFN- γ – which help fire up macrophages. Because the magnitude of the immune response is directly linked to the seriousness of the attack, “the punishment usually fits the crime.”

REVIEW

Complement proteins participate in the construction of membrane attack complexes that can puncture and destroy some bacteria and viruses. Complement proteins also can tag pathogens for ingestion by professional phagocytes, and can act as chemoattractants to recruit phagocytic cells to the battle site.

Complement proteins are present in high concentrations in the blood and in the tissues, so they are always ready to go. This is one of the most important features of the complement system: It works really fast. However, for the complement system to spring into action, it must first be activated. Activation by the alternative (spontaneous) pathway simply requires that a complement protein fragment, C3b, bind to an amino or hydroxyl group on an invader. Because these chemical groups are ubiquitous, the default option in this system is death: Any surface that is not protected against binding by complement fragments will be targeted for destruction. Fortunately, there are multiple mechanisms which protect human cells from complement attack.

In addition to the alternative activation pathway, which can be visualized as grenades going off randomly here and there, there is a second pathway for activating the complement system that is more directed: the lectin activation pathway. Here, a protein called mannose-binding lectin acts as a “guidance system” which targets the complement “bombs” to invaders that have distinctive carbohydrate molecules on their surfaces.

Macrophages and neutrophils are professional phagocytes. Long-lived macrophages reside beneath the surface of all the parts of our body that are exposed to the outside world. There these phagocytic cells act as sentinels. Most of the time, macrophages just eat dead cells and debris. However, if they find an invader, they become activated. In this activated state, they can present antigens to T cells, they can send out signals that recruit other immune system cells to help in the struggle, and they can become vicious killers.

In contrast to sentinel macrophages, most neutrophils can be found in the blood – where they are on call in case of attack. Whereas macrophages are quite versatile, neutrophils mainly do one thing – kill. Neutrophils use cellular adhesion molecules to exit blood vessels at sites of inflammation, and as they exit, they are activated to become killers. Fortunately, these cells only live about five days. This limits the damage they can do to healthy tissues once an invader has been vanquished. On the other hand, if the attack is prolonged, there are plenty more neutrophils that can exit the blood and help out.

Cells of the innate immune system are equipped with pattern-recognition receptors that detect signatures of whole classes of commonly encountered bacteria and viruses. Some PRRs also recognize signals given off by dying cells. When these danger signals are detected, sentinel cells such as macrophages respond by producing battle cytokines that alert other cells and prepare them to repulse the attack.

In response to a viral infection, the pattern-recognition receptors of most cells in the body can trigger the production of type I interferons, IFN- α or IFN- β . These proteins can bind to interferon receptors on the cells that produce them, and this binding results in the expression of hundreds of genes that can limit the virus’s ability to reproduce within the infected cells. IFN- α and IFN- β also can function as warning proteins. When they bind to IFN receptors on nearby, uninfected cells, they prepare these cells for a viral attack. Not only do the warned cells produce proteins that will hinder viral replication, interferon warning also prepares the uninfected cells to commit suicide if they are attacked. This is an altruistic act, because the infected cells and the viruses within them are both destroyed, limiting the spread of the virus to other cells. One of the body’s sentinel cells, the plasmacytoid dendritic cell, can produce huge quantities of type I interferons when infected by a virus. For this reason, pDCs are

important players in the innate immune system's defense against a viral attack.

The natural killer cell is another player on the innate team which is on call from the blood. These cells are a cross between a killer T cell (CTL) and a helper T cell. NK cells resemble helper T cells in that they secrete cytokines which affect the function of both innate and adaptive immune systems. And like CTLs, natural killer cells can destroy infected cells. However, in contrast to killer T cells, which select their targets by surveying peptides displayed by class I MHC molecules, NK cells focus on killing cells that do not express class I MHC molecules – especially

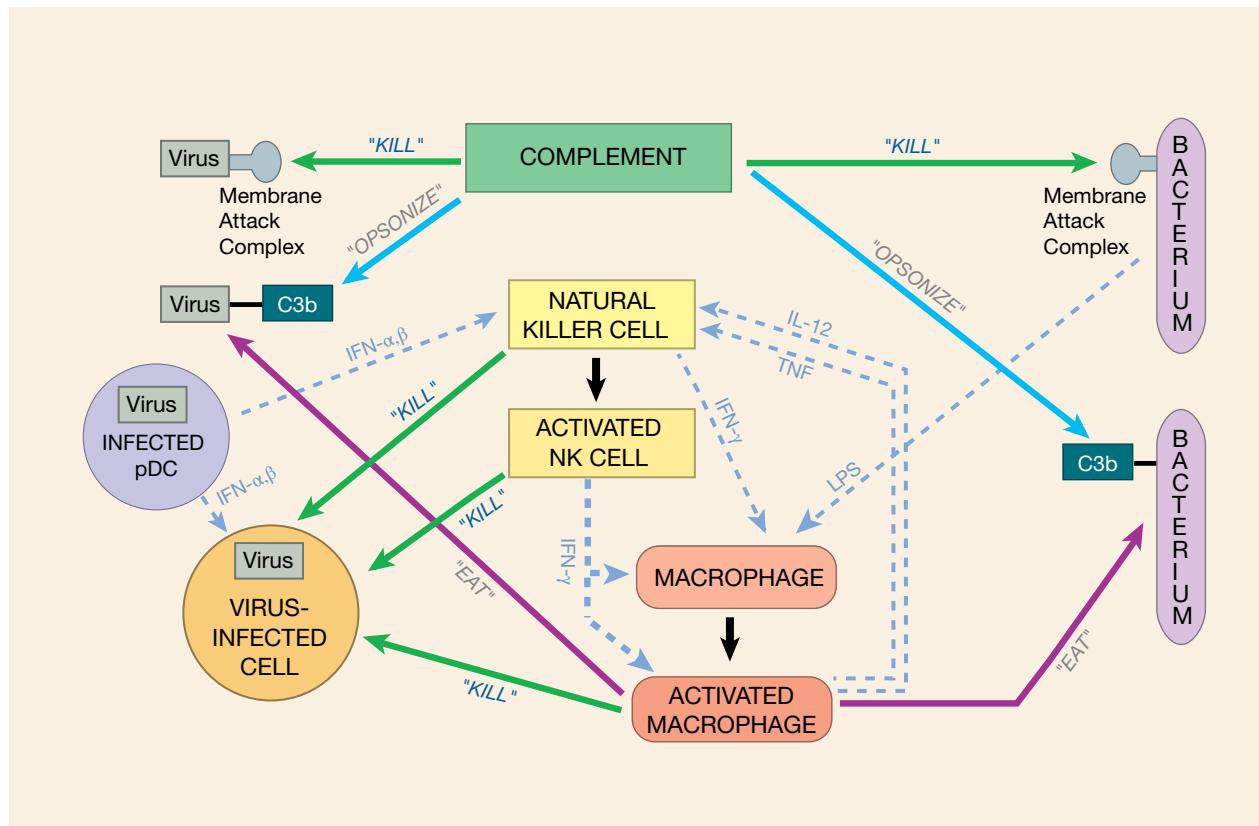
stressed cells that have lost class I MHC expression due to a viral infection.

Phagocytes and the complement proteins provide an immediate response to an attack because these weapons are already in place. As the battle continues, signals given off by the innate system recruit even more defenders from the blood stream, and the innate system warriors cooperate to strengthen the defense. By working together, members of the innate system team provide a fast and effective response to common invaders. Importantly, the system is designed to elicit a defense which avoids over-reaction and yet is adequate to the task.

SUMMARY FIGURE

In this figure, I have summarized some of the concepts we discussed in this lecture. For clarity, I have chosen a macrophage as a representative of the professional phagocytes, a

bacterium as an example of an invader which can reproduce without entering human cells, and a virus as an example of an invader which must enter a human cell to complete its life cycle. After Lectures 3, 4, and 6, I will expand this figure to include players from the adaptive immune system.



KNOWN UNKNOWNS

1. What role(s) might neutrophil extracellular traps (NETs) play in protecting us against disease?
2. How do natural killer cells evaluate “kill” and “don’t kill” signals to determine if they should destroy a target cell?

THOUGHT QUESTIONS

1. What is the fundamental difference between the way the complement system is activated by the alternative pathway and the way it is activated by the lectin activation pathway?
2. How do macrophages and natural killer cells tell friend from foe (i.e., how do they select their targets)?
3. Imagine a splinter has punctured your big toe, and that Gram-negative bacteria which produce LPS have invaded the tissues surrounding the splinter. Sketch the likely sequence of events in which the various players of the innate system team deal with this bacterial invasion.
4. Discuss the ways the innate system can protect against a virus attack.
5. Give examples of the cooperation between players on the innate system team, and tell why this cooperation is important.

LECTURE 3

B Cells and Antibodies

HEADS UP!

B cells and the antibodies they produce are part of the adaptive immune system. B cells must be activated before they can make antibodies. “Fail-safe” mechanisms help prevent inappropriate B cell activation, and the principle of clonal selection insures that only those B cells which make antibodies appropriate to defend against an invader are mobilized. A “mix-and-match” scheme is used to construct the genes that encode a B cell’s antibodies, and during the course of an attack, B cells can upgrade the antibodies they produce to mount a more targeted defense.

INTRODUCTION

Microbes such as bacteria and viruses are always mutating. Just as mutations in bacteria can render them resistant to certain antibiotics, mutations also can change microbes in ways that make them better able to resist immune defenses. When this happens, the immune system must “adapt” by producing new counter-weapons to keep the mutated microbe from taking over. Indeed, a chess match has been going on for millions of years in which the immune systems of animals have constantly been upgraded in response to novel weapons fielded by microbial attackers. The most striking upgrade of the immune system began about 200 million years ago, when, in fish, evolution led to the precursor of what might be called the “ultimate defense” – a system so adaptable that, in principle, it can protect against any possible invader. This defense, the adaptive immune system, has reached its most sophisticated form in humans. Indeed, without an immune system which can recognize and

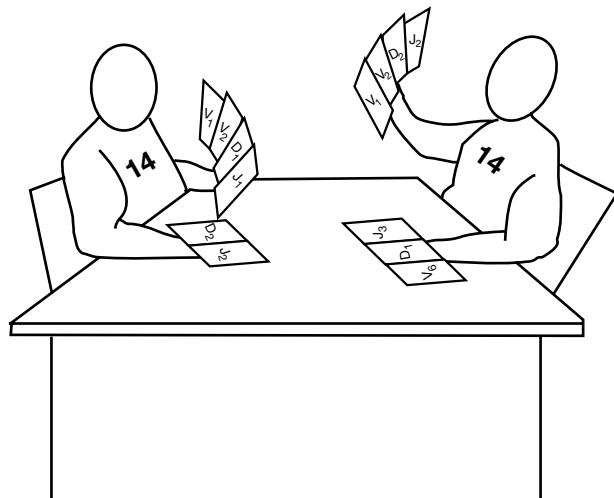
adapt to deal with unusual invaders, human life would not be possible.

In this lecture, we will focus on one of the most important components of the adaptive immune system: the B cell. Like all the other blood cells, B cells are born in the bone marrow, where they descend from stem cells. About one billion B cells are produced each day during the entire life of a human, so even old guys like me have lots of freshly made B cells. During their early days in the marrow, B cells select gene segments coding for the two proteins that make up their B cell receptors (BCRs), and these receptors then take up their positions on the surface of the B cell. The antibody molecule is almost identical to the B cell receptor, except that it lacks the protein sequences at the tip of the heavy chain which anchor the BCR to the outside of the cell. Lacking this anchor, the antibody molecule is exported out of the B cell and is free to travel around the body to do its thing.

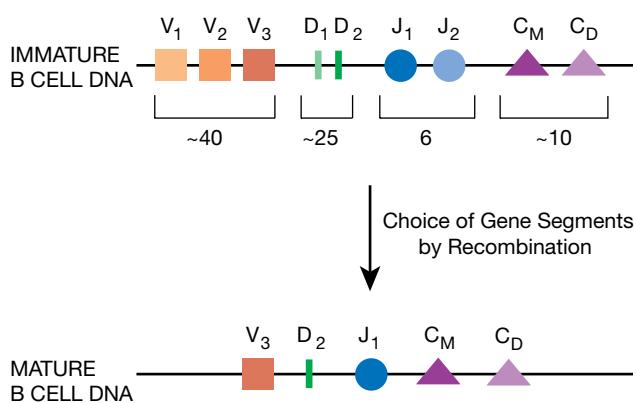
THE B CELL RECEPTOR

I want to tell you a little about the process of selecting gene segments to make a B cell receptor. I think you’ll find it interesting – especially if you like to gamble. The BCR is made up of two kinds of proteins, the heavy chain (Hc) and the light chain (Lc), and each of these proteins is encoded by genes that are assembled from gene segments. The gene segments that will be chosen to make up the final Hc gene are located on chromosome 14, and each B cell has two chromosome 14’s (one from Mom and one from Dad). This raises a bit of a problem because, as we discussed earlier, each B cell makes only one kind of antibody. Therefore, because there are two sets of Hc segments, it is necessary to “silence” the segments on one chromosome 14 to keep a B cell from making two different Hc proteins. Of course, Mother Nature could have

chosen to make one chromosome a “dummy,” so that the other would always be the one that was used – but she didn’t. That would have been too boring! Instead, she came up with a much sweeter scheme, which I picture as a game of cards with the two chromosomes as players. It’s a game of “winner takes all” in which each player tries to rearrange its cards (gene segments) until it finds an arrangement that works. The first player to do this wins.



You will remember from the first lecture that the finished heavy chain protein is assembled by pasting together four separate gene segments (V, D, J, and C), and that lined up along chromosome 14 are multiple, slightly different copies of each kind of segment.



The players in this card game first choose one each of the possible D and J segments, and these are joined together by deleting the DNA sequences in between them. Then one of the many V segments is chosen, and this “card” is joined to the DJ segment, again by deleting the DNA in between. Right next to the J segment is a string of gene segments (C_M, C_D, etc.) that code for various constant regions. By default, the constant regions for IgM and

IgD are used to make the initial BCR, just because they are first in line. Immunologists call these joined-together gene segments a “gene rearrangement,” but it is really more about cutting and pasting than rearranging. Anyway, the result is that the chosen V, D, and J segments and the constant region segments all end up adjacent to each other on the chromosome.

Protein translation stops when the ribosome encounters one of the three stop codons. So if the gene segments are not joined up just right (in frame), the protein translation machinery will encounter a stop codon and terminate protein assembly somewhere in the middle of the heavy chain. If this happens, the result is a useless little piece of protein. In fact, you can calculate that each player only has about one chance in nine of assembling a winning combination of gene segments that will produce a full-length Hc protein. Immunologists call such a combination of gene segments a **productive rearrangement**. If one of the chromosomes that is playing this game ends up with a productive rearrangement, that chromosome is used to construct the winning Hc protein. This heavy chain protein is then transported to the cell surface, where it signals to the losing chromosome that the game is over. The details of how the signal is sent, and how it stops the rearrangement of gene segments on the other chromosome remain to be discovered. However, it is thought to have something to do with changing the conformation of the DNA on the losing chromosome – so that it is no longer accessible to the cut-and-paste machinery.

Since each player only has about a one in nine chance of success, you may be wondering what happens if both chromosomes fail to assemble gene segments that result in a productive rearrangement. Well, the B cell dies. That’s right, it commits suicide! It’s a high-stakes game, because a B cell that cannot express a receptor is totally useless.

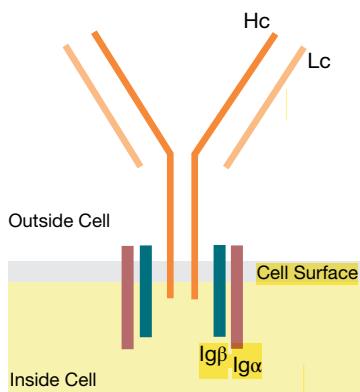
If the heavy chain rearrangement is productive, the baby B cell proliferates for a bit, and then the light chain players step up to the table. The rules of their game are similar to those of the heavy chain game, but there is an additional test which must be passed to win: The completed heavy and light chain proteins must fit together properly to make a complete antibody. If the B cell fails to productively rearrange heavy and light chains, or if the Hcs and Lcs don’t match up correctly, the B cell commits suicide.

The result of this contest is that although a B cell can display as many as 100,000 BCRs on its surface, **every mature B cell produces one and only one kind of BCR or antibody, made up of one and only one kind of Hc and Lc. Nevertheless, because a mix-and-match strategy is used to make the final Hc and Lc genes of each B cell,**

the receptors on different B cells are so diverse that collectively, our B cells can probably recognize any organic molecule that could exist. When you consider how many molecules that might be, the fact that a simple scheme like this can create such diversity is truly breathtaking.

HOW THE BCR SIGNALS

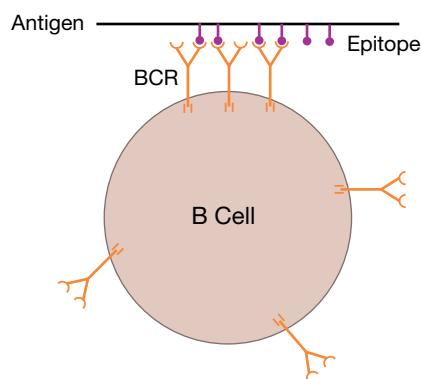
Immunologists call the antigen that a given B cell's receptors recognize its **cognate antigen**, and the tiny region of the cognate antigen that a BCR actually binds to is called its **epitope**. For example, if a B cell's cognate antigen happens to be a protein on the surface of the flu virus, the epitope will be the part of that protein (usually six to twelve amino acids) to which the BCR actually binds. When the BCR recognizes the epitope for which it is matched, it must signal this recognition to the nucleus of the B cell, where genes involved in activating the B cell can be turned on or off. But how does this BCR "antenna" send a signal to the nucleus that it has found its epitope? At first sight it would appear that this could be a bit of a problem, because, as you can see from this figure, the part of the heavy chain that extends through the cell membrane into the interior of the cell is only a few amino acids in length – way too short to do serious signaling.



To make it possible for the external part of the BCR to signal what it has seen, B cells are equipped with two accessory proteins, Ig α and Ig β , which associate with the heavy chain protein and extend into the inside of the cell. Thus, the complete B cell receptor really has two parts: the Hc/Lc part outside the cell that recognizes the antigen but can't signal, plus the Ig α and Ig β proteins that can signal, but which are totally blind to what's going on outside the cell.

To generate an activation signal, many BCRs must be brought close together on the surface of the B cell. When

BCRs are clustered like this, immunologists say they are **crosslinked** – although the receptors are not really linked together. B cell receptors can be clustered, for example, when they bind to an epitope that is present multiple times on a single antigen (e.g., a protein in which a sequence of amino acids is repeated many times).

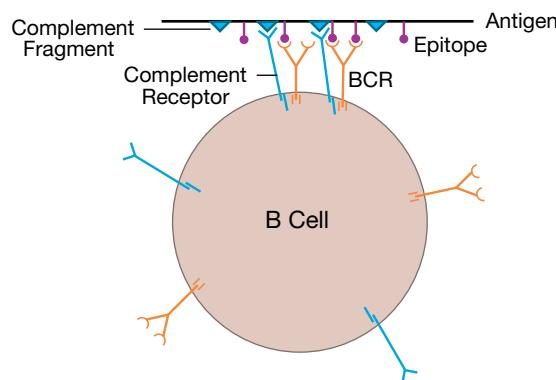


Crosslinking of BCRs also can result when BCRs bind to epitopes on individual antigens that are close together on the surface of an invader. Indeed, the surfaces of most bacteria, viruses, and parasites are composed of many copies of a few different proteins. So if a B cell's receptors recognize an epitope on one of these proteins, lots of BCRs can be clustered. Indeed, the requirement for crosslinking is one way B cells focus on common enemies. Finally, B cell receptors also can be brought together by binding to epitopes on antigens that are **clumped** together (e.g., a clump of proteins). Regardless of how it is accomplished, **crosslinking of B cell receptors is essential for B cell activation**. Here's why.

The tails of the Ig α and Ig β proteins interact with signaling molecules inside the cell. And when enough of these interactions are concentrated in one region, an enzymatic chain reaction is initiated which sends a message to the nucleus of the cell saying, "BCR engaged." So the trick to sending this message is to get lots of Ig α and Ig β molecules together – and that's exactly what crosslinking a B cell's receptors does. The clustering of BCRs brings enough Ig α and Ig β molecules together to set off the chain reaction that sends the "BCR engaged" signal. So BCR crosslinking is key.

You remember from the last lecture that fragments of the complement proteins can bind to (opsonize) invaders. This tag indicates that the invader has been recognized as dangerous by the innate immune system, and invites innate system players such as macrophages to destroy the opsonized invader. It turns out that antigens opsonized by complement fragments also can alert the adaptive immune system. Here's how.

In addition to the B cell receptor and its associated signaling molecules, there is another protein on the surface of a B cell that can play an important role in signaling. This protein is a receptor that can bind to complement fragments which are decorating an invader. Consequently, for an opsonized antigen, there are two receptors on a B cell that can bind to the antigen: the BCR which recognizes a specific epitope on the antigen, and the complement receptor that recognizes the "decorations." When this happens, the opsonized antigen acts as a "clamp" that brings the BCR and the complement receptor together on the surface of the B cell.



When the BCR and the complement receptor are brought together by opsonized antigen, the signal that the BCR sends is greatly amplified. What this means in practice is that the number of BCRs that must be clustered to send the "receptor engaged" signal to the nucleus is decreased at least 100-fold. **Because the complement receptor can have such a dramatic effect on signaling, it is called a co-receptor.** The function of this co-receptor is especially important during the initial stages of an attack, when the amount of antigen available to crosslink B cell receptors is limited. **Recognition of opsonized invaders by the B cell's co-receptor serves to make B cells exquisitely sensitive to antigens which the innate system already has identified as dangerous. This is an excellent example of the "instructive" function of the innate system. Indeed, the decision on whether an invader is dangerous or not is usually made by the innate, not the adaptive system.**

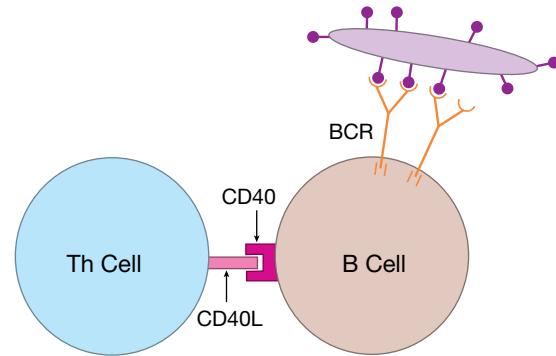
HOW B CELLS ARE ACTIVATED

To produce antibodies, B cells must first be activated. B cells that have never been activated by encountering their cognate antigen are called **naive** or **virgin B cells**. An example would be a B cell that can recognize the smallpox

virus but which happens to reside in a human who has never been exposed to smallpox. In contrast, B cells that have encountered their cognate antigen and have been activated are called **experienced B cells**. There are two ways that naive B cells can be activated to defend us against invaders. One is completely dependent on the assistance of helper T cells (**T cell-dependent activation**) and the second is more or less independent of T cell help (**T cell-independent activation**).

T cell-dependent activation

Activation of a naive B cell requires two signals. The first is the clustering of the B cell's receptors and their associated signaling molecules. However, just having its receptors crosslinked is not enough to fully activate a B cell – a second signal is required. Immunologists call this the **co-stimulatory signal**. In T cell-dependent activation, this second signal is supplied by a helper T (Th) cell. The best-studied co-stimulatory signal involves direct contact between a B cell and a Th cell. On the surface of activated helper T cells are proteins called **CD40L**. If a B cell's receptors have been crosslinked, and if CD40L plugs into (ligates) a protein called **CD40** on the surface of the B cell, that B cell will be activated.



The interaction between these two proteins, CD40 and CD40L, is clearly very important for B cell activation. Humans who have a genetic defect in either of these proteins are unable to mount a T cell-dependent antibody defense.

T cell-independent activation

In response to certain antigens, virgin B cells can also be activated with little or no T cell help. This mode of activation is termed **T cell-independent**. What these antigens have in common is that they have repeated epitopes which can crosslink a ton of B cell receptors. A good example of such an antigen is a carbohydrate of the type found on the surface of many bacterial cells.

A carbohydrate molecule is made up of many repeating units, much like beads on a string. If each “bead” is recognized by the BCR as its epitope, the string of beads can bring together many, many BCRs. The crosslinking of such a large number of BCRs can partially substitute for co-stimulation by CD40L, and can cause a B cell to proliferate. But to be fully activated and produce antibodies, a naive B cell must receive a second signal.

For T cell-independent activation, this second “key” is an unambiguous danger signal – a clear indication that an attack is on. For example, in addition to their BCRs, B cells express Toll-like receptors, and these TLRs can alert a B cell to danger and provide the second key needed for T cell-independent activation. What is important here is that if a B cell has BCRs that can recognize a molecule with repeated epitopes, such as, for example, your own DNA, it may proliferate, but fortunately, no anti-DNA antibodies will be produced. The reason is that your immune system is not engaged in a battle with your own DNA, so there will be no danger signals to provide the necessary co-stimulation. On the other hand, if the innate immune system is battling a bacterial infection, and a B cell’s receptors recognize a carbohydrate antigen with repeated epitopes on the surface of the bacterial invader, that B cell will produce antibodies – because danger signals from the battlefield can supply the second key needed for complete B cell activation. Of course, as is true of T cell-dependent activation, **T cell-independent activation is antigen specific: Only those B cells whose receptors recognize the repeated epitope will be activated.**

One advantage of T cell-independent activation is that B cells can jump right into the fray without having to wait for helper T cells to be activated. The result is a speedier antibody response. Most B cells which are activated without T cell help are found in the spleen. These “helpless” B cells can mount a rapid defense against bacteria such as *Streptococcus pneumoniae* by making IgM antibodies that recognize epitopes on the polysaccharide capsule that surrounds the bacterium. The importance of this T cell-independent activation is demonstrated by the fact that humans who have had their spleens removed are at high risk for infection by *Streptococcus pneumoniae* and other encapsulated bacteria.

There is something else important going on here. Helper T cells only recognize protein antigens – the peptides presented by class II MHC molecules. So if all B cell activation required T cell help, the entire adaptive immune system would be focused on proteins. This wouldn’t be so great, because many common invaders have carbohydrates or fats on their surface that are not found on the surface of human cells. Consequently, these carbohydrates and fats make excellent targets for

recognition by the immune system. So **allowing some antigens to activate B cells without T cell help is a wonderful thing: It increases the universe of antigens that the adaptive immune system can react against to include not only proteins, but carbohydrates and fats as well.**

The logic of B cell activation

You may be asking yourself: Why does B cell activation require two signals? Wouldn’t things go more quickly if all a B cell needed for activation was crosslinking of its receptors? Yes, this probably would speed up antibody production, but it would also be way too dangerous. Because of the diversity of B cell receptors, **there is essentially no limit on what they can recognize – including our own proteins, carbohydrates, and fats.** Most B cells which can recognize our own molecules are eliminated shortly after they are born in the bone marrow (much more on this in Lecture 9). However, this screening process is not 100% effective, and there are self-reactive B cells in circulation which could cause autoimmune disease if they produced antibodies (autoantibodies). To guard against this possibility there is a fail-safe mechanism in place which allows B cell activation only when there is real danger. That’s where the second signal comes in. **For T cell-dependent activation, the B cell and the Th cell must agree that there is a threat before the B cell can receive this second signal. For T cell-independent activation, the second signal is a clear indication that there has been an invasion – a dangerous situation which warrants B cell activation.**

Polyclonal activation

In addition to T cell-dependent and T cell-independent activation of B cells, there is an “unnatural” way that B cells can be activated. In this case, the antigen, usually called a **mitogen**, binds to molecules on the B cell surface that are not B cell receptors, and brings these molecules together. When this happens, BCRs that are associated with these molecules also can be clustered. In contrast to T cell-dependent and T cell-independent activation, this **polyclonal activation** does not depend on the cognate antigen recognized by the BCR – the BCR just comes along for the ride. In this way, many different B cells with many different specificities can be activated by a single mitogen. Indeed, mitogens are favorite tools of immunologists, because they can be used to activate a lot of B cells simultaneously, making it easier to study events that take place during activation.

One example of a mitogen is the highly repetitive structure that makes up the surface of certain parasites. During a parasitic infection, the molecules that make up these structures can bind to receptors (mitogen receptors) on the surface of B cells and cluster them. And when the mitogen

receptors are clustered in this way, the cell's BCRs are also dragged together. The result is polyclonal activation of B cells. But why would the immune system want to react to a parasitic attack by activating B cells whose BCRs do not even recognize the parasite? The answer is that this is not something the immune system was designed to do! By activating a bunch of B cells that will produce irrelevant antibodies, the parasite seeks to distract the immune system from focusing on the job at hand – destroying the parasitic invader. So **polyclonal activation of B cells by a mitogen is actually an example of the immune system gone wrong** – a subject we will discuss at length in another lecture.

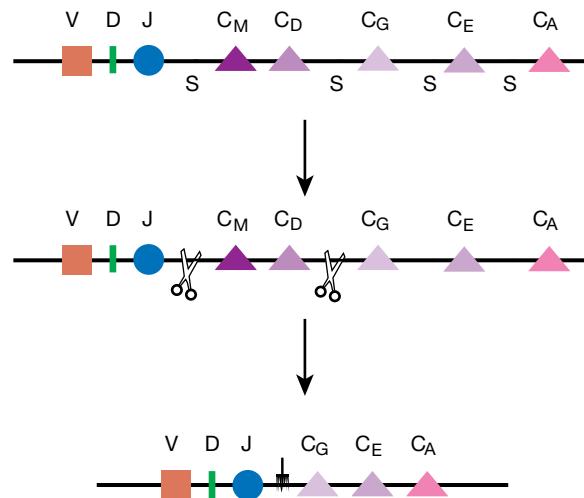
CLASS SWITCHING

Once B cells have been activated they are ready for the next stage in their life: maturation. Maturation can be divided roughly into three steps: **class switching**, in which a B cell can change the class of antibody it produces; **somatic hypermutation**, in which the rearranged genes for the B cell receptor can mutate to increase the affinity of the BCRs for their cognate antigen; and a “career decision,” during which the B cell decides whether to become an antibody factory (a **plasma B cell**) or a **memory B cell**. The exact order of these maturation steps varies, and some B cells may skip one or more steps altogether.

When a virgin B cell is first activated, it produces mainly IgM antibodies – the default antibody class. B cells also can produce IgD antibodies. However, IgD antibodies represent only a tiny fraction of the circulating antibodies in a human, and it is unclear whether they actually perform any significant function in the immune defense. You remember that an antibody's class is determined by the constant (Fc) region of its heavy chain – the “tail” of the antibody molecule, if you will. Interestingly, the same heavy chain messenger RNA is used to make both IgM and IgD, but the mRNA is spliced one way to yield an M-type constant region and another way to produce a D-type constant region.

As a B cell matures, it is possible for it to change the class of antibody it makes from IgM to one of the other antibody classes: IgG, IgE, or IgA. Located just next to the gene segment on chromosome 14 that encodes the constant region for IgM are the constant region segments for IgG, IgE, and IgA. So all that a B cell has to do to switch its class is to cut off the IgM constant region DNA, and paste on one of the other constant regions (deleting the DNA in between). Special switching signals that allow this cutting and pasting to take place are located between the constant region segments. For example, here's what happens when

a B cell switches from an IgM constant region (C_M in this drawing) to an IgG constant region (C_G):



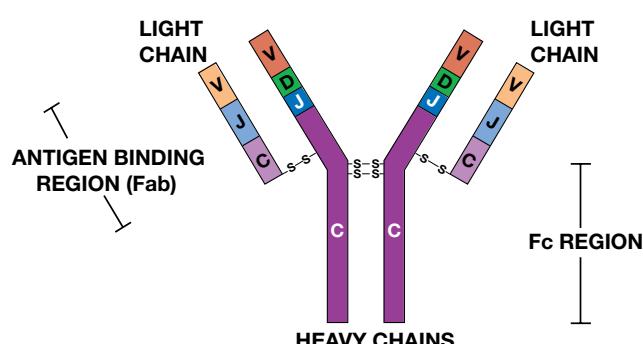
The net result of class switching is that although the part of the antibody that binds to the antigen (the Fab region) remains the same, the antibody gets a new Fc region. This is an important change, because it is the constant region which determines how the antibody will function.

ANTIBODY CLASSES AND THEIR FUNCTIONS

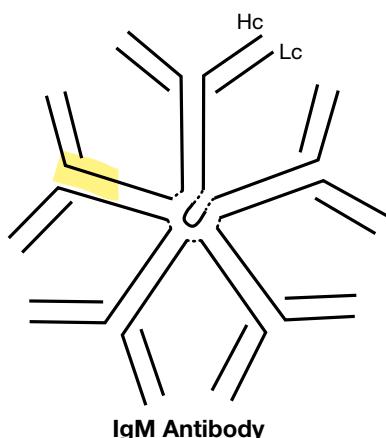
Let's take a look at the four main classes of antibodies: IgM, IgA, IgG, and IgE. As you will see, because of the unique structure of its constant region, each antibody class is particularly well suited to perform certain duties.

IgM antibodies

IgM antibodies were the first class of antibodies to evolve, and even lower vertebrates have adaptive immune systems that produce IgM antibodies. So it makes sense that in humans, **when naive B cells are first activated, they make mainly IgM antibodies**. You may remember that an IgG antibody looks roughly like this.



In contrast, an IgM antibody is like five IgG antibody molecules all stuck together. It's really massive!



Producing IgM antibodies early during an infection actually is quite smart, because IgM antibodies are very good at activating the complement cascade (immunologists call this **fixing complement**). Here's how it works.

In the blood and tissues, some of the complement proteins (about thirty of them!) get together to form a big complex called C1. Despite its size, this complex of proteins cannot activate the complement cascade because it's bound to an inhibitor molecule. However, if two or more C1 complexes are brought close together, their inhibitors fall off, and the C1 molecules can then initiate a cascade of chemical reactions that produces a C3 convertase. Once this happens, the complement system is in business because a C3 convertase converts C3 to C3b, setting up an amplification loop that produces more and more C3b. So the trick to activating the complement system by this classical (antibody-dependent) pathway is to bring two or more of the C1 complexes together – and that's just what an IgM antibody can do.

Once the antigen-binding regions of an IgM antibody have bound to an invader, C1 complexes can bind to the Fc regions of the antibody. Because each IgM antibody has five Fc regions close together (this is the important point), two C1 complexes can bind to the Fc regions of the same IgM antibody, bringing the complexes close enough together to set off the complement cascade. So the sequence of events is: **The IgM antibody binds to the invader, several C1 molecules bind to the Fc region of the IgM antibody, their inhibitors are released, and the C1 molecules trigger the complement chain reaction on the invader's surface.**

The reason the classical activation pathway is so useful is that some clever bacteria have evolved coats which resist the attachment of complement proteins. Fortunately, B cells

can produce antibodies which will bind to essentially any coat a bacterium might put on. Consequently, antibodies can extend the range of the complement system by helping attach complement proteins to the surface of wily bacteria. This is a nice example of the innate immune system (the complement proteins) cooperating with the adaptive immune system (IgM antibodies) to help destroy an invader. In fact, the term "complement" was coined by immunologists when they first discovered that antibodies were much more effective in dealing with invaders if they were "complemented" by other proteins – the complement proteins.

The alternative (spontaneous) complement activation pathway that we talked about in the last lecture is totally nonspecific: Any unprotected surface is fair game. In contrast, the classical (antibody-dependent) activation pathway is quite specific: Only those antigens to which the antibody binds will be targeted for complement attack. In this system, the antibody identifies the invader, and the complement proteins do the dirty work.

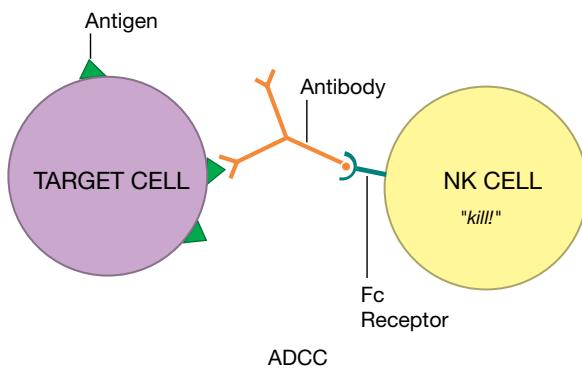
Certain "subclasses" of IgG antibodies can also fix complement, because C1 can bind to the Fc region of these antibodies. However, IgG antibodies are real wimps, with only one Fc region per molecule. So bringing two C1 complexes close enough together to get things started requires that two molecules of IgG bind right next to each other on the surface of the invading pathogen – and this is likely to happen only when there is a lot of IgG around. So, **early in an infection, when antibodies are just beginning to be made, IgM antibodies have a great advantage over IgG antibodies because they fix complement so efficiently.** In addition, IgM antibodies are very good at neutralizing viruses by binding to them and preventing them from infecting cells. Because of these properties, IgM is the perfect "first antibody" to defend against viral or bacterial infections.

IgG antibodies

IgG antibodies come in a number of different subclasses that have slightly different Fc regions and therefore, different functions. For example, one subclass of human IgG antibodies, IgG1, is very good at binding to invaders to opsonize them for ingestion by professional phagocytes. This is because macrophages and neutrophils have receptors on their surfaces that can bind to the Fc portion of IgG1 antibodies once those antibodies have bound to an invader.

Another IgG subclass, IgG3, fixes complement better than any other IgG subclass. In addition, natural killer cells have receptors on their surface that can bind to the Fc region of IgG3 antibodies. As a result, IgG3 can form a

bridge between an NK cell and its target by binding to the target cell (e.g., a virus-infected cell) with its Fab region, and to the NK cell with its Fc region. Not only does this bring the NK cell close to its target, but having its Fc receptors bound actually stimulates an NK cell to be a more effective killer. This process is called antibody-dependent cellular cytotoxicity (ADCC). In ADCC, the NK cell does the killing, but the antibody identifies the target.



Like IgM antibodies, IgG antibodies also are very good at neutralizing viruses. Moreover, IgG antibodies are unique in that they can pass from the mother's blood into the blood of the fetus by way of the placenta. This provides the fetus with a supply of IgG antibodies to tide it over until it begins to produce its own – several months after birth. This extended protection is possible because IgG antibodies are the longest lived antibody class, with a half-life of about three weeks. In contrast, IgM antibodies have a half-life of only about one day.

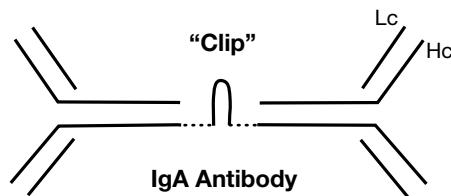
The "G" in IgG stands for "gamma," and IgG antibodies are sometimes called **gamma globulins**. If there is a possibility that you have been exposed to an infectious agent, say hepatitis A virus, your doctor may recommend that you get a gamma globulin shot. These shots are prepared by pooling together antibodies from a large number of people, at least some of whom have been infected with hepatitis A virus and therefore are making antibodies against the virus. The hope is that these "borrowed" antibodies will neutralize most of the virus to which you have been exposed, and that this treatment will help keep the viral infection under control until your own immune system can be activated.

IgA antibodies

Here's a question for you: What is the most abundant antibody class in the human body? No, it's not IgG. It's IgA. This is really a trick question, because I told you earlier that IgG was the most abundant antibody class in the

blood – which is true. It turns out, however, that we humans synthesize more IgA antibodies than all the other antibody classes combined. Why so much IgA? Because **IgA is the main antibody class that guards the mucosal surfaces of the body**, and a human has about 400 square meters of mucosal surfaces to defend. These include the digestive, respiratory, and reproductive tracts. So although there aren't a lot of IgA antibodies circulating in the blood, there are tons of them protecting the mucosal surfaces. Indeed, about 80% of the B cells that are located beneath these surfaces produce IgA antibodies.

One reason IgA antibodies are so good at defending against invaders that would like to penetrate the mucosal barrier is that each IgA molecule is rather like two IgG molecules held together by a "clip."



The clipped-together tail structure of IgA antibodies is responsible for several important properties of this antibody class. The clip functions as a "passport" that can facilitate the transport of IgA antibodies across the epithelial cells that line the intestines and into the interior (lumen) of the intestines. Moreover, this unique structure makes IgA antibodies resistant to acids and enzymes found in the digestive tract. Once inside the intestines, IgA antibodies can "coat" invading pathogens and keep them from attaching to the intestinal cells they would like to infect. In addition, whereas each IgG molecule has two antigen-binding regions, the "dimeric" IgA molecule has four Fab regions to bind antigens. Consequently, dimeric IgA antibodies are very good at collecting pathogens together into clumps that are large enough to be swept out of the body with mucus or feces. In fact, rejected bacteria make up about 30% of normal fecal matter.

All together, these qualities make IgA antibodies perfect for guarding mucosal surfaces such as the intestines or the lungs. Importantly, **it is the IgA class of antibodies that is secreted into the milk of nursing mothers. These IgA antibodies coat the baby's intestinal mucosa and provide protection against pathogens that the baby ingests.** This makes sense, because many of the microbes that babies encounter are taken in through their mouths – babies like to put their mouths on everything, you know.

Although IgA antibodies are very effective against mucosal invaders, they are totally useless at fixing complement.

C1 won't even bind to an IgA antibody's Fc region. Again we see that **the constant region of an antibody determines both its class and its function**. This lack of complement-fixing activity is actually a good thing. If IgA antibodies could initiate the complement reaction, our mucosal surfaces would be in a constant state of inflammation in response to both pathogenic and nonpathogenic microbes. And, of course, having chronically inflamed intestines would not be all that great. So **IgA antibodies mainly function as "passive" antibodies which block the attachment of invaders to cells that line our mucosal surfaces, and usher these unwanted guests out of the body.**

IgE antibodies

Of the four main antibody classes (IgM, IgG, IgA, and IgE), **IgE antibodies are the least abundant in the human body**. However, this antibody class probably has the most interesting history. In the early 1900s, a French physician named Charles Richet was sailing with Prince Albert of Monaco (Grace Kelly's father-in-law). The prince remarked to Richet that it was very strange how some people react violently to the toxin in the sting of the Portuguese man-of-war, and that this phenomenon might be worthy of study.

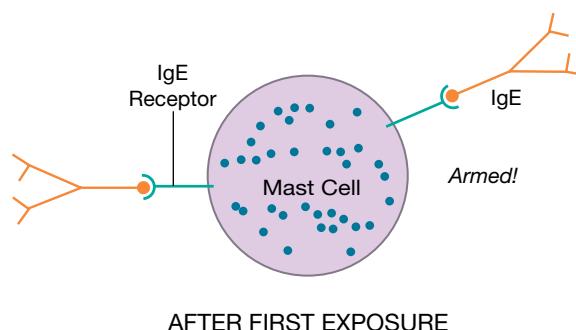
Richet took the prince's advice, and when he returned to Paris, he decided, as a first experiment, to test how much toxin was required to kill a dog. Don't ask me why he decided to use dogs in his experiments. Maybe there were a lot of stray dogs around back then, or perhaps he just didn't like working with mice. Anyway, the experiment was a success and he was able to determine the amount of toxin that was lethal. However, many of the dogs he used in this first experiment survived, because they didn't receive the lethal dose. Not being one to waste a good dog, Richet decided to inject these "leftovers" with the toxin again to see what would happen. His expectation was that these animals might have become immune to the effects of the toxin, and that the first injection would have provided protection (prophylaxis) against a second challenge. You can imagine his surprise, then, when all the dogs died – even the ones that received tiny amounts of toxin in the second injection. Since the first injection had the opposite effect of protection, Richet coined the word **anaphylaxis** to describe this phenomenon ("ana" is a prefix meaning "opposite"). Richet continued these studies on anaphylactic shock, and in 1913 he received the Nobel Prize for his work. I guess one lesson from this is that if a prince suggests you should study something, you might want to take his advice seriously!

Immunologists now know that **anaphylactic shock is caused by mast cells degranulating**. Like macrophages, mast cells are white blood cells that are stationed

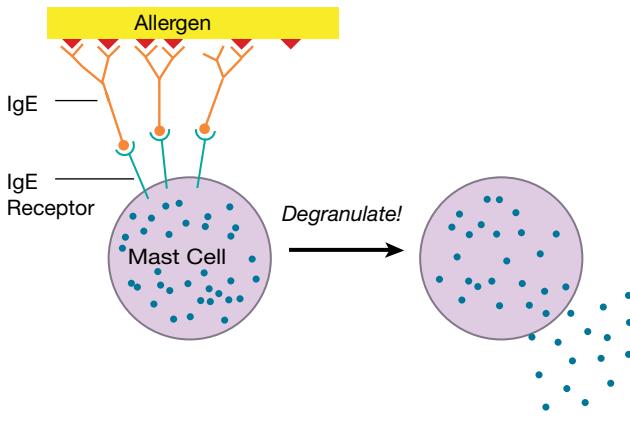
beneath all exposed surfaces (e.g., beneath the skin or the mucosal barrier). As blood cells go, mast cells are very long-lived: They can survive for years in our tissues. There they lie in wait to protect us against infection by parasites that have penetrated our barrier defenses.

Stored safely inside mast cells are granules that contain all kinds of pre-activated, pharmacologically active chemicals, the most famous of which is histamine. Indeed, a mast cell is so full of these granules that its name is derived from the German word *mastung*, which means "well fed." When a mast cell encounters a parasite, it exports its granules (i.e., it "degranulates"), and dumps the contents of these granules onto the parasite to kill it. Unfortunately, in addition to killing parasites, mast cell degranulation also can cause an allergic reaction, and in extreme cases, anaphylactic shock. Here's how this works.

An antigen (e.g., the man-of-war toxin) that can cause an allergic reaction is called an **allergen**. On the first exposure to an allergen, some people, for reasons that are far from clear, make a lot of IgE antibodies directed against the allergen. Mast cells have receptors (IgE receptors) on their surface that can bind to the Fc region of these IgE antibodies. And when this happens, the mast cells are like bombs waiting to explode.



On a second exposure to the allergen, **IgE antibodies that are already bound to the surfaces of mast cells can bind to the allergen**. Because allergens are usually proteins with a repeating sequence, the allergen can cross-link many IgE molecules on the mast cell surface, dragging the IgE receptors together. This clustering of IgE receptors is similar to the crosslinking of B cell receptors in that bringing many of these receptors together results in a signal being sent. In this case, however, the signal says "degranulate," and the mast cell responds by dumping its granules into the surrounding tissues.



Histamines and other chemicals released from mast cell granules increase capillary permeability so that fluid escapes from the capillaries into the tissue – that's why you get a runny nose and watery eyes when you have an allergic reaction. This is usually a rather local effect, but if the toxin spreads throughout the body and triggers massive degranulation of mast cells, things can get serious. In such a case, the release of fluid from the blood into the tissues can reduce the blood volume so much that the heart can no longer pump efficiently, resulting in a heart attack. In addition, histamine from the granules can cause smooth muscles around the windpipe to contract, making it difficult to breathe. In extreme cases, this contraction can be strong enough to cause suffocation. Most of us don't have to worry about being stung by a Portuguese man-of-war. However, some people make lots of IgE antibodies in response to bee toxin, and for those folks, a bee sting can be fatal. Indeed, about 1,500 Americans die each year from anaphylactic shock.

The logic of class switching

This brings us to an interesting question: Why are B cells allowed to switch the class of antibody they make anyway? Wouldn't it be safer just to stick with good old IgM antibodies? I don't think so. Let's suppose you have a viral infection of your respiratory tract, resulting in the common cold. Would you want to be stuck making only IgM antibodies? Certainly not. You'd want a lot of IgA antibodies to be secreted into the mucus that lines your respiratory tract to bind up that virus, and help remove it from your body. On the other hand, if you have a parasitic infection (worms, for example), you'd want IgE antibodies to be produced, because IgE antibodies can cause cells such as mast cells to degranulate, making life miserable for those worms. So

the beauty of this system is that the different classes of antibodies are uniquely suited to defend against different invaders.

ANTIBODY CLASS	ANTIBODY PROPERTIES
IgM	Great complement fixer Good opsonizer First antibody made
IgA	Resistant to stomach acid Protects mucosal surfaces Secreted in milk
IgG	OK complement fixer Good opsonizer Helps NK cell kill (ADCC) Can cross placenta
IgE	Defends against parasites Causes anaphylactic shock Causes allergies

Now suppose it could be arranged so that your immune system makes IgG antibodies when your big toe is infected, IgA antibodies when you have a cold, or IgE antibodies when you have a parasitic infection? Wouldn't that be elegant? Well, it turns out that this is exactly what happens! Here's how it works.

Antibody class switching is controlled by the cytokines that B cells encounter when switching takes place: Certain cytokines or combinations of cytokines influence B cells to switch to one class or another. For example, if B cells class switch in an environment that is rich in IL-4 and IL-5, they preferentially switch their class from IgM to IgE – just right for those worms. On the other hand, if there is a lot of IFN- γ around, B cells switch to produce IgG3 antibodies that are very effective against bacteria and viruses. Or if a cytokine called TGF β is present during the class switch, B cells preferentially change from IgM to IgA antibody production – perfect for the common cold. So, to insure that the antibody response will be appropriate for a given invader, all that is required is for the right cytokines to be present when B cells switch classes. But how could this be accomplished?

You remember that helper T cells are “quarterback” cells which direct the immune response. One way they do this is by producing cytokines which influence B cells to make the antibody class that is right to defend against a given invader. To learn how Th cells know which cytokines to make, you'll have to wait for the next three lectures when we discuss antigen presentation and T cell

activation and function. But for now, I'll just give you the bottom line: **In response to cytokines made by Th cells, B cells can switch from making IgM antibodies to producing one of the other antibody classes.** As a result, the adaptive immune system can respond with antibodies tailor-made for each kind of invader – be it a bacterium, a flu virus, or a worm. What could be better than that?!

SOMATIC HYPERMUTATION

As if class switching weren't great enough, there is yet another amazing thing that can happen to B cells as they mature. Normally, the overall mutation rate of DNA in human cells is extremely low – only about one mutated base per 100 million bases per DNA replication cycle. It has to be this low or we'd all end up looking like Star Wars characters with three eyes and six ears. However, in very restricted regions of the chromosomes of B cells – those regions that contain the V, D, and J gene segments – an extremely high rate of mutation can take place. In fact, mutation rates as high as one mutated base per 1,000 bases per generation have been measured. We're talking serious mutations here! This high rate of mutation is called **somatic hypermutation**, and it occurs after the V, D, and J segments have been selected. So **somatic hypermutation is a relatively late event in the maturation of B cells.** B cells that still make IgM antibodies usually have not undergone somatic hypermutation.

What somatic hypermutation does is to change (mutate) the part of the rearranged antibody gene that encodes the antigen-binding region of the antibody. Depending on the mutation, there are three possible outcomes: The affinity of the antibody molecule for its cognate antigen may remain unchanged, it may be increased, or it may be decreased. Now comes the neat part. In order for maturing B cells to proliferate, they must continually be restimulated by helper T cells. Those B cells whose BCRs have mutated to higher affinity compete more successfully for limited T cell help. Consequently, they proliferate more frequently than do B cells with lower-affinity receptors. Therefore, the result of somatic hypermutation is that you end up with a collection of B cells whose BCRs bind more tightly to their cognate antigen.

By using somatic hypermutation to make changes in the antigen-binding region of a BCR, and by using binding and proliferation to favor B cells whose mutations have increased the BCR's affinity for antigen, B cell receptors can be "fine-tuned." The result is a collection of B cells whose receptors have a higher average affinity for their cognate antigen. This whole process is called **affinity maturation**.

So B cells can change their constant (Fc) region by class switching, and their antigen-binding (Fab) region by somatic hypermutation – and these two modifications produce B cells that are better adapted to deal with invaders. The assistance of helper T cells is usually required for B cells to make either of these upgrades. As a result, B cells that are activated without T cell help (e.g., in response to carbohydrates on the surface of a bacterium) generally don't undergo either class switching or somatic hypermutation.

B CELLS MAKE A CAREER CHOICE

The final step in the maturation of a B cell is the choice of profession. This can't be too tough, because a B cell really only has two fates to choose between: to become a **plasma B cell** or a **memory B cell**. Plasma B cells are antibody factories. If a B cell decides to become a plasma cell, it begins to produce the secreted form of the BCR – the antibody molecule. Although they only live for a few days, these short-lived plasma B cells can synthesize 2,000 of these antibodies each second. The ability of plasma B cells to rapidly make so many antibody molecules helps the immune system keep up with invaders such as bacteria and viruses which multiply very quickly.

Although the B cell's other possible career choice – to become a memory B cell – may not be quite so dramatic as the decision to become a plasma cell, it is extremely important. It is the memory B cell that recalls your first exposure to a pathogen, and helps defend you against subsequent exposures. Immunologists haven't figured out how a B cell "chooses" to become either a memory cell or a plasma cell. However, they do know that the interaction between the co-stimulatory molecule CD40L on the surface of a helper T cell and CD40 on the B cell surface is important in memory cell generation. Indeed, **memory B cells are not produced when B cells are activated without T cell help.**

REVIEW

A B cell's receptors function as the "eyes" of the cell, and actually have two parts: a recognition part (made up of the heavy and light chain proteins) and a signaling part (made up of two other proteins, Ig α and Ig β). The final genes that encode the recognition part are made by mixing and matching gene segments. The result is a collection of B cells with receptors so diverse that they probably can recognize any organic molecule in the universe. For these receptors to signal what they have seen requires that multiple BCRs be clustered (crosslinked). This crosslinking brings the Ig α and Ig β signaling molecules that are associated with the heavy chains close together. And when enough Ig α and Ig β molecules are clustered in this way, the "receptor engaged" signal is sent to the nucleus of the B cell.

B cells also have co-receptor molecules on their surface which can recognize opsonized antigen. When both the B cell's receptors and the co-receptors are engaged by an antigen, the number of BCRs which must be crosslinked to signal activation is dramatically reduced. Consequently, these co-receptors focus the attention of B cells on antigens that have already been recognized by the innate system as dangerous and which have been opsonized.

Activation of a virgin B cell requires two "keys." Crosslinking of the B cell's receptors is the first key, but a second, "co-stimulatory" key also is required. This key usually is provided by a helper T cell, and involves cell-cell contact, during which CD40L molecules on the surface of a helper T cell bind to CD40 proteins on the surface of a B cell. B cells can also be activated without T cell help. The first requirement for this T cell-independent activation is that a large number of the B cell's receptors must be crosslinked. This typically happens when the surface of an invader is made up of many copies of the antigen to which a B cell's receptors bind (its cognate antigen). Although the crosslinking of many B cell receptors is a requisite for T cell-independent activation of a naive B cell, it is not enough. A second, co-stimulatory signal also is needed. This co-stimulation is in the form of a danger signal which confirms that an authentic threat exists. By demanding that two keys must be supplied before a B cell can be activated, a fail-safe system is established that guards against inappropriate B cell activation.

IgM antibodies are the first antibodies produced by B cells in response to a pathogen that has not been encountered before. However, as a B cell matures, it can choose to produce a different class of antibody: either IgG, IgA, or IgE. This class switching does not change the antigen-binding (Fab) region of the antibody. Consequently, the

antibody recognizes the same antigen before and after its class has been switched.

What does change during class switching is the Fc region of the heavy chain. This is the part of the molecule that determines how the antibody functions, with some functions being better suited to certain invaders than to others. For example, IgM and IgG antibodies are able to activate the complement system, so these antibodies are especially useful against bacteria and some viruses. On the other hand, IgA antibodies cannot activate the complement cascade, so they are well suited for protecting mucosal surfaces – where complement activation would not be desirable. Importantly, the choice of antibody class is determined by the cytokines present in the local environment of the B cell when class switching takes place. So by arranging to have the appropriate cytokines produced at the appropriate places, the right class of antibody to defend against a particular invader can be made.

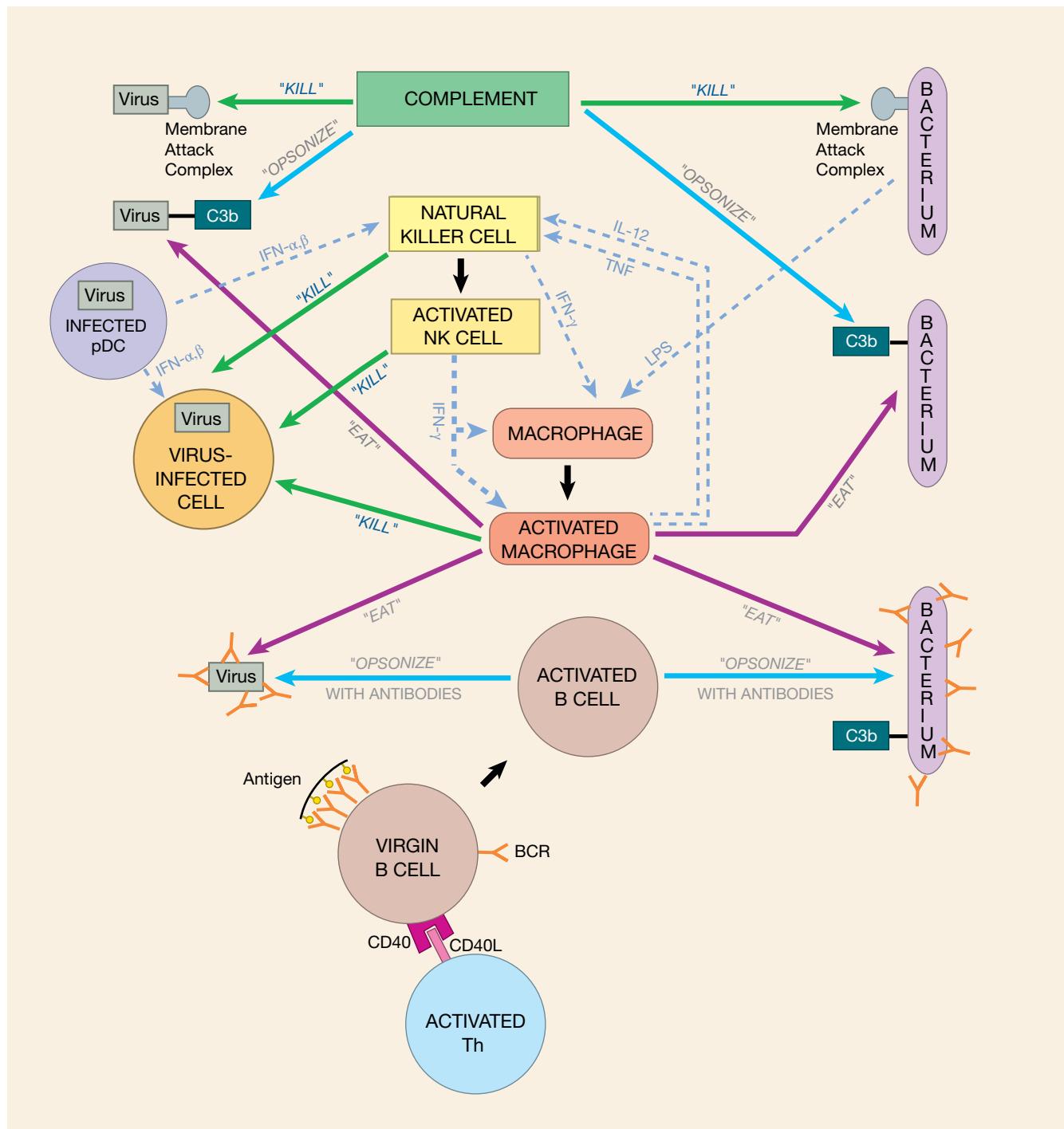
The other change that can take place as a B cell matures is somatic hypermutation. In contrast to class switching, in which the antibody gets a different Fc region, somatic hypermutation alters the antigen-binding region of the antibody. Because the probability that a B cell will proliferate depends on the affinity of its BCR for antigen, the B cells which proliferate most will be those for which somatic hypermutation has increased the binding affinity of their BCRs. The result is a collection of B cells whose BCRs, on average, bind more tightly to the invader than did the original, unmutated BCRs. These upgraded B cells are especially useful as memory cells. Because their affinity-matured BCRs are sensitive to small amounts of antigen, these B cells can be reactivated early in a second infection while the number of invaders is still relatively small.

B cells can be activated with or without T cell help, but the outcomes in these two cases usually are very different. T cell-independent activation generally results in the production of IgM antibodies. In contrast, T cell-dependent activation can result in affinity-matured IgG, IgA, or IgE antibodies. One reason for this difference is that both class switching and somatic hypermutation require ligation of CD40 proteins on B cells. This signal is usually provided by CD40L, a protein found on the surface of activated helper T cells.

As B cells mature, they must decide whether to become short-lived plasma cells, which produce vast quantities of antibodies, or to stick around as longer-lived memory B cells. These memory B cells are responsible for making the antibodies which can protect us from a subsequent attack by the same pathogen.

SUMMARY FIGURE

Our summary figure now includes the innate immune system from the last lecture plus B cells and antibodies.



KNOWN UNKNOWNS

1. The precise mechanism that targets the somatic hypermutation machinery to the antibody genes and protects the rest of the genome from this high rate of mutation is still a mystery.
2. How do B cells decide whether to be a plasma B cell or a memory B cell?

THOUGHT QUESTIONS

1. B cells are produced according to the principle of clonal selection. Exactly what does this mean?
2. Describe what happens during T cell-dependent activation of B cells.
3. How can B cells be activated without T cell help, and why is T cell-independent activation of B cells important in defending us against certain pathogens?
4. Describe fail-safe systems that are involved in B cell activation.
5. What are the main attributes of IgM, IgG, IgA, and IgE antibodies?
6. Why do class switching and somatic hypermutation produce B cells that are better able to defend against invaders?

The Magic of Antigen Presentation

HEADS UP!

For T cells to be activated, their receptors must recognize protein fragments presented by MHC molecules on the surface of special “antigen presenting cells.” Presentation of antigen by class I MHC molecules lets killer T cells “look into” cells to determine whether they are infected and should be destroyed. Presentation of antigen by class II MHC molecules alerts the immune system to invaders that don’t infect cells, and helps guarantee that the decision to deploy the powerful adaptive immune system is not made by a single cell. Within the human population, there are genes for many slightly different MHC molecules. Consequently, it is likely that at least some humans will have MHC molecules which can display protein fragments from any pathogen.

INTRODUCTION

Of all the concepts on which the immune system is based, perhaps the most elegant, and certainly the most unexpected, is antigen presentation: the concept of having one cell present protein fragments to another cell. As you will see, antigen presentation is central to the function of the adaptive immune system, with the cells that present antigen to T cells – the antigen presenting cells (APCs) – playing a pivotal role. Let’s begin by discussing the “billboards” on APCs that actually do the presenting: the class I and class II MHC molecules.

CLASS I MHC MOLECULES

The structures of class I and class II MHC molecules have now been carefully analyzed, so immunologists have a good idea what these molecules look like. Class I molecules have a binding groove that is closed at both ends, so the small protein fragments (**peptides**) they present must fit within the confines of the groove (the “bun,” if you will). Indeed, **when immunologists pried peptides from the grasp of class I molecules and sequenced them, they found that most peptides are eight or nine amino acids in length. These peptides are anchored at the ends, and the slight variation in length is accommodated by letting the peptide bulge out a bit in the center.**

Every human has three genes (**HLA-A**, **HLA-B**, and **HLA-C**) for class I MHC proteins, situated on chromosome 6. Because we have two chromosome 6's (one from Mom and one from Dad), we each have a total of six class I MHC genes. Class I HLA proteins pair with another protein called **β 2-microglobulin** to make up the complete class I MHC molecule. In the human population, there are a total of about 1,500 slightly different forms of the genes that encode the three class I HLA proteins. The proteins encoded by these variants of the HLA-A, HLA-B, and HLA-C genes have roughly the same shape, but they differ by one or a few amino acids. Immunologists call molecules that have many forms “polymorphic,” and the class I HLA proteins certainly fit this description. In contrast, all of us have the same gene for the β 2-microglobulin protein.

Because they are polymorphic, class I MHC molecules can have different binding motifs, and therefore can present peptides which have different kinds of amino acids at their ends. For example, some class I MHC molecules bind to peptides that have hydrophobic amino acids at

one end, whereas other MHC molecules prefer basic amino acids at this anchor position. Since humans have the possibility of expressing up to six different class I molecules, collectively our class I molecules can present a wide variety of peptides. Moreover, although MHC I molecules are picky about binding to certain amino acids at the ends of the peptide, they are rather promiscuous in their selection of amino acids at the center of the protein fragment. As a result, **a given class I MHC molecule can bind to and present a large number of different peptides, each of which “fits” with the particular amino acids present at the ends of its binding groove.**

CLASS II MHC MOLECULES

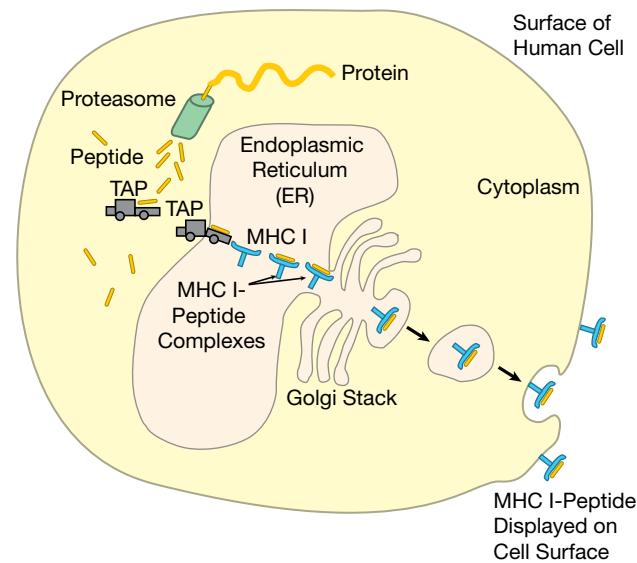
Like class I molecules, the class II MHC molecules (encoded by genes in the HLA-D region of chromosome 6) are wildly polymorphic. Within the human population, there are about 700 different versions of the class II MHC molecules. In contrast to class I MHC molecules, the binding groove of class II MHC molecules is open at both ends, so a peptide can hang out of the groove. As you might expect from this feature, **peptides that bind to class II molecules are longer than those that occupy the closed groove of class I molecules – in the range of thirteen to twenty-five amino acids.** Further, for class II MHC molecules, the critical amino acids that anchor the peptides are spaced along the binding groove instead of being clustered at the ends.

ANTIGEN PRESENTATION BY CLASS I MHC MOLECULES

MHC I molecules are billboards on the surface of a cell that display fragments of proteins manufactured by that cell. Immunologists call these **endogenous proteins**. They include ordinary cellular proteins such as enzymes and structural proteins, as well as proteins encoded by viruses and other microbes that may have infected the cell. For example, when a virus enters a cell, it uses the cellular biosynthetic machinery to produce proteins encoded by viral genes. A sample of these viral proteins is then displayed by class I MHC molecules along with samples of all the normal cellular proteins. So in effect, **the MHC I billboards advertise a sample of all the proteins that are being made inside a cell. Almost every cell in the human body expresses class I molecules on its surface, although the number of molecules varies from cell to cell. Killer T cells (also called cytotoxic lymphocytes or CTLs) inspect the protein fragments displayed by class I MHC**

molecules. Consequently, almost every cell is an “open book” that can be checked by CTLs to determine whether it has been invaded by a pathogen and should be destroyed. A typical human cell has about 100,000 class I molecules on its surface, and after they have been there for about a day, the MHC billboards are replaced by new ones – so the class I MHC display is kept current.

The way endogenous proteins are processed and loaded onto class I MHC molecules is very interesting. When mRNA is translated into protein in the cytoplasm of a cell, mistakes are frequently made. These mistakes can result in the production of useless proteins that don’t fold up correctly. In addition, proteins suffer damage due to normal wear and tear. So to make sure our cells don’t fill up with defective proteins, flawed or worn-out proteins are fed into protein-destroying “machines” in the cytoplasm that function rather like wood chippers. These protein chippers are called **proteasomes**, and they cut proteins up into peptides. Most of these peptides are then broken down further into individual amino acids, which are reused to make new proteins. However, some of the peptides created by the proteasomes are carried by specific transporter proteins (**TAP1** and **TAP2**) across the membrane into the **endoplasmic reticulum (ER)** – a large, sack-like structure inside the cell from which most proteins destined for transport to the cell surface begin their journey.



Once inside the ER, some peptides are chosen to be loaded into the grooves of class I MHC molecules. I say “chosen,” because, as we discussed, not all peptides will fit. For starters, a peptide must be the right length – about nine amino acids. In addition, the amino acids at the ends of the peptide must be compatible with the anchor amino

acids that line the ends of the groove of the MHC molecule. Obviously, not all of the “chips” prepared by the proteasome will have these characteristics, and those that don’t are degraded or shipped back out of the ER into the cytoplasm. Once class I MHC molecules are loaded with peptides, they proceed to the surface of the cell for display. So **there are three main steps in preparing a class I display: generation of a peptide by the proteasome, transport of the peptide into the ER by the TAP transporters, and binding of the peptide to the groove of the MHC I molecule.**

In ordinary cells, such as liver cells and heart cells, the major function of proteasomes is to deal with defective proteins. So as you can imagine, the chippers in these cells are not too particular about how proteins are cut up – they just hack away. As a result, some of the peptides will be appropriate for MHC presentation, but most will not be. In contrast, in cells such as macrophages that specialize in presenting antigen, this chipping is not so random. For example, binding of IFN- γ to receptors on the surface of a macrophage upregulates expression of three proteins called LMP2, LMP7, and MECL1. These proteins replace three “stock” proteins which are part of the normal proteasome machinery. The result of this replacement is that the “customized” proteasomes now preferentially cut proteins after hydrophobic or basic amino acids. Why, you ask? Because the TAP transporter and MHC I molecules both favor peptides that have either hydrophobic or basic C-termini. **So in antigen presenting cells, standard proteasomes are modified so they will produce custom-made peptides, thereby increasing the efficiency of class I display.**

Proteasomes also are not too particular about the size of peptides they make, and since the magic number for class I presentation is about nine amino acids, you might imagine that the ER would be flooded with useless peptides that are either too long or too short. However, it turns out that the TAP transporter has the highest affinity for peptides that are eight to sixteen amino acids long. Consequently, **the TAP transporter screens peptides produced by proteasomes, and preferentially transports those which have the right kinds of C-termini and that are of approximately the correct length.** Once candidate peptides have been transported into the ER, enzymes trim off excess N-terminal amino acids to make the peptide the right size for binding to class I MHC molecules.

An important feature of this “chop it up and present it” system is that the majority of proteins chopped up by proteasomes are newly made proteins which are structurally flawed – not old, worn-out proteins that need to be recycled. Consequently, most peptides displayed by class I MHC molecules are derived from newly synthesized

proteins, making it possible for the immune system to react quickly to an infection.

ANTIGEN PRESENTATION BY CLASS II MHC MOLECULES

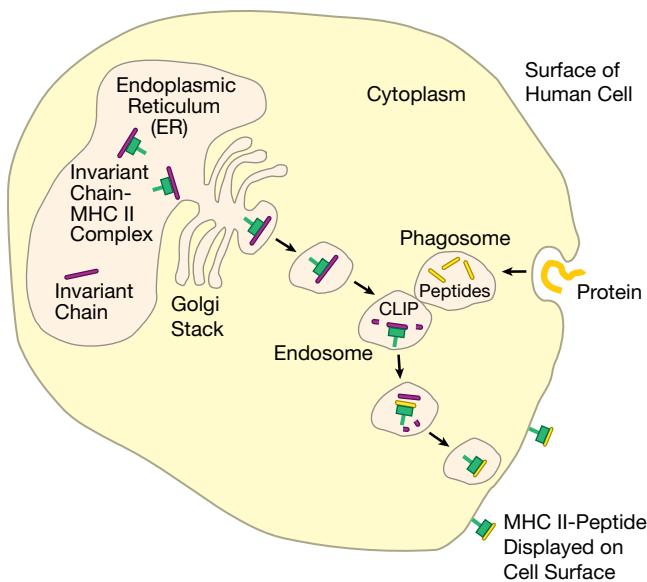
Whereas class I MHC molecules are designed to present protein fragments to killer T cells, class II MHC molecules present peptides to helper T cells. And in contrast to class I MHC molecules, which are expressed on almost every kind of cell, class II molecules are expressed exclusively on cells of the immune system. This makes sense. Class I molecules specialize in displaying proteins that are manufactured inside the cell, so the ubiquity of class I molecules gives CTLs a chance to check most cells in the body for infection. On the other hand, class II MHC molecules function as billboards that advertise what is happening outside the cell to alert helper T cells to danger. Therefore, relatively few cells expressing class II are required for this task – just enough to sample the environment in various parts of the body.

The two proteins that make up the class II MHC molecules (called the α and β chains) are produced in the cytoplasm and are injected into the endoplasmic reticulum where they bind to a third protein called the **invariant chain**. This invariant chain protein performs several functions. First, it sits in the groove of the MHC II molecule and keeps it from picking up other peptides in the ER. This is important, because the ER is full of endogenous peptides that have been processed by proteasomes for loading onto class I MHC molecules. If these protein fragments were loaded onto class II molecules, then class I and class II MHC molecules would display the same kind of peptides: those made from proteins produced in the cell. Since the goal is for class II MHC molecules to present fragments of proteins that come from outside the cell, the **exogenous peptides**, the invariant chain performs an important function: It acts as a “chaperone” that makes sure “inappropriate suitors” (endogenous peptides) don’t get picked up by MHC II molecules in the ER.

Another function of the invariant chain is to guide class II MHC molecules out through the Golgi stack to special vesicles in the cytoplasm called **endosomes**. It is within endosomes that class II MHC molecules are loaded with peptides. The current thinking is that while class II MHC molecules are making their way from the ER to an endosome, proteins that are hanging around outside the cell are enclosed in a phagosome, and brought into the cell. This phagosome then merges with the endosome, and enzymes present in the endosome chop up the exogenous

proteins into peptides. During this time, endosomal enzymes also destroy all of the invariant chain except for the piece called **CLIP** that actually is guarding the groove of the MHC molecule. Amazingly, although the exogenous proteins and the invariant chain are hacked to pieces by enzymes in the endosome, the class II MHC molecule itself remains unscathed. This is presumably because the MHC molecule is cleverly folded so that the enzymes cannot gain access to their favorite cleavage sites.

Meanwhile, a cellular protein, **HLA-DM**, which also has traveled to the endosome, catalyzes the release of the “placeholder,” CLIP. This allows an exogenous peptide to be loaded into the now-empty groove of the class II MHC molecule. But HLA-DM does more than just kick CLIP out to make room for the peptide. HLA-DM competes with potential peptides for binding to the class II MHC molecule, insuring that only peptides which bind tightly will be presented. Finally, the complex of MHC plus peptide is transported to the cell surface for display.



It is important to recognize that **there are two separate loading sites and pathways for class I and class II MHC molecules. It is this separation of loading sites and pathways that allows the class I billboard to advertise what's going on inside the cell (for killer T cells), and the class II billboard to advertise what's happening outside (for helper T cells).**

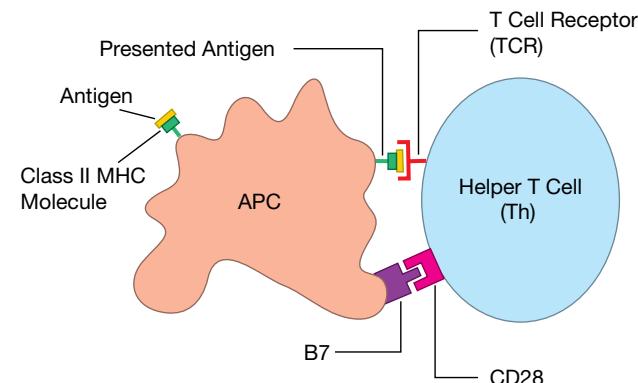
ANTIGEN PRESENTING CELLS

Before a killer T cell can kill or a helper T cell can help, it must be activated. For this to happen, a T cell must recognize its cognate antigen presented by an MHC

molecule on the surface of another cell. But this is not enough. It must also receive a second, co-stimulatory signal. Only certain cells are equipped to provide both class I and class II MHC display as well as co-stimulation. These are the antigen presenting cells (APCs).

Because the job of antigen presenting cells is to activate killer and helper T cells, these cells really should have been named “T cell-activating cells.” This would have avoided confusion with the ordinary cells in the body, which cannot activate T cells, but which do use class I MHC molecules to present antigens made inside these cells to alert killer T cells. Does it seem to you that immunologists just like to make things confusing? I sometimes think so. Anyway, to keep this straight, just remember that the term **“antigen presenting cell” always refers to those special cells which can provide both the high levels of MHC proteins and the co-stimulatory molecules required for T cell activation.**

Co-stimulation usually involves a protein called B7 on the surface of an antigen presenting cell that “plugs into” a protein called CD28 on the surface of a T cell.



Three types of antigen presenting cells have been identified: activated dendritic cells, activated macrophages, and activated B cells. All of these are white blood cells, and since new blood cells are made continuously, APCs can be replenished as needed.

Activated dendritic cells

Dendritic cells (DCs) have a characteristic starfish-like shape, and get their name from the word “dendrite,” which is commonly used to describe the projections on nerve cells. It is important to note that these cells are very different from the plasmacytoid dendritic cells (pDCs) mentioned earlier – cells whose primary function is to produce large amounts of interferon α and β in response to a viral attack. In fact, although they are called “dendritic cells,” resting pDCs are round like B cells and T cells.

Only after they are activated by a viral infection do they assume the starfish-like shape of a dendritic cell. Dendritic cells once were considered to be only a curiosity. However, it is now appreciated that these cells are the most important of all the antigen presenting cells – because **dendritic cells can initiate the immune response by activating virgin T cells**. Here's how this works.

The first DCs described were starfish-shaped “Langerhans” cells that are found in the tissues just below the skin. However, dendritic cells have since been discovered all over the body. What is now clear is that these dendritic cells are sentinel cells which take up positions beneath the barriers of epithelial cells that represent our first line of defense. In normal tissues (tissues that have not been infected), DCs resemble wine tasters. Although they can take up about four times their volume of extracellular fluid per hour, they mostly just take it in and spit it back out. In this “resting” state, DCs express some B7 and relatively low levels of MHC molecules on their surface. As a result, they are not good at presenting antigen to T cells, especially to virgin T cells. This is because **naive T cells require extensive receptor crosslinking by MHC-peptide complexes as well as powerful co-stimulation in order to be activated**.

If there is a microbial invasion, and the tissues in which a dendritic cell resides become a battleground, the dendritic cell will become “activated.” DCs can be activated by signals which come from other immune system cells that are engaged in battle. For example, both neutrophils and macrophages give off tumor necrosis factor (TNF) when they are trying to destroy an attacker, and this battle cytokine can activate DCs. Also, interferon α or β given off by virus-infected cells can trigger DC activation. Finally, dendritic cells have pattern-recognition receptors (e.g., Toll-like receptors) which they use to recognize molecular patterns that are characteristic of broad classes of invaders. The signals received by these pattern-recognition receptors can play important roles in activating dendritic cells.

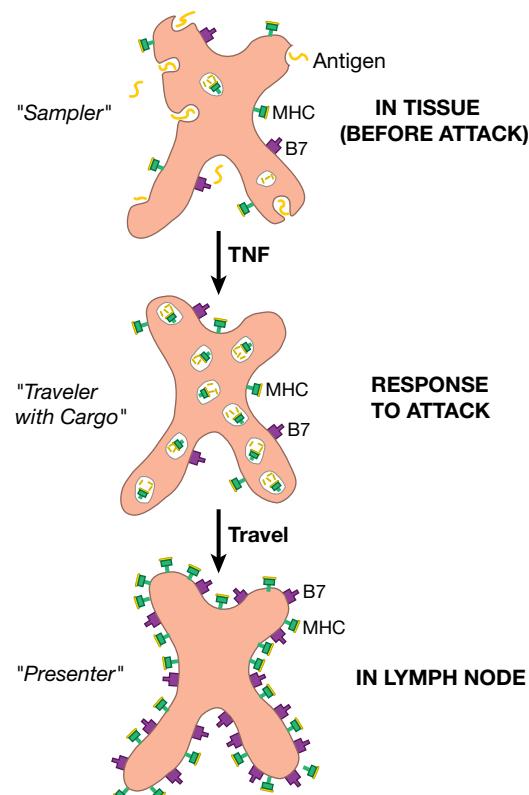
Dendritic cells travel

When a dendritic cell is activated by battle cytokines, by chemicals given off by dying cells, by ligation of its pattern-recognition receptors, or by a combination of these signals, the lifestyle of this “wine taster” changes dramatically. No longer does the dendritic cell “sip and spit.” Now it “swallows” what it has taken in. Typically, a DC remains in the tissues for about six hours after activation, collecting a representative sample of battle antigens. At that point, phagocytosis ceases, and the activated dendritic cell leaves the tissues and travels through the

lymphatic system to the nearest lymph node. **It is its ability to travel when activated which makes the dendritic antigen presenting cell so special.**

Inside a resting DC are large numbers of “reserve” class II MHC molecules. When a resting DC is activated and starts to “mature,” these class II MHC molecules begin to be loaded with antigens from the battle scene. And by the time a DC reaches its destination – a trip that usually takes about a day – these battle antigen-loaded class II MHC molecules will be prominently displayed on the surface of the cell. Also during its journey, the DC upregulates expression of its class I MHC molecules. Consequently, if the dendritic cell was infected by a virus out at the battle scene, by the time it reaches a lymph node, fragments of viral proteins will be on display on the dendritic cell’s class I MHC billboards. Finally, while traveling, the DC increases production of B7 co-stimulatory proteins. So **when it reaches a lymph node, the mature dendritic cell has everything it needs to activate virgin T cells: high levels of class I and class II MHC molecules loaded with the appropriate peptides, and plenty of B7 proteins.**

Three Phases in the Life of a Dendritic Cell



Now, why do you think DCs, which wildly sample antigens out in the tissues, stop their sampling when they begin their journey to a lymph node? Of course. **Dendritic**

cells take a “snapshot” of what is happening on the “front lines,” and carry this image to a lymph node – the place where virgin T cells congregate. There the traveling dendritic cells activate those virgin T cells whose T cell receptors recognize the invader that is “in the picture.” The fact that battle cytokines such as TNF trigger the migration of DCs to a lymph node also makes perfect sense. After all, you want DCs to mature, travel to lymph nodes, and present antigen only if a battle is on.

Once a DC reaches a lymph node, it only lives for about a week. This short lifetime may seem strange at first. After all, this doesn’t give a dendritic cell very long to meet up with the “right” virgin T cell which is circulating through the lymph nodes, looking for its cognate antigen. However, dendritic cells can interact with hundreds or even thousands of T cells every hour, and their short presentation life insures that dendritic cells carry snapshots of the battle which are up-to-date. In addition, after a dendritic cell has been activated, but before it begins its travels, it produces special cytokines (**chemokines**) which encourage white blood cells called **monocytes** to leave the blood, enter the tissues, and become dendritic cells. Consequently, **activated dendritic cells recruit their own replacements**. These newly recruited DCs can carry fresh images of the battle to lymph nodes as the battle continues.

There is another reason for the short lifetime of dendritic cells. In Lecture 2, I mentioned that it is very important that the magnitude of an immune response be in proportion to the seriousness of the attack. The short lifetime of DCs helps make this happen. Here’s how.

During a microbial attack, the number of T cells activated will depend on the number of mature dendritic cells that bring news of the battle to nearby lymph nodes. If the attack is weak, relatively few battle cytokines will be produced by warring macrophages, and only a small number of dendritic cells will be dispatched with their cargo. And because these DCs only live a short time once they reach the lymph node, only a limited number of T cells will be activated – just enough to deal with the small number of microbial invaders. On the other hand, if the infection is serious, many battle cytokines will be produced, many dendritic cells will be activated and travel to nearby lymph nodes, many more DCs will be recruited from the blood, and many T cells will be activated. Consequently, one result of the dendritic cell’s short lifetime is that the number of DCs in the lymph nodes at a given moment will reflect the current situation at the battle site, and the magnitude of the immune response will be in proportion to the severity of the infection.

So **dendritic antigen presenting cells are sentinel cells that sample antigens out in the tissues. If there is an**

invasion, DCs become activated and travel to nearby lymph nodes. There they initiate the adaptive immune response by presenting antigen collected at the battle scene to virgin helper T cells and CTLs. Activated DCs are short-lived, and the rapid turnover of these cells insures that the “pictures” they bring to a lymph node are continuously updated. Moreover, the number of dendritic cells dispatched from the tissues and the number of replacement dendritic cells recruited will depend on the severity of the attack. Consequently, the immune system is able to mount a response that is proportional to the danger posed by the invasion. Can you imagine a more ingenious system? I don’t think so!

Dendritic cells are classified as part of the innate immune system because their receptors are “hard-wired” and not “adaptable” like those of B and T cells. However, as I’m sure you now understand, **DCs actually function as a “bridge” between the innate and the adaptive systems.**

Activated macrophages

Macrophages also are sentinel cells which stand guard over areas of our body that are exposed to the outside world. They can function as garbage collectors, antigen presenting cells, or ferocious killers – depending on the signals they receive from the microenvironment in which they reside. In a resting state, macrophages are good at tidying up, but they are not much good at antigen presentation. This is because macrophages only express enough MHC and co-stimulatory molecules to function as antigen presenting cells after they have been activated by battle cytokines such as IFN- γ , or by having their pattern-recognition receptors ligated by invading pathogens.

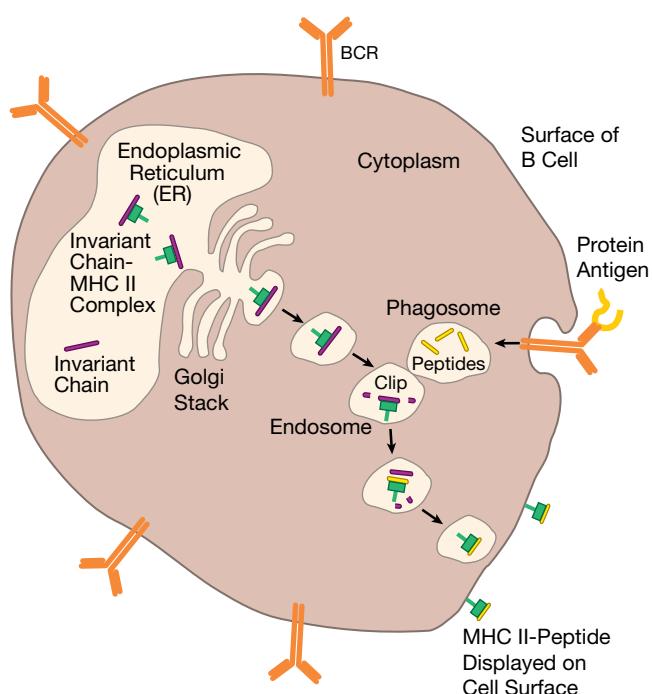
So macrophages resemble dendritic cells in that they efficiently present antigen only when there is something dangerous to present. However, it is important to recognize that **dendritic antigen presenting cells don’t kill and macrophages don’t travel**. Indeed, DCs can be pictured as “photojournalists” who don’t carry weapons, who take snapshots of the fighting, and who then leave the battlefield to file their reports. In contrast, macrophages are heavily armed soldiers who must stand and fight. After all, macrophages are one of our main weapons in the early defense against invaders. Nevertheless, their lack of mobility raises an interesting question: What good is the activated macrophage’s capacity to present antigen if it can’t travel to lymph nodes where virgin T cells are located? Here’s the answer.

Once they have been activated by dendritic cells, T cells exit the lymph nodes, circulate through the blood, and enter inflamed tissues to help with the battle. However, these “experienced” T cells must be continually restimulated.

Otherwise, they think the battle has been won, and they go back to a resting state or die of neglect. That's where activated macrophages come in. Out in the tissues, macrophages act as "refueling stations" which keep experienced T cells activated, so they can continue to participate in the battle. So **mature dendritic cells activate virgin T cells, and activated tissue macrophages mainly function to restimulate experienced T cells.**

Activated B cells

The third type of antigen presenting cell is the activated B cell. A virgin B cell is not much good at antigen presentation, because it expresses only low levels of class II MHC molecules and little or no B7. However, once a B cell has been activated, the levels of class II MHC molecules and B7 proteins on its surface increase dramatically. As a result, **an experienced B cell is able to act as an antigen presenting cell for Th cells.** B cells do not function as APCs during the initial stages of an infection, because at that time they are still naive – they haven't been activated. However, later in the course of the infection or during subsequent infections, presentation of antigen by experienced B cells plays an important role. This is because B cells have one great advantage over the other APCs: **B cells can concentrate antigen for presentation.** After a B cell's receptors have bound to their cognate antigen, the whole complex of BCR plus antigen is removed from the cell surface and dragged into the cell. There the antigen is processed, loaded onto class II MHC molecules, and transported back to the cell surface for presentation.



B cell receptors have a high affinity for antigen, so they act like "magnets," collecting antigen for presentation to Th cells. Because a threshold number of T cell receptors must be crosslinked by presented antigen before a Th cell can be activated, it is estimated that activated B cells have a 100- to 10,000-fold advantage over other APCs in activating helper T cells at times when there is relatively little antigen around. Presentation of antigen by B cells is also very fast. Less than half an hour elapses between the time antigen is captured by a B cell's receptors and the time it is displayed on the cell surface by class II MHC molecules.

In summary, **when an invader is first encountered, all the B cells which could recognize that particular invader are virgins, so the important APCs are activated dendritic cells. Then, while the battle is raging, activated macrophages on the front lines present antigen to warring T cells to keep them pumped up. Later in the infection, or if this same invader is encountered again, experienced B cells are extremely important APCs – because they can quickly activate helper T cells by concentrating small amounts of antigen for presentation.**

THE LOGIC OF CLASS I MHC PRESENTATION

To really appreciate why antigen presentation is one of Mother Nature's greatest "inventions," we need to think a little about the logic behind this amazing activity. For starters, we need to ask the question: Why bother with MHC presentation at all? Why not just let a T cell's receptors recognize un-presented antigen the way a B cell's receptors do? This is really a two-part question, since we are talking about two rather different displays: class I and class II. So let's examine these one at a time.

One reason for class I presentation is to focus the attention of killer T cells on infected cells, not on viruses and other pathogens that are outside our cells in the blood and tissues. So long as pathogens remain outside of our cells, antibodies can tag them for destruction by professional phagocytes, and can bind to them and prevent them from initiating an infection. Since each plasma B cell can pump out about 2,000 antibody molecules per second, these antibodies are "cheap" weapons that deal quite effectively with extracellular invaders. However, once microbes enter a cell, antibodies can't get at them. When this happens, killer T cells – the high-tech, "expensive" weapons, specifically designed to destroy infected cells – are needed. And the requirement that killer T cells recognize antigens presented by class I

MHC molecules on infected cells insures that CTLs won't waste their time going after invaders which are outside of cells – invaders that antibodies can usually deal with quite effectively.

In addition, **it would be extremely dangerous to have un-presented antigen signal T cell killing.** Imagine how terrible it would be if uninfected cells happened to have debris from dead viruses stuck to their surface, and killer T cells recognized this un-presented antigen and killed those innocent bystander cells. That certainly wouldn't do.

Another reason class I display is so important is **that most proteins made in a pathogen-infected cell remain inside the cell and never make their way to the cell surface. So without class I display, many pathogen-infected cells would go undetected by killer T cells. In fact, part of the magic of the class I MHC display is that, in principle, every protein of an invading pathogen can be chopped up and displayed by class I MHC molecules for killer T cells to view.**

Finally, because their receptors recognize "native" antigens that have not been fragmented and presented, B cells are actually at a disadvantage. The reason is that most proteins must be folded in order to function properly. As a result of this folding, many epitopes that a B cell's receptors might recognize are unavailable for viewing – because they are on the inside of a folded protein molecule. In contrast, **when a protein is chopped up into short pieces and presented by class I MHC molecules, epitopes cannot be hidden from killer T cells.**

So the logic of class I MHC presentation is easy to understand, but why are MHC molecules so polymorphic? After all, there are so many different forms in the human population that most of us inherit genes for six different class I molecules. Doesn't this seem a bit excessive?

Well, suppose there were only a few different class I MHC proteins. Now imagine what might happen if a virus were to mutate so that none of its peptides would bind to any of these MHC I molecules. Such a virus might wipe out the entire human population because no killer T cells could be activated to destroy virus-infected cells. So polymorphic MHC molecules give at least some people in the population a chance of surviving an attack by a clever pathogen.

Okay, but why do we have six genes for class I MHC proteins? That seems like a lot, especially since the class I MHC proteins are so polymorphic. The answer is that the possibility of "owning" up to six different class I MHC molecules increases the probability that each of us, individually, will have at least one class I MHC molecule into which a given pathogen's protein fragments will fit.

Indeed, people infected with HIV-1 who have inherited the maximum number of different class I MHC molecules (six) live significantly longer on average than do individuals who have genes encoding only five or fewer different class I molecules. The thinking here is that as HIV-1 mutates, having a larger number of different class I molecules increases the probability that mutated viral proteins can be presented. Why six, not ten, genes for class I MHC molecules? I haven't a clue!

THE LOGIC OF CLASS II MHC PRESENTATION

Okay, so class I MHC presentation makes a lot of sense. But what about class II presentation? At first glance, this dual display (class I and class II) by antigen presenting cells might seem overly complicated. What must be appreciated, however, is that many pathogens do not infect human cells: They are quite happy living and reproducing outside our cells in our tissues or blood. If antigen presenting cells could only display proteins made by pathogens that infect them, intelligence on many of the most dangerous microbes would never reach the command centers in lymph nodes. **By using class II MHC molecules to advertise a sampling of the total environment at the battle front, intelligence on all types of invaders can be made available to helper T cells.**

But couldn't helper T cells just recognize un-presented antigen? After all, they aren't killers, so there isn't the problem of bystander killing. That's true, of course, but there is still a safety issue here. **Antigen presenting cells only present antigen efficiently when a battle is going on, and helper T cells are screened to be sure that they do not react against our own proteins. Consequently, both the helper T cell and the antigen presenting cell must "agree" that there has been an invasion before a helper T cell can be activated. So the requirement that helper T cells only recognize presented antigen insures that the decision to deploy the potentially deadly adaptive immune system is not made by a single cell.**

Also, like class I molecules, class II molecules present small fragments of proteins. As a result, **the number of targets that a helper T cell can "see" during presentation far exceeds those available for viewing in a large, folded protein. The consequence of this expanded number of targets is a stronger, more diverse immune reaction in which many different helper T cells will be activated – helper T cells whose receptors recognize the many different epitopes that make up the antigens of an invader.**

CROSS-PRESENTATION

Although the separation of class I and class II pathways is the “law,” it has been shown that a certain subset of antigen presenting cells can take up exogenous antigens and shuttle them into the class I pathway for presentation by class I MHC molecules. Such an unlawful use of the class I display has been termed **cross-presentation**. The idea is that if a clever pathogen (e.g., a virus) figured out a way to avoid infecting antigen presenting cells, yet could still infect and reproduce in other cells of the body, cross-presentation would give the immune system a chance to activate CTLs against this pathogen. So far, the rules that govern cross-presentation, and the mechanisms involved have not been clearly defined. Moreover, it is not known whether cross-presentation by class I MHC molecules of antigen taken up from outside an APC is important for the normal functioning of the human immune system.

NON-CLASSICAL MHC MOLECULES AND LIPID PRESENTATION

Class I and class II MHC molecules are called classical MHC molecules. So as you might expect, there also are non-classical MHC molecules. The best studied of these is the CD1 family of proteins. These non-classical MHC molecules resemble class I MHC molecules in that they consist of a long, heavy chain protein which is paired with the $\beta 2$ -microglobulin protein. However, in contrast to classical MHC molecules, which have grooves that are suitable to bind short peptides, the CD1, non-classical MHC molecules have the proper shape to bind lipids. CD1 molecules can “sample” lipids from various compartments within a cell, and can present these molecules on the surface of antigen presenting cells, where they can activate T cells. Consequently, it has been postulated that these non-classical MHC molecules give T cells a way of surveying the lipid composition of cells, just as class I MHC molecules allow T cells to examine a cell’s proteins.

For every rule in immunology there seems to be an exception, and the rule here has been that T cells only recognize fragments of proteins presented by class I and class II MHC molecules. Obviously, CD1 presentation of lipids to T cells is an exception to this rule. So far, however, it is not clear how important lipid presentation is for the immune defense. Consequently, I will “stick to the rule” that T cells only recognize protein antigens. Be aware, however, that this may change as more research is done on CD1-presented lipids.

MHC PROTEINS AND ORGAN TRANSPLANTS

In addition to their natural role in antigen presentation, MHC molecules also are important in the unnatural setting of organ and tissue transplantation. Transplantation studies actually began in the 1930s with experiments involving mouse tumors. In those days, tumors were usually induced by rubbing some horrible chemical on the skin of a mouse, and then waiting a long time for a tumor to develop. Because it was so much trouble to make these tumors, biologists wanted to keep the tumor cells alive for study after the mouse had died. They did this by injecting some of the tumor cells into another, healthy mouse, where the cells would continue to grow. What they observed, however, was that the tumor cells could only be successfully transplanted when the donor and recipient were from a strain of mice in which there had been a lot of inbreeding. And the more inbred the strain, the better the chance for survival of the transplant. This provided the impetus for the creation of the many inbred mouse strains that immunologists depend on today.

Once inbred mouse strains were available, immunologists began to study the transplantation of normal tissues from one mouse to another. Right away they noticed that if a small patch of skin from one mouse was grafted onto the skin of another mouse, this new skin retained its healthy pink color and continued to grow – so long as the two mice were from the same inbred strain. In contrast, when this experiment was tried with mice that were not inbred, the transplanted skin turned white within hours (because the blood supply had been cut off) and invariably died. Immunologists figured this immediate graft rejection must be due to some genetic incompatibility, because it did not occur with inbred mice that have the same genes. To identify the genes that are involved in tissue compatibility (**histocompatibility**), immunologists bred mice to create strains that differed by only a few genes, yet which were still incompatible for tissue transplants. Whenever they did these experiments, they kept identifying genes that were grouped in a complex on mouse chromosome 17 – a complex they eventually called the “major histocompatibility complex” or MHC.

So **the MHC molecules that we have been discussing in the context of antigen presentation are the very same molecules that are responsible for immediate rejection of transplanted organs**. It turns out that killer T cells are particularly sensitive to MHC molecules that are “foreign,” and when they see them, they attack and kill the cells that express them. Some of their favorite targets are the cells that make up the blood vessels contained within the donated organ. By destroying these vessels, CTLs cut off the blood supply to

the transplanted organ, usually resulting in its death. For this reason, transplant surgeons try to match donors and recipients who have the same MHC molecules. However, finding such a match is difficult. Indeed, it is estimated that if you had access to organs contributed by 10,000,000 different individuals who were not related to you, the chance of

your finding an exact match to all your class I and class II MHC molecules would only be about 50%. So the diversity of MHC molecules, which is so important in protecting us from new or mutated invaders, creates a real problem for organ transplantation. Clearly, the immune system did not evolve with organ swapping in mind!

REVIEW

Class I MHC molecules function as billboards that display what is going on inside a cell. For example, when a virus infects a cell, it uses that cell's biosynthetic machinery to produce viral proteins. Some of these proteins are cut up into small pieces (peptides) by the proteasome, and carried by the TAP transporters into the endoplasmic reticulum (ER). There the peptides are "interviewed" by class I molecules. Those that are about nine amino acids in length with appropriate amino acids at their ends are bound in the grooves of class I MHC molecules, and are transported to the surface of the cell. By scanning the MHC I-peptide complexes displayed there, killer T cells can look into a cell to determine whether it has been infected and should be destroyed.

Class II MHC molecules also are billboards, but they are designed to alert helper T cells that a battle is being waged. Class II molecules are assembled in the ER, just like class I molecules, but because invariant chain proteins occupy their binding grooves, class II molecules do not pick up peptides in the ER. Instead, the class II-invariant chain complex is transported out of the ER and into another cellular compartment called an endosome. There they meet up with proteins that have been taken into the cell by phagocytosis and cut up into peptides by enzymes. These peptides then replace the invariant chains that have been guarding the grooves of the class II molecules, and the MHC-peptide complexes are transported to the cell surface for display to Th cells. By this clever mechanism, class II molecules pick up peptides derived from proteins taken in from outside the cell, but avoid peptides derived from proteins made within the cell.

The display by MHC molecules of fragmented proteins has several advantages over a display of intact proteins. First, most viral proteins normally remain hidden inside an infected cell and are not found on the cell surface. Therefore, these proteins would never be seen by killer T cells unless they were advertised by class I MHC molecules. In addition, because protein folding can hide large portions of a protein from view, chopping a protein up into small peptides reveals many potential T cell targets that would be inaccessible in an intact protein. Consequently, MHC display greatly increases the probability that CTLs will recognize an infected cell and that helper T cells will be alerted to a microbial attack.

Both class I and class II MHC molecules are extremely polymorphic, and humans have multiple genes for both classes of MHC molecules. Consequently, it is likely that your MHC molecules will be able to display peptides from most pathogens, and that at least some people in the population will have MHC molecules capable of displaying peptides from any pathogen.

Antigen presenting cells are special immune system cells that can provide both class I and class II MHC display as well as co-stimulation. The most important antigen presenting cell during the initial stages of an attack is the dendritic cell, because this cell can activate virgin T cells. When a DC detects danger signals at the scene of the battle, it begins to mature, and migrates with its cargo of battle antigen to a nearby lymph node. There, the dendritic cell uses class II MHC molecules to display fragments of the proteins it has collected out in the tissues, and class I MHC molecules to display fragments of proteins made by viruses or bacteria that may have infected the dendritic cell out at the battle site. In this way, the dendritic cell effectively takes a snapshot of what is going on at the front, carries it to the place where T cells are plentiful, and then does its "show-and-tell" thing to activate T cells.

Macrophages, activated by danger signals, can also function as antigen presenting cells. However, activated macrophages don't travel to lymph nodes to present antigen. They stay put in the tissues and battle invaders. Consequently, macrophages are most useful for presenting antigen after the adaptive immune system has been activated. At that time, activated macrophages out in the tissues can keep experienced T cells fired up, prolonging the time that they are effective in dealing with invaders.

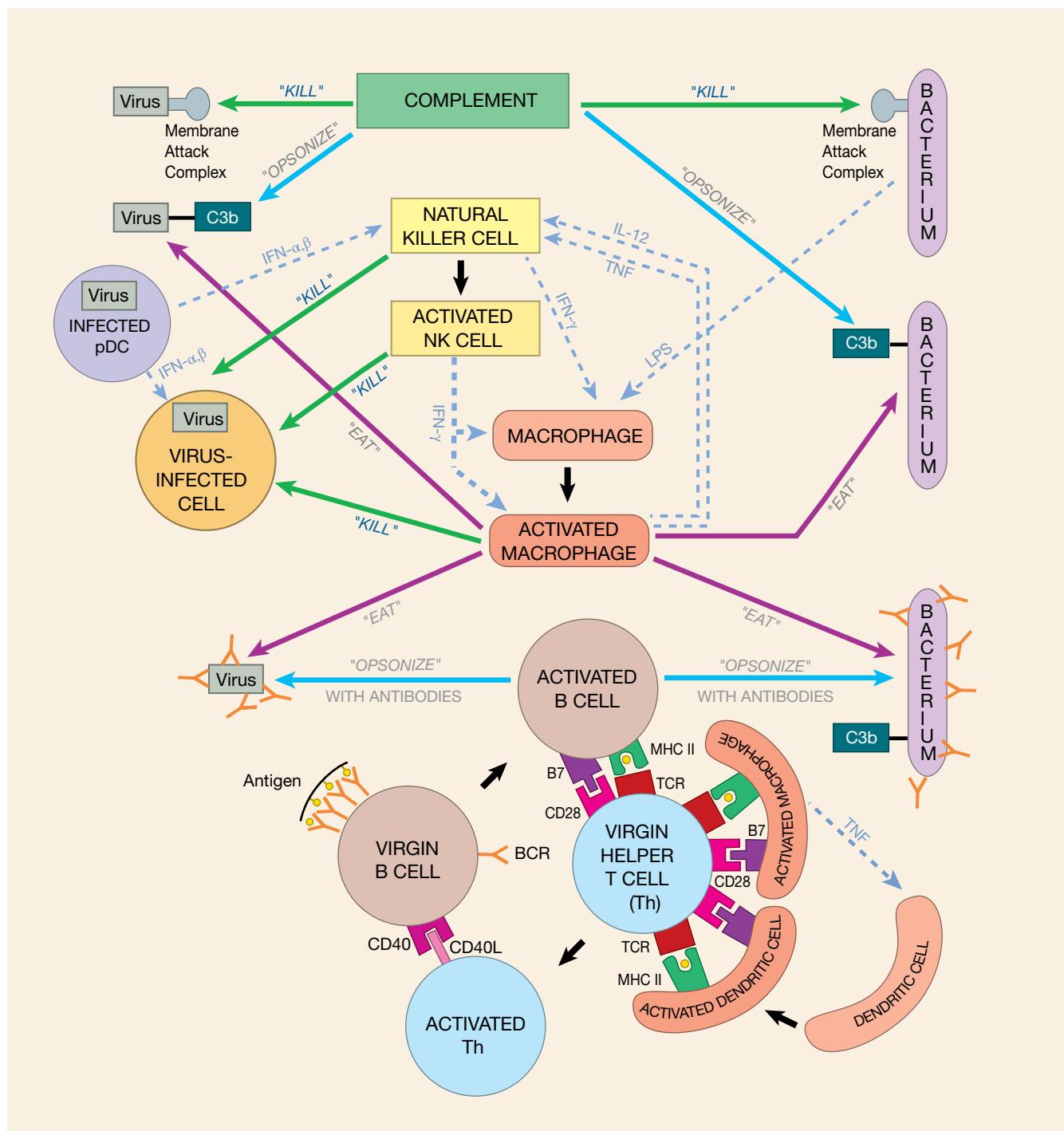
Activated B cells are the third type of antigen presenting cell, but again, these cells aren't useful in initiating the adaptive response against a new invader. The reason is that before B cells can function as antigen presenting cells, they must first be activated by helper T cells – and Th cells must wait to be activated by dendritic cells. So B cells don't get "certified" to be antigen presenting cells until after the adaptive immune response has already fired up. Nevertheless, once activated, B cells have a great advantage over DCs and macrophages:

B cells can use their receptors as “antigen collectors” to concentrate small amounts of antigen for presentation to helper T cells. Consequently, relatively late in the initial infection or

early in a subsequent infection by the same attacker, B cells play a major role as antigen presenting cells.

SUMMARY FIGURE

You will notice that our summary figure now includes antigen presenting cells with their MHC and B7 molecules.



KNOWN UNKNOWNS

1. How important for the normal functioning of the human immune system is cross-presentation by class I MHC molecules of antigen taken up from outside an APC?
2. How important for protection against disease is the presentation to T cells of lipids by non-classical CD1 MHC molecules?

THOUGHT QUESTIONS

1. Give several reasons why antigen presentation by class I MHC molecules is important for the function of the adaptive immune system.
2. Why does antigen presentation by class II MHC molecules make good sense?
3. Describe the different roles that activated dendritic cells, activated macrophages, and activated B cells play in the presentation of antigen during the course of an infection.
4. During their lifetimes, dendritic antigen presenting cells can be "samplers," "travelers," and "presenters." Describe what DCs are doing during each of these three stages.
5. Some peptides are presented more efficiently than others. What factors influence the efficiency of presentation by class I and class II MHC molecules?

LECTURE 5

T Cell Activation

HEADS UP!

Before they can do any work, T cells must be activated. This requirement helps insure that T cells will spring into action only when there is real danger and that only useful weapons will be mobilized. T cell activation requires recognition of the invader by the T cell's receptors, the function of co-receptor molecules that focus the attention of TCRs on the appropriate MHC molecule (class I or class II), and co-stimulation provided by an activated antigen presenting cell. There are many similarities between the ways B cells and T cells are activated – but there are also important differences.

INTRODUCTION

The innate immune system maintains large stockpiles of weapons. This makes sense because common invaders are attacking our bodies almost continuously, and the weapons of the innate immune system are useful against a wide variety of these “everyday” enemies. In contrast, only about one in a million B or T cells will have receptors that can recognize a given invader. Consequently, it would not be wise to stockpile B or T cells, because in our entire lifetime we will probably never encounter the invader which a particular B or T cell could defend against. Indeed, **an important feature of the adaptive immune system is that its weapons are made on demand: Only those B and T cells whose receptors can recognize the “invader du jour” are mobilized.** The first step in mobilizing these weapons is activation, and in this lecture, we’re going to focus on how T cells are activated. What they do once they are activated will be the subject of the next lecture.

T CELL RECEPTORS

T cell receptors (TCRs) are molecules on the surface of a T cell that function as the cell’s “eyes” on the world. Without these receptors, T cells would be flying blind with no way to sense what’s going on outside. T cell receptors come in two flavors: $\alpha\beta$ and $\gamma\delta$. Each type of receptor is composed of two proteins, either α and β or γ and δ . Like the heavy and light chains of the B cell receptor, the genes for α , β , γ , and δ are assembled by mixing and matching gene segments. In fact, in B and T cells, the same proteins (**RAG1** and **RAG2**) initiate the splicing of gene segments by making double-stranded breaks in chromosomal DNA. As the gene segments are mixed and matched, a “competition” ensues from which each T cell emerges with either an $\alpha\beta$ or a $\gamma\delta$ receptor, but not both. Generally, all the TCRs on a mature T cell are identical – although there are exceptions to this rule.

Traditional T cells

Over 95% of the T cells in circulation have **$\alpha\beta$ T cell receptors**, and express either CD4 or CD8 **co-receptor molecules** (more about these co-receptors in a bit). The $\alpha\beta$ receptors of these “traditional” T cells recognize a complex composed of a peptide and an MHC molecule on the surface of a cell. Each “mature” T cell will have receptors that recognize peptides associated either with class I MHC molecules or with class II MHC molecules. Importantly, the **$\alpha\beta$ receptors of a traditional T cell recognize both the peptide and the MHC molecule and, unlike B cells, T cells cannot undergo hypermutation to change the affinity of their TCRs for their cognate antigen.**

Non-traditional T cells

In addition to traditional T cells, several kinds of “non-traditional” T cells have been discovered. T cells which have **$\gamma\delta$ receptors** are considered to be non-traditional

because, in contrast to traditional T cells, most $\gamma\delta$ T cells do not express either the CD4 or CD8 co-receptor molecules. T cells with $\gamma\delta$ receptors are most abundant in areas such as the intestine, the uterus, and the tongue, which are in contact with the outside world. Interestingly, mice have lots of $\gamma\delta$ T cells in the epidermal layer of their skin, but humans do not. This serves to remind us that so far as the immune system is concerned, humans are not just big mice. After all, human and mouse lineages diverged roughly 65 million years ago, and humans are relatively large animals that can live for a long time. In contrast, mice are small and short-lived. An “elderly” mouse is about two years old! Consequently, we would predict that the immune systems which evolved to protect humans and mice, although similar, would be different. And they are.

Although $\alpha\beta$ TCRs are thought to be about as diverse as BCRs, $\gamma\delta$ receptors are much less diverse. Moreover, the receptors of $\gamma\delta$ T cells in the tongue and uterus tend to favor certain gene segments during rearrangement, whereas $\gamma\delta$ receptors in the intestine prefer other combinations of gene segments. The thinking here is that, **like players on the innate immune system team, $\gamma\delta$ T cells stand watch on the “front lines,” and have receptors which are “tuned” to recognize invaders that usually enter at certain locations.**

There is a lot about $\gamma\delta$ T cells which is still mysterious. For example, it is not known where these cells grow up. Traditional T cells mature in the thymus, and although $\gamma\delta$ T cells also are found in the thymus, nude mice, which lack a thymus, still produce functional $\gamma\delta$ T cells. In most cases, it also is not known exactly what the receptors on $\gamma\delta$ T cells recognize, but it is believed that, like B cells, $\gamma\delta$ T cells focus on un-presented antigen. The receptors of some $\gamma\delta$ T cells recognize proteins (e.g., MICA and MICB) which are expressed on the surface of cells that are under stress. Consequently, it has been postulated that $\gamma\delta$ T cells are designed to kill cells that become stressed as the result of a microbial infection. Nevertheless, the exact mission of $\gamma\delta$ T cells is not clear.

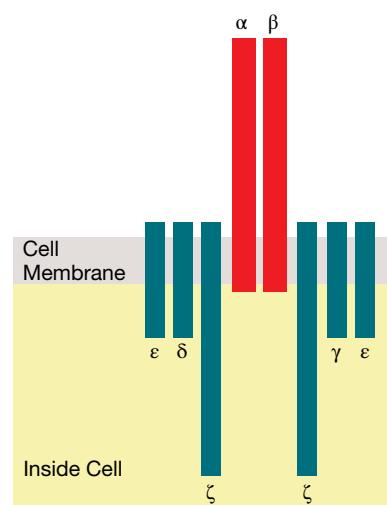
There is another type of non-traditional T cell that is mentioned frequently, but about which relatively little is known: the **NKT cell**. In a human, only about 1% of the T cells in the blood are of this type. As its name implies, this non-traditional T cell has some of the properties of the natural killer (NK) cells of the innate system, and some of the properties of traditional T cells of the adaptive immune system. NKT cells mature in the thymus and have $\alpha\beta$ receptors. However, in contrast to the $\alpha\beta$ receptors of traditional T cells, which are incredibly diverse, the repertoire of receptors expressed by NKT cells is quite limited. Moreover, the receptors of NKT cells recognize lipids

presented by non-classical CD1 MHC molecules instead of protein fragments presented by class I or class II MHC molecules. It has been proposed that NKT cells evolved as a weapon designed to protect us against microbes such as tuberculosis which produce characteristic lipid molecules. However, normal mice and mice that have been engineered to lack NKT cells are equally susceptible to infection with TB, and, so far, it is not clear how important NKT cells are in protecting humans against bacterial infections.

Because much more is known about traditional T cells than about their non-traditional cousins, and because traditional T cells seem to be the ones that are most important for protecting us from disease, we will limit our discussion in this book to T cells of the traditional variety.

HOW A T CELL’S RECEPTORS SIGNAL

Once a TCR has recognized its cognate antigen presented by an MHC molecule, the next step is to transmit a signal from the surface of the T cell, where recognition takes place, to the nucleus of the T cell. For the T cell to switch from a resting state to a state of activation, gene expression must be altered, and these genes are, of course, located in the cell’s nucleus. Normally, this type of signaling across the cell membrane involves a transmembrane protein that has two parts: an external region which binds to a molecule (called a **ligand**) that is outside the cell, and an internal region which initiates a biochemical cascade that conveys the “ligand bound” signal to the nucleus. Here the TCR runs into a bit of a problem. As is true of the BCR, the $\alpha\beta$ TCR has a perfectly fine extracellular domain that can bind to its ligand (the combination of MHC molecule and peptide), but the cytoplasmic tails of the α and β proteins are only about three amino acids long – much too short to signal.



To handle the signaling chores, a few bells and whistles had to be added to the TCR: a complex of proteins collectively called **CD3**. In humans, this signaling complex is made up of four different proteins: γ , δ , ϵ , and ζ (gamma, delta, epsilon, and zeta). The CD3 proteins are anchored in the cell membrane and have cytoplasmic tails that are long enough to signal just fine. Please note, however, that the γ and δ proteins that are part of the CD3 complex are not the same as the γ and δ proteins that make up the $\gamma\delta$ T cell receptor.

The whole complex of proteins (α , β , γ , δ , ϵ , ζ) is transported to the cell surface as a unit. If any one of these proteins fails to be made, you don't get a TCR on the surface. Consequently, most immunologists consider the functional, mature TCR to be this whole complex of proteins. After all, the α and β proteins are great for recognition, but they can't signal. And together, the γ , δ , ϵ , and ζ proteins signal just fine, but they are totally blind to what's going on outside the cell. You need both parts to make it work. As with BCRs, **signaling involves clustering TCRs together in one area of the T cell surface**. When this happens, a threshold number of kinase enzymes are recruited by the cytoplasmic tails of the CD3 proteins, and the activation signal is dispatched to the nucleus.

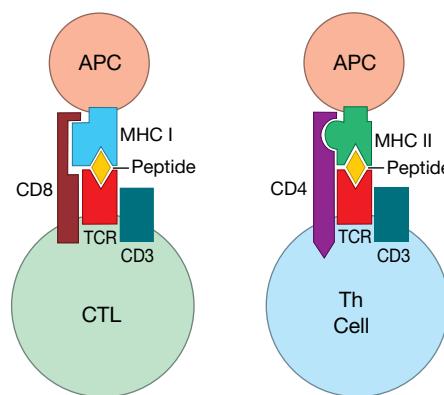
When the α and β chains of the TCR were first discovered, it was thought that the TCR was just an on/off switch whose only function was to signal activation. But now that you have heard about the CD3 proteins, let me ask you: Does this look like a simple on/off switch? No way! **This TCR can send signals that result in very different outcomes, depending on how, when, and where it is triggered.** For example, in the thymus, if a T cell's receptors recognize MHC plus self peptide, the TCRs can trigger the T cell to commit suicide to prevent autoimmunity. Later in its life, if its TCRs recognize their cognate antigen presented by MHC molecules, but that T cell does not receive the required co-stimulatory signals, the T cell may be neutered (anergized) so it can't function. And, of course, when a TCR is presented with its cognate antigen, and co-stimulatory signals are available, the TCR can signal activation. So this same T cell receptor, depending on the situation, signals death, anergy, or activation. In fact, there are now documented cases in which the alteration of a single amino acid in a presented peptide can change the signal from activation to death! Clearly this is no on/off switch, and immunologists are working very hard to understand exactly how TCR signaling is "wired," and what factors influence the signaling outcomes.

CD4 AND CD8 CO-RECEPTORS

In addition to the T cell receptor, there are two more molecules which are involved in antigen recognition by T cells – the **CD4 and CD8 co-receptors**. Now, doesn't it seem that Mother Nature got carried away when she added on these CD4 and CD8 co-receptors? I mean, there are already two proteins, α and β , to use for antigen recognition, and four more, γ , δ , ϵ , and ζ , to use for signaling. Wouldn't you think that would do it? Apparently not, so there must be essential features of the system that require CD4 and CD8 co-receptors. Let's see what these might be.

Killer T cells and helper T cells perform two very different functions, and they "look at" two different molecules, class I and class II MHC, respectively, to get their cues. But how do CTLs know to focus on peptides presented by class I molecules and how do Th cells know to scan APCs for peptides presented by class II? After all, it wouldn't be so great if a CTL got confused, recognized a class II-peptide complex on an APC, and killed that antigen presenting cell. So here's where CD4 and CD8 come in.

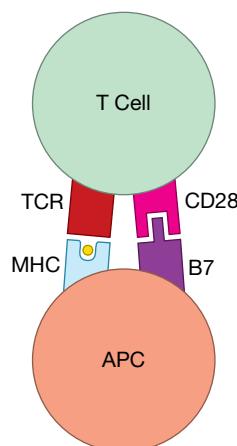
When T cells begin maturing in the thymus, they express both types of co-receptors on their surface. Immunologists call them CD4⁺CD8⁺ or "double-positive" cells. Importantly, **CD4 co-receptors will only "clip onto" class II MHC molecules, and CD8 co-receptors will only match with class I MHC molecules. So CD4 and CD8 co-receptors help focus the attention of Th cells and CTLs on the proper MHC molecule.** The latest thinking is that double-positive T cells scan APCs, looking for MHC molecules that their TCRs can bind to. If a T cell's receptors have the right shape to bind to class II MHC molecules on the surface of an APC, the CD4 co-receptors will clip on. Conversely, if the TCRs are shaped properly to bind to class I MHC molecules, the CD8 co-receptors will connect.



CD4 and CD8 molecules have tails that extend through the T cell's plasma membrane and into the cytoplasm. Although these tails are different, they both have the capacity to signal. So when a CD4 molecule clips onto a class II MHC molecule, expression of the CD8 co-receptor is downregulated, and the T cell becomes a "single-positive" CD4⁺ T cell that is committed to function as a helper T cell. In contrast, if the CD8 co-receptor clips onto the class I MHC molecule, CD4 expression is terminated, and that cell becomes a killer T cell. That's the idea, but exactly how these co-receptor molecules help "instruct" T cells to function as helpers or killers is not known.

CO-STIMULATION

In a naive T cell, the "connection" between the cell's receptors and its nucleus is not very good. It's as if the T cell had an electrical system in which a large resistor were placed between the sensor (the TCR) and the piece of equipment it is designed to regulate (gene expression in the nucleus). Because of this "resistor," a lot of the signal from the TCR is lost as it travels to the nucleus. The result is that a prohibitively large number of TCRs would have to engage their cognate antigen before the signal that reaches the nucleus would be strong enough to have any effect. If, however, while the TCRs are engaged, the T cell also receives **co-stimulation**, the signal from the TCRs is amplified many times, so that fewer (probably about 100-fold fewer) TCRs need to be engaged to activate a naive T cell. Although a number of different molecules have been identified which can co-stimulate T cells, the best studied examples are the **B7** proteins (B7-1 and B7-2) which are expressed on the surface of antigen presenting cells. B7 molecules provide co-stimulation to T cells by plugging into receptor molecules called **CD28** on the T cell's surface.



So in addition to having their T cell receptors ligated by MHC-peptide, naive T cells must also receive co-stimulatory signals before they can be activated. Co-stimulation can be thought of as an "amplifier" that strengthens the "I'm engaged" signal sent by a T cell's receptors, thereby lowering the threshold number of TCRs which must be crosslinked by MHC-peptide complexes. Interestingly, once a naive T cell has been activated, the connection between the TCRs and the nucleus strengthens. It is as if an experienced T cell has been "re-wired" so that the resistor present in a naive T cell is bypassed. As a result of this re-wiring, amplification of the TCR signal is not as important for an experienced T cell as it is for a virgin T cell. Consequently, experienced T cells have a reduced requirement for co-stimulation.

A TIME-LAPSE PHOTO OF HELPER T CELL ACTIVATION

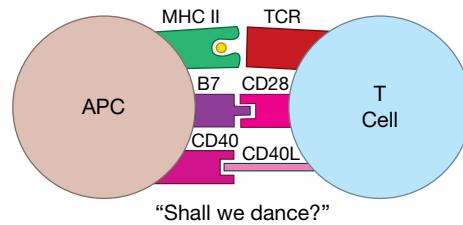
In the lymph nodes, helper T cells quickly scan dendritic cells to see if their cognate antigen is being displayed. A single dendritic cell typically hosts about 1,000 such "visits" each hour. If a T cell does find a dendritic cell displaying its cognate antigen, the T cell "lingers," because complete activation of a naive helper T cell usually takes several hours. During this time, a number of important events take place. First, adhesion molecules on the surface of the dendritic cell bind to their adhesion partners on the T cell, helping keep the two cells together. Next, the CD4 co-receptor molecules on the surface of the T cell clip onto the class II MHC molecules on the dendritic cell and strengthen the interaction between the two cells. In addition, the engagement of its TCRs upregulates the expression of adhesion molecules on the Th cell surface, strengthening the "glue" that holds the APC and the T cell together. This is important, because the initial binding between a TCR and an MHC-peptide complex is actually rather weak – to allow for rapid scanning. Consequently, the Velcro-like adhesion molecules are extremely important for T cell activation. The clustering of TCRs and adhesion molecules at the point of contact between an APC and a T cell results in the formation of what immunologists call an **immunological synapse**.

Engagement of a helper T cell's receptors also upregulates expression of **CD40L** proteins on its surface, and when these proteins plug into the **CD40** proteins on the surface of a dendritic cell, several remarkable things happen. Although mature dendritic cells express MHC and co-stimulatory molecules (e.g., B7) when they first enter lymph nodes, the expression level of these proteins increases when CD40 proteins on the APC are engaged by

the CD40L proteins on a Th cell. In addition, engagement of a dendritic cell's CD40 proteins prolongs the life of the dendritic cell. This extension of a "useful" dendritic cell's life span makes perfect sense. It insures that the particular dendritic cells which are presenting a T cell's cognate antigen will stick around long enough to help activate a lot of these T cells. So **the interaction between a dendritic cell and a naive helper T cell is not just one-way. These cells actually perform an activation "dance" in which they stimulate each other. The end result of this cooperation is that the dendritic cell becomes a more potent antigen presenting cell, and the Th cell is activated to express the high levels of CD40L required for helping activate B cells.**

After activation is complete, the helper T cell and the antigen presenting cell part. The APC then goes on to activate other T cells, while the recently activated Th cells proliferate to build up their numbers. During an infection, a single activated T cell can give rise to about 10,000 daughter cells during the first week or so of proliferation. This proliferation is driven by growth factors such as IL-2. Naive T cells can make some IL-2, but they don't have IL-2 receptors on their surface so they can't respond to this cytokine. In contrast, activated Th cells produce large amounts of IL-2, and they also express receptors for this cytokine on their surface. As a result, newly activated helper T cells stimulate their own proliferation. **This coupling of activation to the upregulation of growth factor receptors is the essence of clonal selection: Those Th cells that are selected for activation (because their TCRs recognize an invader) upregulate their growth factor receptors and proliferate to form a clone.** Moreover, the magnitude of T cell proliferation is dependent on the strength of the interaction between the TCR and the MHC-peptide. **T cells with high-affinity receptors proliferate more to build up their numbers than do T cells whose receptors don't bind tightly to MHC-presented peptides.**

So the sequence of events during the activation of a helper T cell is this: Adhesion molecules mediate weak binding between the Th and the APC while TCRs engage their cognate antigen presented by the APC. TCR engagement strengthens the adhesion between the two cells and upregulates CD40L expression on the Th cell. CD40L then binds to CD40 on the APC and increases the expression of MHC and co-stimulatory molecules (e.g., B7) on the APC surface. The co-stimulation provided to the Th cell by the APC amplifies the "TCR engaged" signal, resulting in the activation of the Th cell. So as a result of the B7/CD28 and CD40L/CD40 interactions, the Th cell and the DC actually stimulate each other. It's a win-win for them both.



When activation is complete, the cells disengage and the Th cell proliferates, driven by growth factors which bind to receptors that appear on the Th cell surface as a result of activation. This proliferation produces a clone of helper T cells which can recognize the invader advertised by the antigen presenting cell.

HOW KILLER T CELLS ARE ACTIVATED

For a helper T cell to be activated, its receptors must recognize their cognate antigen displayed by class II MHC molecules on the surface of a dendritic cell. The Th cell must also receive co-stimulatory signals from that same dendritic cell. This requirement that two cells (the Th cell and the DC) agree that there has been an invasion is a powerful safeguard against the activation of "rogue" helper T cells – cells which might direct an attack against our own tissues, causing autoimmune disease.

Although the events involved in the activation of helper T cells are pretty clear, the question of how naive killer T cells are activated is one of the most important unsolved mysteries in immunology. It has been known for some time that for a naive killer T cell to be fully activated, three cells must be involved: a CTL with receptors that recognize the invader; a dendritic cell, which uses its class I MHC molecules to present fragments of the invader's proteins to the CTL; and a helper T cell which provides "help" to the CTL. One way this might happen would be for the dendritic cell, the Th cell, and the CTL to engage in a *ménage à trois*. There is, however, a potential problem with this scenario. Early in an infection, there are very few of any of these cells around. Consequently, the probability is quite small that a helper T cell and a killer T cell would simultaneously find a dendritic cell which is presenting their cognate antigens.

Experiments have now shown that in response to an invasion by microbes which can infect cells (the microbes that CTLs are designed to defend against), T cell help is not required during the initial activation of killer T cells. A two-cell interaction between a naive CTL and an infected dendritic cell is sufficient. During this meeting, the CTL's receptors recognize their cognate antigen

displayed by class I MHC molecules on the dendritic cell, and they receive co-stimulation (e.g., via B7) from that same dendritic cell. What this means is that **a naive killer T cell can be activated in a way that is analogous to the way a naive Th cell is activated: by encountering an activated dendritic cell.** It is important to note that even when CTLs are activated without Th cell help, the requirement that an activated dendritic cell present antigen to the CTL insures that **the decision to activate a T cell always involves more than one cell.**

Requiring only a two-cell interaction for the activation of naive Th cells and CTLs makes perfect sense in terms of getting the adaptive immune system fired up before invaders take over completely. However, although CTLs activated without Th cell help do proliferate somewhat to build up their numbers and can kill infected cells, these “helpless” CTLs do not kill with high efficiency, and they do not live very long. Consequently, **helpless activation of CTLs results in a small burst of killer T cells designed to deal quickly with invaders early in an infection.** In contrast, **CTLs that are fully activated with assistance from helper T cells can proliferate robustly, can kill efficiently, and can become memory killer T cells (cells which can defend against a subsequent invasion by the same attacker).** And this, of course, brings us back to the question of how CTLs can be fully activated by Th cells and DCs without requiring a three-cell interaction.

One possibility, the “sequential model,” postulates that when helper T cells are activated, the dendritic cells which activate them become “licensed” to fully activate CTLs. According to this model, the ligation of the DC’s CD40 proteins by the Th cell’s CD40L proteins changes (licenses)

the DC, so that when it disengages from the Th cell, it is equipped to fully activate CTLs with which it subsequently comes into contact. It is thought that this licensing involves the upregulation of proteins on the surface of the DC, which can then engage receptor proteins on the CTL’s surface, but this isn’t certain. The sequential model, in which the DC and the Th cell meet first, and then the licensed DC and the CTL meet later, would avoid the need for all three cells to meet simultaneously. In this scenario, Th cells act indirectly by using dendritic cells as an intermediary to provide help to activate CTLs. Once CTLs have been fully activated, and have traveled to the battle scene, Th cells can directly help CTLs by providing cytokines such as IL-2 to keep CTLs functioning at full strength.

It also has been demonstrated that when an activated dendritic cell and a helper T cell “hook up,” chemokines are generated which can attract naive killer T cells to their location, making a *ménage à trois* more likely. Moreover, the meeting between an activated dendritic cell and a helper T cell typically lasts for several hours. Consequently, cytokine-directed migration and extended Th-DC interaction times could give a CTL which also recognizes the invader a better chance to join the party. Finally, relatively late in an immune response, there will be many activated dendritic cells, Th cells, and CTLs present in lymph nodes and other secondary lymphoid organs – perhaps enough of each of these cell types to make a three-cell interaction probable.

How CTLs are activated is an excellent example of a question which still has not been fully answered by immunologists. And it is an important question! Understanding how CTLs are activated is critical for designing vaccines and for crafting treatments for diseases that involve CTLs.

REVIEW

There are many similarities between the ways B cells and T cells are activated. BCRs and TCRs both have “recognition” proteins that extend outside the cell and which are incredibly diverse because they are made by mixing and matching gene segments. For the BCR, these recognition proteins are the light and heavy chains that make up the antibody molecule. For the TCR, the molecules that recognize antigen are the α and β proteins. TCRs and BCRs have cytoplasmic tails that are too short to signal recognition, so additional molecules are required for this purpose. For the BCR, these signaling proteins are called Ig α and Ig β . For the TCR, signaling involves a complex of proteins called CD3.

For B or T cells to be activated, their receptors must be clustered by antigen, because this crosslinking brings together many of their signaling molecules in a small region of the cell. When the density of signaling molecules is great enough, an enzymatic chain reaction is set off that conveys the “receptor engaged” signal to the cell’s nucleus. There, in the “brain center” of the cell, genes involved in activation are turned off or on as a result of this signal.

Although crosslinking of receptors is essential for the activation of B or T cells, it is not enough. Naive B and T cells also require co-stimulatory signals that are not antigen specific. This two-signal requirement for activation

sets up a fail-safe system which protects against the inappropriate activation of B or T cells. For B cell activation, a helper T cell can provide co-stimulation through surface proteins called CD40L that plug into CD40 proteins on the B cell surface. B cells also can be co-stimulated by “danger signals,” including invader-specific molecular signatures or battle cytokines. For T cells, co-stimulation usually involves B7 proteins on an activated dendritic cell that engage CD28 proteins on the surface of the T cell.

Early in an infection, B cells and killer T cells can be activated without the assistance of helper T cells. Helpless plasma B cells make IgM antibodies because they have not switched to a class of antibodies that might be more appropriate to defend against the particular invader. They usually have not undergone somatic hypermutation, so their BCRs have not been “fine tuned.” And they only live a short time. Likewise, helpless CTLs do not proliferate robustly, are short-lived, and do not kill as efficiently as T cells which have been assisted by helper T cells. Although helpless B and T cells have these deficiencies, they can provide an important rapid response to pathogens while more “sophisticated” B and T cells are being produced.

Both BCRs and TCRs can associate with co-receptor molecules which serve to amplify the signal that the BCRs and TCRs send. For B cells, this co-receptor recognizes antigen that has been opsonized by complement. If the BCR recognizes an antigen, and if that antigen also is “decorated” with complement protein fragments, the antigen serves as a “clamp” that brings the BCR and the complement receptor together on the surface of the B cell, greatly amplifying the “receptor engaged” signal. As a consequence, B cells are much more easily activated (many fewer BCRs need to be crosslinked) by antigen that has been opsonized by complement.

T cells also have co-receptors. Th cells express CD4 co-receptor molecules on their surface, and CTLs express CD8 co-receptors. When a TCR binds to antigen presented

by an MHC molecule, the co-receptor on the T cell surface clips onto the MHC molecule. This serves to strengthen the signal that is sent by the TCR to the nucleus, so that the T cell is more easily activated (fewer TCRs need to be crosslinked). These co-receptors only work with the “right” MHC types: class I for CTLs with CD8 co-receptors, and class II for Th cells with CD4 co-receptors. Consequently, co-receptors really are “focus” molecules. The B cell co-receptor helps B cells focus on antigens that have already been identified by the complement system as dangerous (those that have been opsonized). The CD4 co-receptor focuses the attention of Th cells on antigens displayed by class II MHC molecules, and the CD8 co-receptor focuses CTLs on antigens displayed by class I MHC molecules.

Of course, there is an important difference between what B cells and T cells “look at.” The BCR recognizes antigen in its “natural” state – that is, antigen which has not been chopped up and bound to MHC molecules. This antigen can be a protein or almost any other organic molecule (e.g., a carbohydrate or a fat). In contrast, the $\alpha\beta$ receptors of traditional T cells only recognize fragments of proteins presented by classical MHC molecules. And whereas a B cell’s receptors only bind to one thing – its cognate antigen – the TCR binds to both the presented peptide and the MHC molecule. Because the universe of antigens recognized by the BCR includes proteins, carbohydrates, and fats, B cells can respond to a greater variety of invaders than can T cells. On the other hand, because the TCR looks at small fragments of proteins, it can recognize targets that are hidden from view of the BCR in an intact and tightly folded protein.

Another difference between B cells and T cells is that during an infection, the BCR can undergo somatic hypermutation and selection. So B cells can “draw from the deck” to try to get a better hand. In contrast, the TCR does not hypermutate, so T cells must be satisfied with the cards they are dealt.

KNOWN UNKNOWNS

- 1.** How do antigen presenting cells and helper T cells work together to activate naive killer T cells?
- 2.** Many viruses kill the cells they infect. So why aren’t APCs killed before they can present viral antigens to activate CTLs?
- 3.** What is the mechanism by which T cells are “instructed” to become either helper T cells or killer T cells?

THOUGHT QUESTIONS

1. What is the difference between a co-receptor and co-stimulation? Give examples and tell why each is important for B or T cell activation.
2. Why are cellular adhesion molecules important during T cell activation? Don't these "sticky" molecules just slow the process down?
3. What happens when dendritic cells and helper T cells "dance"?
4. Essentially all players on the innate and adaptive immune system teams must be activated before they can "get into the game." Trace the steps in the "activation cascade" which begins when an LPS-carrying Gram-negative bacterium enters a wound, and which ends when antibodies are produced that can recognize the bacterium.
5. "Fail-safe technology" is used to prevent inappropriate activation of the adaptive immune system. Can you give several examples?

HEADS UP!

Two of the most important weapons of the adaptive immune system are helper T cells, which secrete just the right combination of cytokines to orchestrate an appropriate defense, and killer T cells, which can “execute” infected cells and the pathogens within them. However, it is the innate immune system which “instructs” the adaptive immune system, telling it which weapons to mobilize to defend against a given invader and where these weapons should be deployed in the body.

INTRODUCTION

Once helper T cells and killer T cells have been activated, they are ready to go to work – to become what immunologists call **effector cells**. The primary job of an effector killer T cell is to destroy cells that have been infected by viruses or bacteria. Effector helper T cells have two main duties: They can remain in the blood and lymphatic circulation and travel from lymph node to lymph node, providing help for B cells or for killer T cells, or they can exit blood vessels at the sites where a battle is going on to provide help for the soldiers of the innate and adaptive immune systems.

HELPER T CELLS AS CYTOKINE FACTORIES

Helper T cells can produce many different cytokines – protein molecules which they use to communicate with the rest of the immune system. As the “quarterback” of the immune system team, the helper T cell uses cytokines

to “call the plays.” The cytokines involved include TNF, IFN- γ , IL-4, IL-5, IL-6, IL-10, IL-17, and IL-21. However, a single Th cell doesn’t secrete all these different cytokines. In fact, Th cells tend to secrete subsets of cytokines – subsets which are appropriate to orchestrate an immune defense against particular types of invaders. So far, three major subsets have been identified: Th1, Th2, and Th17. You shouldn’t take this to mean, however, that there are only three different combinations of cytokines that can be secreted by Th cells. In fact, immunologists initially had a hard time finding helper T cells that secreted exactly the Th1 or Th2 cytokine subsets in humans. Clearly, there are helper T cells which give off mixtures of cytokines that don’t conform to the Th1/Th2/Th17 paradigm. Nevertheless, this concept turns out to be quite useful in trying to make sense of the combination of cytokines (the cytokine “profile”) that Th cells produce. I also should mention that in addition to these three Th subsets which are involved in activating the immune system, there is a subset of Th cells which functions to suppress the immune response. We will discuss these “regulatory T cells” in subsequent lectures.

Of course, all of this begs the question: How does a helper T cell know which cytokines are appropriate for a given situation? Well, as any football fan knows, behind every good quarterback, there is a good coach.

THE DENDRITIC CELL AS “COACH” OF THE IMMUNE SYSTEM TEAM

For a helper T cell to make an informed decision about which cytokines to make, at least two pieces of information are required. First, it’s necessary to know what type of invader the immune system is dealing with. Is it a virus, a bacterium, a parasite, or a fungus? Second, it is essential to determine where in the body the invaders are located. Are they in the respiratory tract, the digestive

tract, or the big toe? Virgin helper T cells don't have direct access to either type of information. After all, they are busy circulating through the blood and lymph, trying to find their cognate antigen. What is needed is an "observer" who has actually been at the battle site, who has collected the pertinent information, and who can pass it along to the helper T cell. And which of the immune system cells could qualify as such an observer? The dendritic antigen presenting cell, of course!

Just as a football coach scouts the opposing team and formulates a game plan, so a dendritic cell, acting as the "coach" of the immune system team, collects information on the invasion, and decides how the immune system should react. That's why dendritic cells are so important. They don't just turn naive helper T cells and killer T cells on. **Dendritic cells actually function as the "brains" of the immune system, processing information pertaining to the invasion and producing a plan of action.**

What are the inputs that dendritic cells integrate to produce the game plan? These are of two types. The first input comes to the dendritic cell through the pattern-recognition receptors we discussed in Lecture 2. These cellular receptors recognize conserved patterns that are characteristic of various classes of invaders. For example, Toll-like receptor 4 (TLR4) senses the presence of LPS, which is a component of the cell wall of Gram-negative bacteria. It can also detect proteins made by certain viruses. TLR2 specializes in identifying molecules that are "signatures" of Gram-positive bacteria. TLR3 recognizes the double-stranded RNA produced during many viral infections. And TLR9 recognizes the unmethylated DNA dinucleotide, CpG, which is characteristic of bacterial DNA.

Although TLRs were the first pattern-recognition receptors to be characterized, additional families of PRRs have now been discovered. Consequently, the emerging picture is that different types of antigen presenting cells (e.g., dendritic cells or macrophages) in different parts of the body display distinct sets of these PRRs which are "tuned" to recognize various structural features of common microbial invaders. By integrating the signals from these diverse pattern-recognition receptors, an APC gathers information on the type of invader to be defended against.

The second "scouting report" dendritic cells employ when formulating their game plan is received through various cytokine receptors on their surface. Because different pathogens elicit the production of different cytokines during an infection, dendritic cells can learn a lot about an invader by sensing the cytokine environment. So **dendritic cells out on the front lines collect "intelligence"**

about an invader through pattern-recognition receptors and cytokine receptors. It is then up to the dendritic cell to "decode" these inputs in order to discern the type of invasion, and to decide which weapons need to be mobilized.

Ordinary cells in different areas of the body (e.g., skin cells or cells that underlie the intestines) produce characteristic mixtures of cytokines in response to invaders, and these cytokines provide dendritic cells with information about the area of the body that is under attack. In fact, these cytokines imprint dendritic cells with a "regional identity." This ability to remember where they encountered invaders helps DCs dispatch the weapons of the adaptive immune system to the parts of the body where they are needed.

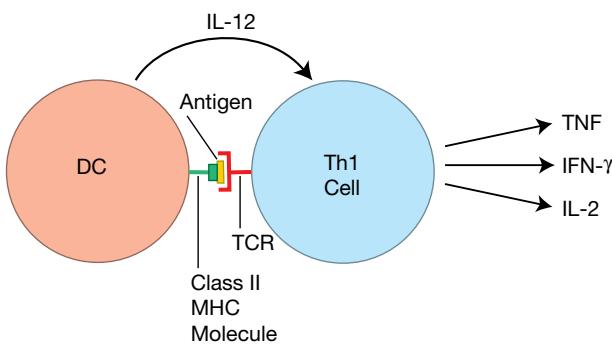
But how is the dendritic cell's game plan conveyed to the Th cell – the cell that will direct the action? There are two ways that the coach instructs the quarterback. First, the mixture of co-stimulatory molecules displayed on the surface of an activated dendritic cell will depend on the type of invader the DC has encountered. These co-stimulatory molecules can "plug into" receptor molecules on the surface of helper T cells to pass this information along. Although B7 is the best-studied co-stimulatory molecule, other co-stimulatory molecules have been identified, and more are certain to be discovered.

In addition to co-stimulatory surface molecules, activated dendritic cells produce cytokines which can convey information to the helper T cell. So the bottom line is this: **Co-stimulatory molecules and cytokines are used by dendritic cells to pass along the "game plan" to helper T cells. And the particular combination of co-stimulatory molecules and cytokines which a dendritic cell offers to a Th cell will depend on what the dendritic cell has observed at the battle scene.** To get a better idea of how this all works, let's look more closely at Th1, Th2, and Th17 cells and the subsets of cytokines they produce.

Th1 HELPER T CELLS

If you have a puncture wound that results in a bacterial infection or if you are attacked by a virus that replicates in the tissues, resident dendritic cells will be alerted through their pattern-recognition receptors and by receiving battle cytokines produced by macrophages and other cells in the inflamed tissues. These signals activate the dendritic cell and imprint it with the special characteristics of an APC which has observed a bacterial or viral infection in the tissues. The details of exactly how this is accomplished

aren't clear yet, but the result is that when this DC leaves such a battle site and travels through the lymph to a nearby lymph node, it will produce the cytokine IL-12. And when the IL-12-secreting DC presents the battle antigens it has acquired to a virgin helper T cell in the lymph node, that Th cell will be instructed to produce the typical Th1 cytokines: TNF, IFN- γ , and IL-2.



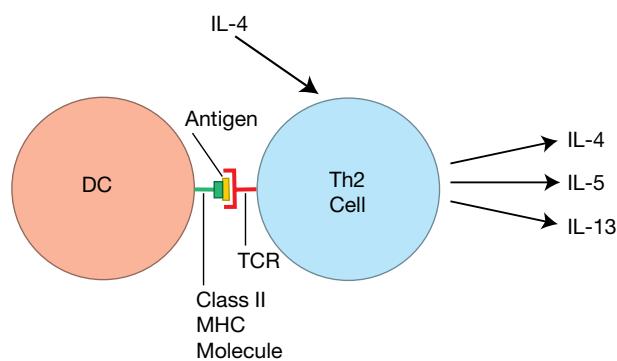
Why these particular cytokines? Let's see what these cytokines do. The TNF secreted by Th1 helper T cells helps activate macrophages and natural killer cells. However, macrophages only stay activated for a limited time. They are lazy fellows which like to go back to resting and garbage collecting. Fortunately, the IFN- γ produced by Th1 cells acts as a "prod" that keeps macrophages fired up and engaged in the battle. IFN- γ also influences B cells during class switching to produce human IgG3 antibodies. These antibodies are especially good at opsonizing viruses and bacteria and at fixing complement. Finally, IFN- γ causes cells infected with bacteria or viruses to increase expression of their class I MHC molecules, so that they are more efficient at displaying an invader's antigens. This makes infected cells better targets for killing by CTLs.

NK cells can kill three or four target cells in about sixteen hours, but then they "tire out." The IL-2 produced by Th1 cells can "recharge" NK cells, enabling them to continue killing. IL-2 is also a growth factor which stimulates the proliferation of CTLs, NK cells, and Th1 cells themselves – so that more of these important weapons will be available to deal with the attack. And IL-2 acts as a "survival factor" for CTLs, helping to extend their lifetime.

Altogether, **the Th1 cytokines are the perfect package to help defend against a viral or bacterial attack in the tissues. The Th1 cytokines instruct the innate and adaptive systems to mobilize cells and produce antibodies that are especially effective against these invaders, and these cytokines also keep the warriors of the immune system fired up until the invaders have been defeated.**

Th2 Helper T Cells

Now suppose that you have been infected by a parasite (e.g., hook worms) or you have eaten some food that is contaminated with pathogenic bacteria. In the tissues that line your intestines, a battle will be raging. Dendritic cells from that area will travel to nearby lymph nodes, and will activate those helper T cells which have T cell receptors that can recognize the worm or bacterial antigens presented by the DC. This results in helper T cells which are "programmed" to produce the Th2 subset of cytokines, which includes IL-4, IL-5, and IL-13.

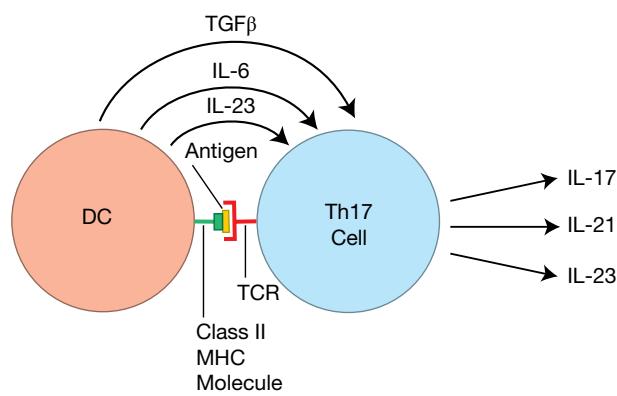


Why IL-4, IL-5, and IL-13, you ask? IL-4 is a growth factor that stimulates the proliferation of helper T cells which have committed to secrete the Th2 profile of cytokines. So, like Th1 cells, Th2 cells produce their own growth factor. IL-4 is also a growth factor for B cells, and this cytokine can influence B cells to class switch to produce IgE antibodies – powerful weapons against parasites such as hook worms. IL-5 is a cytokine which encourages B cells to produce IgA antibodies, antibodies that are especially useful against bacteria which invade via the digestive tract. And IL-13 stimulates the production of mucus in the intestines. This mucus helps prevent more intestinal parasites or pathogenic bacteria from breaching the intestinal barrier and entering the tissues. So **the Th2 cytokine profile is just the ticket if you need to defend against parasites or pathogenic bacteria that have invaded via the digestive tract.**

In the figure above, you will notice that IL-4, which causes a naive Th cell to commit to becoming a Th2 cell, does not come from the dendritic cell. Of course, once the helper T cell commits to the Th2 cytokine profile, there will be plenty of IL-4 around – because this is one of the cytokines Th2 cells secrete. Nevertheless, the source of IL-4 initially required for Th2 commitment has not yet been identified.

Th17 HELPER T CELLS

If areas of the body protected by mucosal barriers are attacked by fungi (e.g., *Candida albicans*, which causes vaginal yeast infections) or by extracellular bacteria, dendritic cells will travel to a nearby lymph node to activate helper T cells which recognize the antigens the DC is presenting. These traveling dendritic cells can produce TGF β and either IL-6 or IL-23, which, together with co-stimulatory molecules, will influence newly activated helper T cells to produce the Th17 subset of cytokines, which includes IL-17, IL-21, and IL-23.

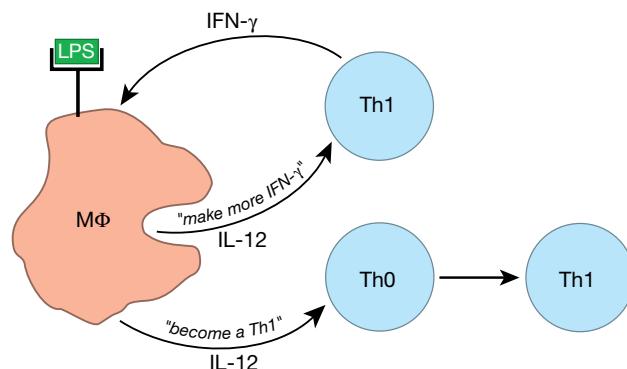


Secretion of the “signature cytokine,” IL-17, results in the recruitment of massive numbers of neutrophils to the site of infection. These neutrophils destroy fungi and some extracellular bacteria against which warriors recruited by Th1 and Th2 cells would be relatively ineffective. Indeed, patients who have a genetic defect in IL-17 secretion suffer from devastating fungal infections, even though their Th1 and Th2 helper T cells function normally. IL-23 is a growth factor which causes helper T cells that have committed to being Th17 cells to proliferate to build up their numbers. IL-21 can cause B cells that guard the mucosal surfaces to produce IgG3 and IgA antibodies. IgG3 is an antibody isotype that is especially good at activating the complement cascade on the surface of bacteria, and IgA antibodies can bind invaders and help usher them out of the body with the mucus. **So if you are attacked by fungi or extracellular bacteria, the cytokines secreted by Th17 cells are there to help protect you.**

Th0 HELPER T CELLS

Some helper T cells (the **Th0** cells) remain “unbiased” when they are first activated, retaining the ability to produce a wide range of cytokines. It appears that DCs tell

these helper T cells where to go, but not what to do. However, once Th0 cells reach the battle scene, the cytokine environment they encounter there causes them to commit to the cytokine profile required for the defense. For example, when Th0 cells exit the blood to fight a bacterial infection in the tissues, they encounter an environment rich in IL-12. This is because Th1 cells that are already fighting bacteria there produce IFN- γ . This cytokine, together with danger signals such as the bacterial molecule LPS, activates tissue macrophages, which secrete large amounts of IL-12. And when Th0 cells receive the IL-12 signal, they “realize” what type of battle is being fought and commit to becoming Th1 cells – Th cells which produce the cytokines needed to defend against bacteria.



Likewise, Th0 cells can become Th2 or Th17 cells when they reach a battle site that is rich in IL-4 or IL-6 and TGF β , respectively. So **previously uncommitted Th0 cells can be “converted” by the cytokine environment at the scene of the battle to become Th1, Th2, or Th17 cells – whichever is appropriate for the defense.**

LOCKING IN THE HELPER T CELL PROFILE

Once helper T cells commit to a particular cytokine profile, they begin to secrete cytokines which encourage the proliferation of that particular type of Th cell – be it Th1, Th2, or Th17. This sets up a positive feedback loop which results in even more of the “selected” Th cells being produced.

In addition to positive feedback, there is also negative feedback at work. For example, IFN- γ made by Th1 cells actually decreases the rate of proliferation of Th2 cells, so that fewer Th2 cells will be produced. And one of the Th2 cytokines, IL-10, acts to decrease the rate of proliferation of Th1 cells. **The result of all this positive and negative feedback is a large number of helper T cells which are strongly biased toward the production of a certain subset of cytokines.**

There is an important point about helper T cell bias which I want to be sure you understand. **Cytokines have a very limited range.** They can travel only short distances in the body before they are captured by cellular receptors or are degraded. Consequently, **when we talk about helper T cells being biased toward secreting a certain cytokine profile, we are talking about something very local.** Clearly, you wouldn't want every Th cell in your body to be of the Th1 type, because then you'd have no way to defend against a respiratory infection. Conversely, you wouldn't want to have only Th2 cells, because the IgA or IgE antibodies made in response to the Th2 cytokines would be useless if you get a bacterial infection in your big toe. In fact, **it is the local nature of cytokine signaling which gives the immune system the flexibility to simultaneously mount defenses against many different invaders that threaten different parts of the body.**

It is also important to note that dendritic cells are members of the innate system team. Consequently, **the innate immune system not only informs the adaptive system when there is danger, it also gives instructions to the adaptive system so that the appropriate weapons are sent to the right places.**

DELAYED-TYPE HYPERSENSITIVITY

There is an example of "signal calling" by Th cells that I think you'll find interesting. It is termed **delayed-type hypersensitivity (DTH)**, and it was first observed by Robert Koch when he was studying tuberculosis back in the latter part of the nineteenth century. Koch purified a protein, tuberculin, from the bacterium which causes tuberculosis, and used it to devise his famous "tuberculin skin test." If you've had this test, you'll recall that a nurse injected something under your skin, and told you to check that area in a few days. If the spot where you were injected became red and swollen, you were instructed to come back in to see the doctor. Here's what that's all about.

The "something" you were injected with was Koch's tuberculin protein. If you have active TB or have been infected with it in the past, your immune system will include memory Th1 cells that were made in response to the infection. When the nurse injects the tuberculin protein, dendritic cells stationed beneath the skin take up the protein and present tuberculin peptides to these memory cells, and they are reactivated. Now the fun begins, because these Th cells secrete IFN- γ and TNF, which are Th1-type cytokines that activate resident tissue macrophages near the site of injection and help recruit neutrophils and additional macrophages to the area. The result

is a local inflammatory reaction with redness and swelling: the signal that your TB test is positive. Of course, the reason you have to wait several days for the test to "develop" is that memory helper T cells must be reactivated, proliferate, and produce those all-important cytokines that orchestrate the inflammatory reaction.

On the other hand, if you have never been exposed to the tuberculosis bacterium, you will have no memory helper T cells to reactivate. Without the cytokines supplied by activated Th cells, there will be no inflammatory reaction to the tuberculin protein, and your skin test will be scored as negative.

What is interesting here is that **delayed-type hypersensitivity is both specific and nonspecific.** The specificity comes from Th cells that direct the immune response after recognizing the tuberculin peptide presented by dendritic cells. The nonspecific part of the reaction involves the neutrophils and macrophages that are recruited and activated by cytokines secreted by the Th cells. This is yet another example of the cooperation that goes on between the adaptive and innate immune systems.

You may be wondering why the tuberculin used for the test doesn't activate naive T cells, so that the next time you are tested, you will get a positive reaction. The reason is that the tuberculin protein does not, by itself, cause an inflammatory reaction (i.e., a battle situation), and you remember that dendritic cells only mature and carry antigen to a lymph node if a battle is on. Consequently, if a protein that is injected under your skin is judged by the innate system not to be dangerous, the adaptive immune system will not be activated. This illustrates again how important the innate immune system is for initiating an immune response: **If your innate system does not recognize an invader as dangerous and put up a fight, your adaptive system usually will just ignore the intrusion.**

HOW CTLs KILL

So far in this lecture, we have discussed what activated helper T cells do. Now it is time to focus on killer T cells. Once a CTL has been activated, it proliferates rapidly to build up its numbers. These effector T cells then leave the lymph node, enter the blood, and travel to the area of the body where the invaders they can kill are located. When an effector T cell reaches the battle site, it exits the blood, and begins to hack away at infected cells. Most killing by CTLs requires contact between the CTL and its target cell, and CTLs have several weapons they can use during this "hand-to-hand" combat.

One weapon CTLs employ involves the production of a protein called **perforin**. Perforin is a close relative of the C9 complement protein that is part of the membrane attack complex. Like its cousin, perforin can bind to cell membranes and drill holes in them. For this to happen, a killer T cell's TCRs must first identify the target. Then adhesion molecules on the CTL hold the target cell close while the killer cell delivers a mixture of perforin and an enzyme called **granzyme B** onto the surface of the target cell. What happens next is still a bit uncertain, but the latest thinking is this: The perforin damages the target cell's outer membrane, and when the cell tries to repair this damage, both granzyme B and perforin are taken into the cell in a vesicle made from the target cell's membrane. Once inside the target cell, the perforin molecules make holes in the entry vesicle, allowing the granzyme B to escape into the cytoplasm of the cell. So **perforin helps a CTL deliver granzyme B into the cytoplasm of its target cell where granzyme B triggers an enzymatic chain reaction that causes the cell to commit suicide by apoptosis**. This kind of "assisted suicide" usually involves the destruction of the target cell's DNA by the cell's own enzymes. One important feature of this type of killing is that it is "directed": The CTL delivers its lethal cargo right onto the target cell, so that other cells in the area are not damaged during the slaughter.

After a killer T cell has made contact with its target, it only takes about half an hour to kill the cell, and during each attack, the CTL only uses a fraction of its perforin and granzyme B. Consequently, a single killer T cell can execute multiple target cells. You may be wondering why the CTL doesn't kill itself when it delivers these deadly enzymes to the surface of its target. Nobody knows!

The second way a CTL can kill is by using a protein on its surface called Fas ligand (FasL) which can bind to the Fas protein on the surface of a target cell. When this happens, a suicide program is set in motion within the target cell, and, again, the cell dies by apoptosis. Interestingly, natural killer cells use these same two mechanisms (perforin/granzyme B or FasL) to kill their targets.

It is worth mentioning here that **there actually are two different ways a cell can die: by necrosis or by apoptosis**. Although the end result is the same (a dead cell), the two processes are quite different. Cells usually die by necrosis either as the result of a wound (e.g., a cut or a burn) or when they are killed by an attacking virus or bacterium. **During necrosis, enzymes and chemicals that are normally safely contained within a living cell are released by the dying cell into the surrounding tissues, where they can do real damage.** In contrast, death by apoptosis is much tidier. As a cell dies by apoptosis, its contents are enclosed in little "garbage bags" (vesicles) made from the outer membrane of the dying cell. These vesicles are then eaten and destroyed by nearby macrophages as part of their garbage-collecting duty. Consequently, **during apoptosis, the contents of the target cell don't get out into the tissues to cause damage.** So by killing their targets by inducing apoptosis rather than necrosis, CTLs can rid the body of virus-infected cells without causing the collateral tissue damage that would result from necrotic cell death.

There is another reason why triggering cells to die by apoptosis is an especially effective way for killer T cells to destroy virus-infected cells. **When virus-infected cells die by apoptosis, the DNA of unassembled viruses is destroyed along with the target cell's DNA. In addition, DNA or RNA viruses that have reached various stages of assembly within the cell are enclosed in apoptotic vesicles and are disposed of by macrophages. It is this ability to destroy infected cells and the viruses they contain by inducing apoptosis that makes a killer T cell such a potent antiviral weapon.**

Although the main job of CTLs is to destroy infected cells, killer T cells can also secrete cytokines. For example, CTLs can produce IFN- γ , a cytokine that upregulates expression of class I MHC molecules on nearby cells. This results in a more robust class I display, making it easier for CTLs to recognize infected cells.

REVIEW

In your body, dendritic antigen presenting cells are stationed beneath all surfaces that are exposed to the outside world. Because of where they are located, DCs can observe an invasion first hand. In fact, the intelligence they acquire at the scene of the battle is complete enough to allow them to formulate a plan of action for the rest of

the immune system. This information is gathered in part through the dendritic cell's pattern-recognition receptors, which detect the "signatures" of different types of invaders. In addition, DCs have receptors which sense the cytokines given off by other immune system cells that are engaged in the battle. Non-immune cells which reside

where the battle is raging also can produce cytokines, and these cytokines can imprint dendritic cells with a regional identity – so that they “remember” where the battle is taking place.

Armed with all this information on the type of invader and the location of the attack, DCs travel to nearby lymph nodes, where they activate T cells. During this process, the game plan is conveyed to helper T cells in the form of co-stimulatory molecules and cytokines expressed by the dendritic cells. This information tells helper T cells which cytokines to make in order to orchestrate the appropriate defense against a particular invader. In a sense, the DC functions as the coach of the immune system team, while the Th cell performs the duties of quarterback, calling the plays designed by the coach. The DC is part of the innate immune system. Consequently, the innate system not only determines when the adaptive system should be activated in response to danger, but it also instructs the adaptive system on which weapons to deploy and where to send them.

In response to the instructions delivered by dendritic cells, helper T cells produce combinations of cytokines that mobilize the weapons especially suited to deal with the invader which is attacking at the moment. Uncommitted

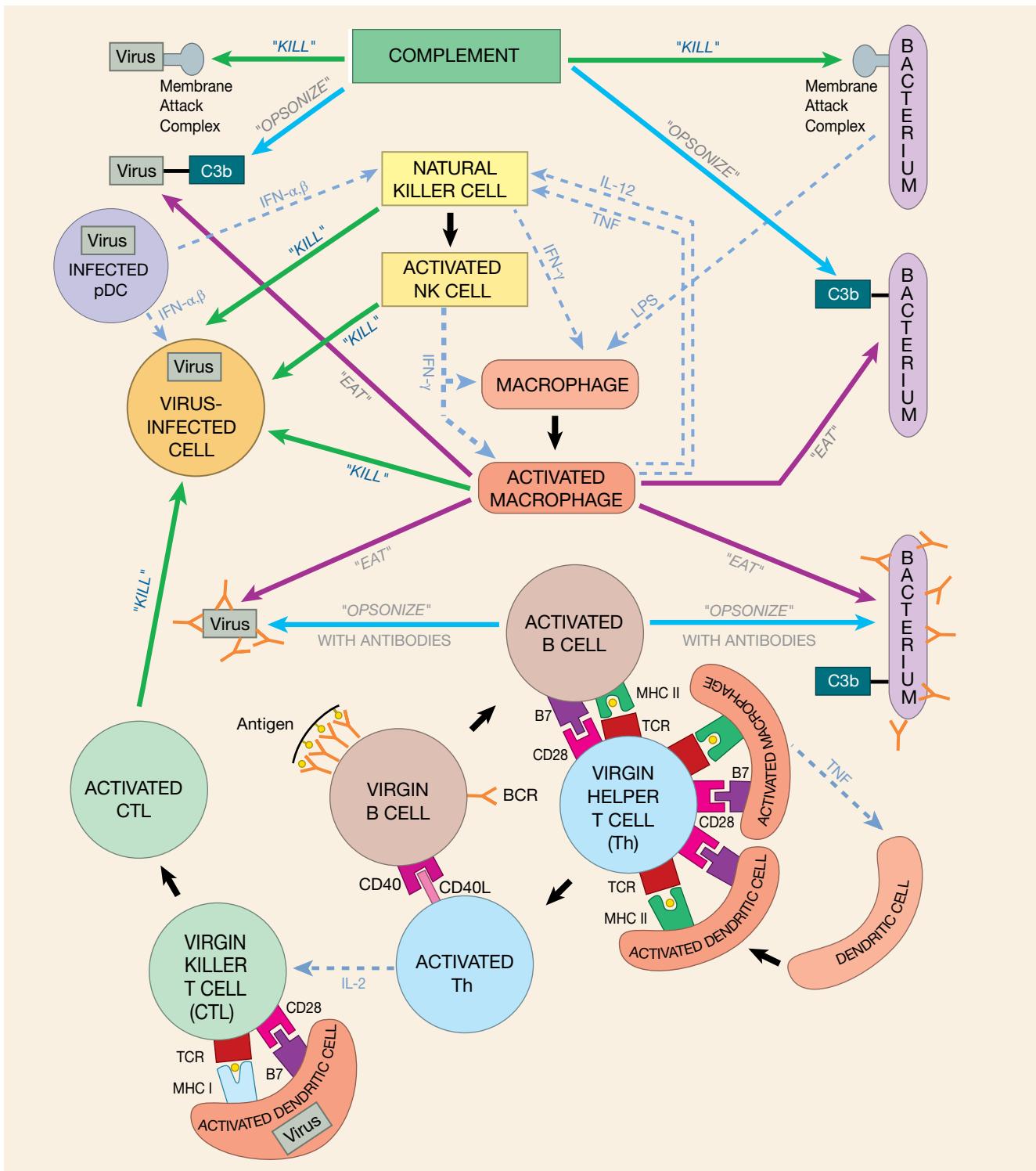
Th cells also can be dispatched to the scene of the conflict where, under the influence of battle cytokines, they become committed to secreting a particular cytokine profile. And once a Th cytokine profile has been established, positive and negative feedback tend to lock in this particular profile. Importantly, the cytokines produced by helper T cells have a very short range, so their effects are quite localized. This feature allows the immune system to defend against different types of invaders which attack different parts of the body.

When we are attacked by viruses or bacteria which infect human cells, dendritic cells can activate killer T cells, and dispatch them to the area of the body under attack. CTLs destroy infected cells by forcing them to commit suicide by a process called apoptosis. When a cell dies by apoptosis, its contents are enclosed in vesicles which are quickly ingested by nearby macrophages. This garbage disposal system keeps the potentially destructive chemicals and enzymes within the dying cell from getting out into the tissues and doing damage. And triggering cells to die by apoptosis has the great advantage that the pathogens which infected the cell also are packaged up and disposed of. Although Th cells function as cytokine factories, CTLs also can produce cytokines such as IFN- γ .

SUMMARY FIGURE

Here is our final summary figure, showing both the innate and adaptive systems – and the network they form.

Can you identify all the players, and do you understand how they interact with each other?



KNOWN UNKNOWNS

1. How do DCs integrate all the information collected at the battle scene and orchestrate a defense against specific invaders which are attacking at particular locations?
2. What are the major sources of IL-4 which encourage Th cells to express the Th2 cytokine profile?
3. Exactly how do CTLs and NK cells use perforin and granzyme B to kill target cells? And how do they protect themselves while they do this?

THOUGHT QUESTIONS

1. How does a helper T cell know which cytokine profile to produce?
2. How does a helper T cell “call the plays” for B cells?
3. How does a helper T cell orchestrate the actions of innate system players such as macrophages and NK cells?
4. Cytokines have a limited range. Why is this a good thing?
5. What is the difference between death by necrosis and death by apoptosis?

LECTURE 7

Secondary Lymphoid Organs and Lymphocyte Trafficking

HEADS UP!

The secondary lymphoid organs are strategically placed to intercept invaders which penetrate our barrier defenses. During an infection, rare T cells must find antigen presenting cells which display their cognate antigen, and B cells must encounter the small number of helper T cells that can assist them in producing antibodies. Secondary lymphoid organs make it possible for antigen presenting cells, T cells, and B cells to meet under conditions that favor activation. The trafficking of immune system cells throughout our body is controlled by the modulated expression of adhesion molecules on the surface of these cells. Virgin and experienced lymphocytes move in different traffic patterns.

INTRODUCTION

In earlier lectures, we discussed the requirements for B and T cell activation. For example, in order for a helper T cell to assist a B cell in producing antibodies, that Th cell must first be activated by finding an antigen presenting cell which is displaying its cognate antigen. Then the B cell must find that same antigen displayed in a fashion which crosslinks its receptors. And finally, the B cell must find the activated Th cell. When you recognize that the volume of a T or B cell is only about one one-hundred-trillionth of the volume of an average human, the magnitude of this “finding” problem becomes clear. Indeed, it begs the question, “How could a B cell ever be activated?”

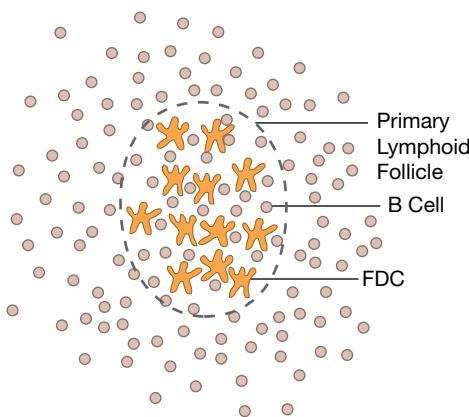
The answer is that the movements of the various immune system players are carefully choreographed, not

only to make activation efficient, but also to make sure that the appropriate weapons are delivered to the locations within the body where they are needed. Consequently, to really understand how this system works, one must have a clear picture of where in the body all these interactions take place. So it is time now for us to focus on the “geography” of the immune system.

The adaptive immune system’s defense against an attacker actually has three phases: recognition of danger, production of weapons appropriate for the invader, and transport of these weapons to the site of attack. **The recognition phase takes place mainly in the secondary lymphoid organs, which function as “staging areas” for the adaptive immune response. These organs include the lymph nodes, the spleen, and the mucosal-associated lymphoid tissue (called the MALT for short).** You may be wondering: If these are the secondary lymphoid organs, what are the primary ones? **The primary lymphoid organs are the bone marrow, where B and T cells are born, and the thymus, where T cells receive their early training.**

LYMPHOID FOLLICLES

All secondary lymphoid organs have one anatomical feature in common: They all contain **lymphoid follicles**. These follicles are critical for the functioning of the adaptive immune system, so we need to spend a little time getting familiar with them. Lymphoid follicles start life as “primary” lymphoid follicles: loose networks of **follicular dendritic cells (FDCs)** embedded in regions of the secondary lymphoid organs that are rich in B cells. So **lymphoid follicles really are islands of FDCs within a sea of B cells.**

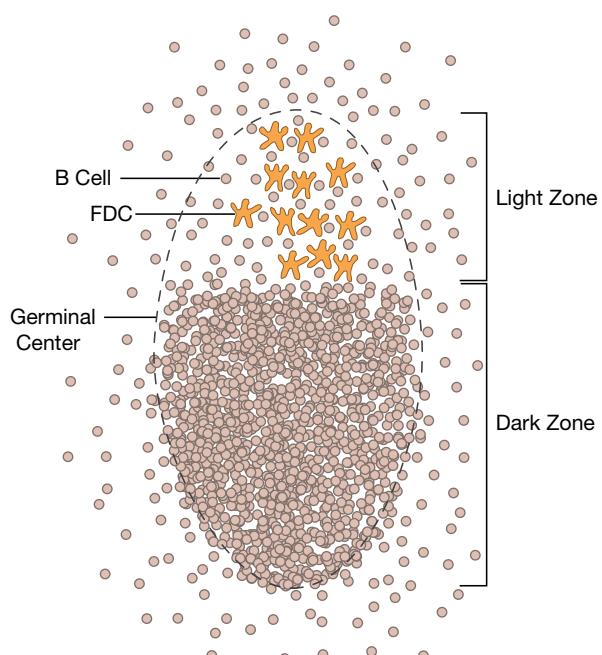


Although FDCs do have a starfish-like shape, they are very different from the antigen presenting dendritic cells (DCs) we talked about before. Those dendritic cells are white blood cells that are produced in the bone marrow, and which then migrate to their sentinel positions in the tissues. Follicular dendritic cells are regular old cells (such as skin cells or liver cells) that take up their final positions in the secondary lymphoid organs as the embryo develops. In fact, FDCs are already in place during the second trimester of gestation. Not only are the origins of follicular dendritic cells and antigen presenting dendritic cells quite different, these two types of starfish-shaped cells have very different functions. **Whereas the role of dendritic APCs is to present antigen to T cells via MHC molecules, the function of follicular dendritic cells is to display antigen to B cells.** Here's how this works.

Early in an infection, complement proteins bind to invaders, and some of this complement-opsonized antigen will be delivered by the lymph or blood to the secondary lymphoid organs. Follicular dendritic cells that reside in these organs have receptors on their surface which bind complement fragments, and as a result, **FDCs pick up and retain complement-opsonized antigen**. In this way, follicular dendritic cells become "decorated" with antigens that are derived from the battle being waged out in the tissues. Moreover, **by capturing large numbers of antigens and by holding them close together, FDCs display antigens in a way that can crosslink B cell receptors**. Later during the battle, when antibodies have been produced, **invaders opsonized by antibodies also can be retained on the surface of follicular dendritic cells – because FDCs have receptors that can bind to the constant region of antibody molecules**. FDCs are not phagocytic, and the antigen–antibody or antigen–complement complexes they capture on their surface can remain on display for weeks or months.

So follicular dendritic cells capture opsonized antigens and "advertise" these antigens to B cells in a configuration that can help activate them. Those B cells whose receptors are crosslinked by binding to their cognate antigens, hanging from these follicular dendritic "trees," proliferate to build up their numbers. Once this happens, the follicle begins to grow and become a center of B cell development. Such an active lymphoid follicle is called a "secondary lymphoid follicle" or **germinal center**. The role of complement-opsonized antigen in triggering the development of a germinal center cannot be overemphasized: Lymphoid follicles in humans who have a defective complement system never progress past the primary stage. Thus, we see again that **for the adaptive immune system to respond, the innate system must first react to impending danger**.

As they proliferate in germinal centers, B cells become very "fragile." Unless they receive the proper "rescue" signals, they will commit suicide (die by apoptosis). Fortunately, helper T cells can rescue these B cells by providing the co-stimulation they need. And when a B cell whose receptors have been crosslinked by antigen receives the required co-stimulatory signals, it is temporarily rescued from apoptotic death and continues to proliferate. The rate at which B cells multiply in a germinal center is truly amazing: The number of B cells can double every six hours! These proliferating B cells push aside other B cells that have not been activated, and establish a region of the germinal center called the "dark zone" – because it contains so many proliferating B cells that it looks dark under a microscope.



After this period of proliferation, some of the B cells “choose” to become plasma B cells and leave the germinal center to produce antibodies. Because these B cells have received T cell help, they are fully competent to produce large quantities of invader-specific antibodies. However, these are mostly IgM antibodies because these B cells have not class switched. And they have usually undergone very little somatic hypermutation to increase the average affinity of their receptors for their cognate antigen. Consequently, these B cells produce good antibodies – but not great antibodies. But that’s okay. These IgM, “unrefined” antibodies are extremely useful early in infection before better antibodies can be made.

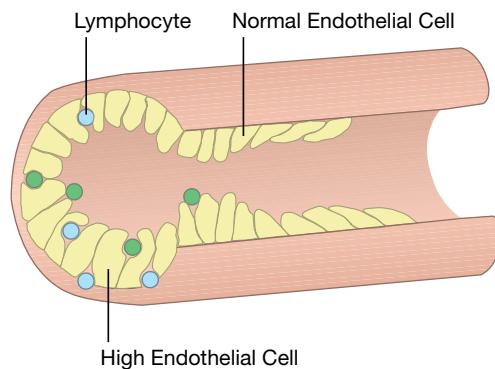
Other B cells remain in the germinal center, proliferate some more, and undergo somatic hypermutation to enhance the affinity of their receptors for antigen. Somatic hypermutation takes place in the dark zone of the germinal center, and after each round of hypermutation, the B cells migrate to the light zone where the affinity of their mutated BCRs for antigen is tested. Those B cells whose mutated BCRs do not have a high enough affinity for antigen will die by apoptosis, and will be eaten by macrophages in the germinal center. In contrast, B cells are rescued from apoptosis if the affinity of their receptors is great enough to be efficiently crosslinked by their cognate antigen displayed on FDCs – and if they also receive co-stimulation from activated Th cells that are present in the light zone of the germinal center. The picture is that B cells “cycle” between periods of proliferation and mutation in the dark zone and periods of testing and restimulation in the light zone. Sometime during all this action, probably in the dark zone, B cells can switch the class of antibody they produce.

In summary, lymphoid follicles are specialized regions of secondary lymphoid organs in which B cells percolate through a lattice of follicular dendritic cells that have captured opsonized antigen on their surface. B cells that encounter their cognate antigen and receive T cell help are rescued from death. These “saved” B cells proliferate and can undergo somatic hypermutation and class switching. Clearly lymphoid follicles are extremely important for B cell development. That’s why all secondary lymphoid organs have them.

HIGH ENDOTHELIAL VENULES

A second anatomical feature common to all secondary lymphoid organs except the spleen is the **high endothelial venule (HEV)**. The reason HEVs are so important is that they are the “doorways” through which B and

T cells enter these secondary lymphoid organs from the blood. Most endothelial cells that line the inside of blood vessels resemble overlapping shingles which are tightly “glued” to the cells adjacent to them to prevent the loss of blood cells into the tissues. In contrast, within most secondary lymphoid organs, the small blood vessels that collect blood from the capillary beds (the postcapillary venules) are lined with special endothelial cells that are shaped more like a column than a shingle.



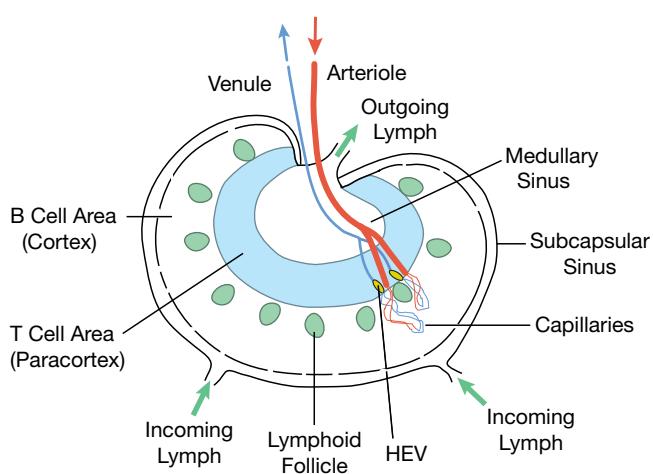
These tall cells are the high endothelial cells. So **a high endothelial venule is a special region in a small blood vessel (venule) where there are high endothelial cells**. Instead of being glued together, high endothelial cells are “spot welded.” As a result, there is enough space between the cells of the HEV for lymphocytes to wriggle through. Actually, “wriggle” may not be quite the right term, because lymphocytes exit the blood very efficiently at these high endothelial venules: Each second, about 10,000 lymphocytes exit the blood and enter an average lymph node by passing between high endothelial cells.

Now that you are familiar with lymphoid follicles and high endothelial venules, we are ready to take a tour of some of the secondary lymphoid organs. On our tour today, we will visit a lymph node, a Peyer’s patch (an example of the MALT), and the spleen. As we explore these organs, you will want to pay special attention to the “plumbing.” How an organ is connected to the blood and lymphatic systems gives important clues about how it functions.

LYMPH NODES

A lymph node is a plumber’s dream. This bean-shaped organ has incoming lymphatics which bring lymph into the node, and outgoing lymphatics through which lymph exits. In addition, there are small arteries (arterioles) that carry the blood that nourishes the cells of the lymph node,

as well as veins through which this blood leaves the node. If you look carefully at this figure, you can also see the high endothelial venules.



With this diagram in mind, can you see how lymphocytes (B and T cells) enter a lymph node? That's right, they can enter from the blood by pushing their way between the cells of the high endothelial venules. There is also another way lymphocytes can enter the lymph node: with the lymph. After all, lymph nodes are like "dating bars," positioned along the route the lymph takes on its way to be reunited with the blood in the upper torso. And B and T cells actively engage in "bar hopping," being carried from node to node by the lymph. Although lymphocytes have two ways to gain entry to a lymph node, they only exit via the lymph – those high endothelial venules won't let them back into the blood.

Since lymph nodes are places where lymphocytes find their cognate antigen, we also need to discuss how this antigen gets there. When dendritic cells stationed out in the tissues are stimulated by battle signals, they leave the tissues via the lymph, and carry the antigen they have acquired at the battle scene into the secondary lymphoid organs. So this is one way antigen can enter a lymph node: as "cargo" aboard an APC. In addition, antigen which has been opsonized, either by complement or by antibodies, can be carried by the lymph into the node. There the opsonized antigen will be captured by FDCs for display to B cells.

When lymph enters a node, it percolates through holes in the **subcapsular sinus** (sinus is a fancy word for "cavity"), through the cortex and paracortex, and finally into the medullary sinus – from whence it exits the node via the outgoing lymphatic vessels.

The walls of the subcapsular sinus are "carpeted" with macrophages that are strategically positioned to capture

and devour pathogens as they enter a lymph node. This substantially reduces the number of invaders that the adaptive immune system will need to deal with, and it helps keep these pathogens from entering the blood stream. This is important because blood can carry invaders throughout the body, potentially turning a localized infection into a systemic one. So an important function of a lymph node is as a "lymph filter."

The subcapsular sinus also is home to dendritic cells. It can take up to five days for migratory dendritic cells in infected tissues to load up on antigen and travel to nearby lymph nodes. In contrast, antigen drained from infected tissues can reach lymph nodes much more quickly. Consequently, lymph node-resident DCs can take up this antigen and help initiate an adaptive immune response, even before migratory dendritic cells arrive.

The high endothelial venules are located in the paracortex, so B and T cells pass through this region of the node when they arrive from the blood. T cells tend to accumulate in the paracortex, being retained there by adhesion molecules. This accumulation of T cells makes good sense, because dendritic cells are also found in the paracortex – and of course, one object of this game is to get T cells together with these antigen presenting cells. On the other hand, B cells entering a lymph node accumulate in the cortex, the area where lymphoid follicles are located. This localization of B cells works well, because the FDCs that display opsonized antigen to B cells are located in this region of the lymph node. So **a lymph node is a highly organized place with specific areas for antigen presenting cells, T lymphocytes, B lymphocytes, and macrophages.**

Lymph node choreography

The fact that different immune system cells tend to hang out in specific places in a lymph node begs the question: How do they know where to go and when to go there? It turns out that the movements of these cells in this secondary lymphoid organ are carefully choreographed by cytokines called **chemokines** (short for chemoattractive cytokines). Here's how this works.

Follicular dendritic cells in a lymph node produce a chemokine called CXCL13. Naive B cells which enter the node express receptors for this chemokine and are attracted to the area of the node where FDCs are displaying opsonized antigen. If a B cell finds its cognate antigen advertised there, it downregulates expression of the receptors for CXCL13 and upregulates expression of another chemokine receptor, CCR7. This receptor detects a chemokine produced by cells in the region of the lymph node where activated Th cells and B cells meet – the

border between the B and T cell areas. Consequently, once a B cell has found its antigen, it is attracted by the “smell” of this chemokine to the location in the lymph node where it can receive help from activated Th cells.

Meanwhile, activated Th cells downregulate expression of the chemokine receptors that have been retaining them in the T cell areas. At the same time, they upregulate expression of CXCR5 chemokine receptors, which cause them to be attracted to the border of the follicle – where antigen-activated B cells are waiting for their help. So **the movement of immune system cells through a lymph node is orchestrated by the up- and downregulation of chemokine receptors, and the localized production of chemokines that can be detected by these receptors.**

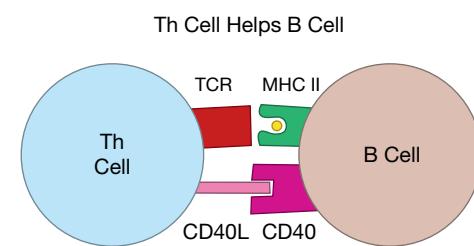
Now, of course, human cells don’t come equipped with little propellers like some bacteria do, so they can’t “swim” in the direction of the source of a chemokine. What human cells do is “crawl.” In general terms, the end of the cell that senses the greatest concentration of the chemokine “reaches out” toward the chemokine source, and the other end of the cell is retracted. By repeating this motion, a cell can crawl “up the concentration gradient” toward the source of a cytokine.

So the choreography of immune system cells within a lymph node is carefully controlled by chemokines and chemokine receptors. But what about antigens which arrive with the lymph? How does this antigen find its way to lymphoid follicles, where it can be captured by follicular dendritic cells and displayed in a way that will crosslink B cell receptors? For a long time it was assumed that antigen which arrived in the lymph would just pass through gaps in the floor of the subcapsular sinus, diffuse throughout the node, and that some of it would end up in the lymphoid follicles. And this does happen. However, it has recently been discovered that within each lymph node there is an elegant system of “pipes” (**conduits**), which facilitates the rapid delivery of antigen directly from the subcapsular sinus, where lymph enters the node, to the lymphoid follicles. This conduit system is quite extensive, so it is certain that these pipes do more than just carry antigen to lymphoid follicles. But so far, the other functions of these conduits remain unclear.

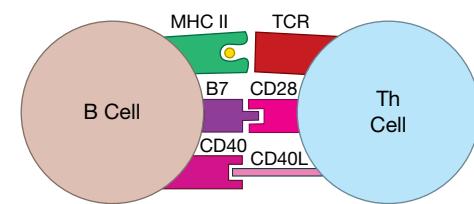
T cell help

At this point, you may be asking, “How do Th cells that have reached the border of the follicle know which B cells to help?” It’s a good question with an interesting answer. It turns out that when B cells recognize their cognate antigen displayed by follicular dendritic cells, the B cell’s receptors bind tightly to this antigen, and the complex of receptor and cognate antigen is taken inside the B cell. So **B cells**

actually “pluck” antigen from FDC “trees.” Once inside the B cell, the antigen is enzymatically digested, loaded onto class II MHC molecules, and presented on the surface of the B cell for Th cells to see. However, to reach full maturity, B cells that have plucked their antigen need co-stimulation. Activated Th cells can provide this co-stimulation because they express CD40L proteins that can plug into CD40 proteins on the surface of the B cell. But **Th cells only can provide this stimulation to B cells which are presenting the Th cell’s cognate antigen.**



Moreover, Th cells that have been activated by recognizing their cognate antigen in the T cell area also need the assistance of activated B cells in order to mature fully. This assistance involves cell-cell contact during which B7 proteins on the B cell surface bind to CD28 proteins on the Th cell surface.



What this means is that **at the border of the lymphoid follicle, an activated Th cell and an activated B cell do a “dance” that is critical for their mutual maturation.** Th cells provide the CD40L that B cells need. And B cells, acting as antigen presenting cells, provide the presented antigen and the B7 co-stimulation that helper T cells require to complete their maturation. Th cells which have participated in this dance are called **follicular helper T cells (Tfh)**, and these Tfh cells are now fully prepared to enter the lymphoid follicle to rescue fragile, germinal center B cells, and to help these B cells switch classes or undergo somatic hypermutation.

The encounter between Th and B cells at the boundary between the follicle and the T cell zone can last for more than an hour. Some of these B cells then proliferate, move to the medulla of the lymph node, and begin to produce relatively low-affinity, mostly IgM antibodies. Although these plasma B cells usually have not been “upgraded” by

class switching or somatic hypermutation, they are important because they provide a relatively fast response to an invasion. Other B cells and their Tfh partners move into the germinal center, where class switching and somatic hypermutation can take place. Indeed, **both class switching and somatic hypermutation usually require the interaction between CD40L proteins on Tfh cells and CD40 proteins on the surface of germinal center B cells.**

Somatic hypermutation is actually “driven” by the interaction between germinal center B cells and Tfh cells in the light zone of the follicle. B cells with higher affinity receptors are able to “pluck” more antigen from follicular dendritic cells and present more of this antigen via class II MHC molecules to Tfh cells. In return, the B cells receive greater help from these Tfh cells, causing the B cells to proliferate more when they enter the dark zone of the germinal center. This process enriches the B cell pool in cells with higher affinity BCRs.

It is important to note that during this process of bidirectional stimulation, the part of the protein which the B cell recognizes (the B cell epitope) is usually different from the part of the protein that the Th cell recognizes (the T cell epitope). After all, a B cell’s receptors bind directly to a region of the protein which happens to have the right shape to “fit” the B cell’s receptors. In contrast, a T cell’s receptors bind to a fragment of the protein that has the right amino acid sequence to fit into the groove of an MHC molecule. Consequently, **although the B cell epitope and the T cell epitope are “linked” – because they come from the same protein – these epitopes are usually different.**

Recirculation through lymph nodes

After a T cell enters a lymph node, it frantically checks several hundred dendritic cells, trying to find one that is presenting its cognate antigen. If a T cell is not successful in this search, it leaves the node and continues to circulate through the lymph and blood. If a helper T cell does encounter a dendritic cell presenting its cognate antigen in the paracortex, the Th cell will be activated and will begin to proliferate. This proliferation phase lasts a few days while the T cell is retained in the lymph node by adhesion molecules. During this time, a T cell can have multiple sequential encounters with DCs that are presenting its cognate antigen, increasing the T cell’s activation level. The expanded population of T cells then leaves the T cell zone. Most newly activated Th cells exit the node via the lymph, recirculate through the blood, and enter other lymph nodes via high endothelial venules.

This process of recirculation is fast – it generally takes about a day to make the whole circuit – and it is extremely important. Here’s why.

There are four major ingredients which must be “mixed” before the adaptive immune system can produce antibodies: APCs to present antigen to Th cells, Th cells with receptors that recognize the presented antigen, opsonized antigen displayed by follicular dendritic cells, and B cells with receptors that recognize the antigen. Early in an infection there are very few of these ingredients around, and naive B and T cells just circulate through the secondary lymphoid organs at random, checking for a match to their receptors. So the probability is pretty small that the rare Th cell which recognizes a particular antigen will arrive at the very same lymph node that is being visited by the rare B cell with specificity for that same antigen. However, when activated Th cells first proliferate to build up their numbers and then recirculate to lots of lymph nodes and other secondary lymphoid organs, the Th cells with the right stuff get spread around – so they have a much better chance of encountering those rare B cells which require their help.

B cells that have encountered their cognate antigen displayed on follicular dendritic cells migrate to the border of the lymphoid follicle where they meet activated Th cells that have migrated there from the paracortex. It is during this meeting that B cells first receive the co-stimulation they require for activation. Together, the B and Th cells enter the lymphoid follicles, and the B cells proliferate. Many of the newly made B cells then exit the lymphoid follicle via the lymph and become plasma cells. These cells take up residence in the secondary lymphoid organs and pump out IgM antibodies. Other activated B cells remain in the lymphoid follicle, where they proliferate more and can undergo class switching and additional rounds of somatic hypermutation before they too leave the follicle. In contrast to activated Th cells, activated B cells usually do not recirculate through the lymph and blood and enter other secondary lymphoid organs. Why travel? These B cells have found a secondary lymphoid organ that provides everything they need – antigen displayed on FDCs and Tfh cells to help them.

Killer T cells are activated in the paracortex of the lymph node if they find their cognate antigen presented there by dendritic cells. Once activated, CTLs proliferate and recirculate. Some of these CTLs enter other secondary lymphoid organs and begin this cycle again, and others exit the blood at sites of infection to kill pathogen-infected cells.

As everyone knows, lymph nodes that drain sites of infection tend to swell. For example, if you have a viral infection of your upper respiratory tract (e.g., influenza), the cervical nodes in your neck may become swollen. In fact, during a serious infection, lymph nodes can swell to ten times their normal size. This swelling is due in part to the proliferation of lymphocytes within the node. In addition, cytokines produced by helper T cells in an active lymph node recruit additional macrophages which tend to plug up the medullary sinuses. As a result, fluid is retained in the node, causing further swelling.

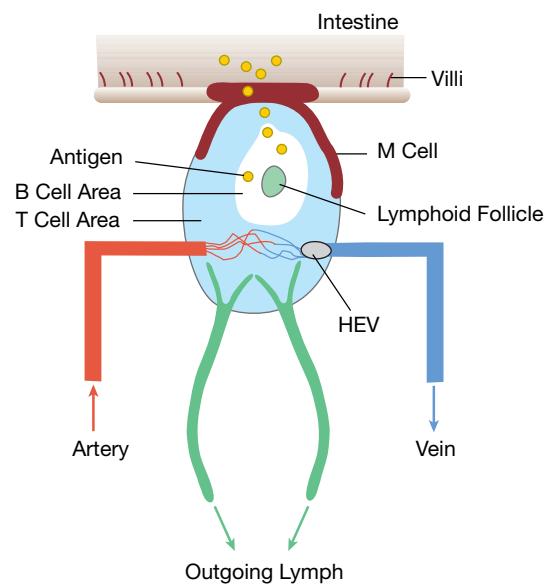
The frenzied activity in germinal centers is generally over in about three weeks. By that time, the invader has usually been repulsed, and a lot of the opsonized antigen has been picked from the follicular dendritic trees by B cells. At this point, most B cells will have left the follicles or will have died there, and the areas that once were germinal centers will look much more like primary lymphoid follicles. And your lymph nodes no longer will be swollen.

Interestingly, when surgeons remove a cancer from some organ in the body, they generally inspect the lymph nodes that drain the lymph from that organ. If they find cancer cells in the draining lymph nodes, it is an indication that the cancer has begun to metastasize via the lymphatic system to other parts of the body – the first stop being a nearby lymph node.

In summary, **lymph nodes act as “lymph filters” which intercept antigen that arrives from infected tissues either alone or as dendritic cell cargo. These nodes provide a concentrated and organized environment of antigen, APCs, T cells, and B cells in which naive B and T cells can be activated, and experienced B and T cells can be restimulated. In a lymph node, naive B and T cells can mature into effector cells that produce antibodies (B cells), provide cytokine help (Th cells), and kill infected cells (CTLs).** In short, a lymph node can do it all.

PEYER'S PATCHES

Back in the late seventeenth century, a Swiss anatomist, Johann Peyer, noticed patches of smooth cells embedded in the villi-covered cells that line the small intestine. We now know that these **Peyer's patches** are examples of mucosal-associated lymphoid tissues (MALT) which function as secondary lymphoid organs. Peyer's patches begin to develop before birth, and an adult human has about 200 of them. Here is a diagram that shows the basic features of a Peyer's patch.



Peyer's patches have high endothelial venules through which lymphocytes can enter from the blood, and, of course, there are outgoing lymphatics that drain lymph away from these tissues. However, unlike lymph nodes, there are no incoming lymphatics that bring lymph into Peyer's patches. So if there are no incoming lymphatics, how does antigen enter this secondary lymphoid organ? Do you see that smooth cell which crowns the Peyer's patch – the one that doesn't have villi on it? That's called an **M cell**. These remarkable cells are not coated with mucus, so they are, by design, easily accessible to micro-organisms that inhabit the intestine. M cells are “sampling” cells – cells which specialize in transporting antigen from the interior (lumen) of the small intestine into the tissues below. To accomplish this feat, M cells enclose intestinal antigens in vesicles (endosomes). These endosomes are then transported through the M cell, and their contents are spit out into the tissues that surround the small intestine. So, **whereas lymph nodes sample antigens from the lymph, Peyer's patches sample antigens from the intestine – and they do it by transporting these antigens through M cells.**

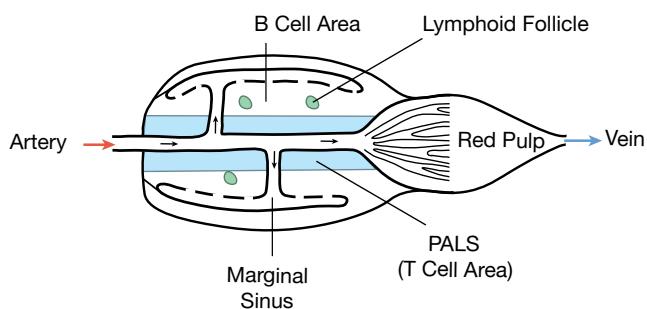
Antigen that has been collected by M cells can be carried by the lymph to the lymph nodes that drain the Peyer's patches. Also, if the collected antigen is opsonized by complement or antibodies, it can be captured by follicular dendritic cells in the lymphoid follicles that reside beneath the M cells. In fact, except for its unusual method of acquiring antigen, a Peyer's patch is quite similar to a lymph node, with high endothelial venules to admit B and T cells, and special areas where these cells congregate.

M cells actually are quite selective about the antigens they transport. They don't just take "sips" of whatever is currently within the intestine (how disgusting!). No, these cells only transport antigens that can bind to molecules on the surface of the M cell. This selectivity makes perfect sense. The whole idea of the M cell and the Peyer's patch is to help initiate an immune response to pathogens that invade via the intestinal tract. And for a pathogen to be troublesome, it has to be able to bind to cells that line the intestines and gain entry into the tissues below. Indeed, most of the stuff we eat will just pass through the small intestine in various stages of digestion without binding to anything. So the minimum requirement for a microbe to be dangerous is that it be able to bind to the surface of an intestinal cell. Consequently, by ignoring all the "non-binders," M cells concentrate the efforts of a Peyer's patch on potential pathogens, and help avoid activating the immune system in response to innocuous food antigens.

THE SPLEEN

The final secondary lymphoid organ on our tour is the spleen. This organ is located between an artery and a vein, and it functions as a blood filter. Each time your heart pumps, about 5% of its output goes through your spleen. Consequently, it only takes about half an hour for your spleen to screen all the blood in your body for pathogens.

As with Peyer's patches, there are no lymphatics that bring lymph into the spleen. However, in contrast to lymph nodes and Peyer's patches, where entry of B and T cells from the blood occurs only via high endothelial venules, the spleen is like an "open-house party" in which everything in the blood is invited to enter. Here is a schematic diagram of one of the filter units that make up the spleen.



When blood enters from the splenic artery, it is diverted out to the marginal sinuses from which it percolates through the body of the spleen before it is collected into

the splenic vein. As they ride along with the blood, naive B cells and T cells are temporarily retained in different areas – T cells in a region called the **periarteriolar lymphocyte sheath (PALS)** that surrounds the central arteriole, and B cells in the region between the PALS and the marginal sinuses.

Of course, since the spleen has no lymphatics to transport dendritic cells from the tissues, you might ask, "Where do the antigen presenting cells in the spleen come from?" The answer is that the marginal sinuses, where the blood first enters the spleen, is home to "resident" dendritic cells. These cells take up antigens from invaders in the blood and use them to prepare a class II MHC display. Resident dendritic cells also can be infected by pathogens in the blood, and can use their class I MHC molecules to display these antigens. Once activated, resident dendritic cells travel to the PALS where T cells have gathered. So although the dendritic cells which present antigens to T cells in the spleen are travelers, their journey is relatively short compared with that of their cousins which travel to lymph nodes from a battle being waged out in the tissues. Helper T cells that have been activated by APCs in the PALS then move into the lymphoid follicles of the spleen to give help to B cells. And you know the rest of this story!

Some of the most dangerous blood-borne pathogens such as *Streptococcus pneumoniae* and *Haemophilus influenzae* surround themselves with a polysaccharide capsule. Helper T cells can only be activated when their TCRs recognize epitopes derived from protein antigens, so they are unable to help B cells whose receptors recognize polysaccharide capsules. And if B cells in the spleen could not be activated and make antibodies to protect against these dangerous invaders, we'd be in trouble. Fortunately, **the spleen is one of the main places in the body where B cells can be activated without the assistance of Th cells**. These "helpless" B cells, called **marginal zone B cells**, are stationed out in the marginal sinuses where they come in contact with blood as it enters the spleen. And because these marginal zone B cells do not have to wait for T cells to be activated, they can respond quickly before encapsulated bacteria have a chance to multiply to dangerous levels. The importance of this Th-independent B cell activation is underscored by the fact that humans who have lost their spleen (e.g., due to injury) are susceptible to serious infections by encapsulated bacteria.

How these marginal zone B cells are activated without T cell help is still a mystery. It likely has to do with the fact that bacterial capsules are composed of many repeating carbohydrate molecules, so there are many epitopes close together to cluster a ton of BCRs. T cell-independent activation also probably depends on B cells using their

pattern-recognition receptors and complement receptors to identify these bacteria as being truly dangerous. But nobody knows for sure.

THE LOGIC OF SECONDARY LYMPHOID ORGANS

By now, I'm sure you've caught on to what is going on here. **Each secondary lymphoid organ is strategically positioned to intercept invaders that enter the body via different routes.** If the skin is punctured and the tissues become infected, an immune response is generated in the lymph nodes that drain those tissues. If you eat contaminated food, an immune response is initiated in the Peyer's patches that line your small intestine. If you are invaded by blood-borne pathogens, your spleen is there to filter them out and to fire up the immune response. And if an invader enters via your respiratory tract, another set of secondary lymphoid organs that includes your tonsils is there to defend you.

Not only are the secondary lymphoid organs strategically positioned, they also provide an environment that is conducive to the mobilization of weapons that are appropriate to the kinds of invaders they are most likely to encounter. Exactly how this works isn't clear yet. However, it is believed that **the different cytokines found in the various secondary lymphoid organs determine the local character of the immune response.** For example, Peyer's patches specialize in turning out Th cells that secrete a Th2 profile of cytokines as well as B cells that secrete IgA antibodies – weapons that are perfect to defend against intestinal invaders. In contrast, if you are invaded by bacteria from a splinter in your toe, the lymph node behind your knee will produce Th1 cells and their associated cytokines as well as B cells that secrete IgG antibodies – weapons ideal for defending against those bacteria.

Certainly **the most important function of the secondary lymphoid organs is to bring lymphocytes and antigen presenting cells together in a way that maximizes the probability that the cells of the adaptive immune system will be activated.** Indeed, the secondary lymphoid organs make it possible for the immune system to react efficiently – even when only one in a million T cells is specific for a given antigen. Earlier, I characterized secondary lymphoid organs as dating bars where T cells, B cells, and APCs mingle in an attempt to find their partners. But in fact, it's even better than that. Secondary lymphoid organs actually function more like "dating services." Here's what I mean.

When people use a dating service to find a mate, they begin by filling out a questionnaire that records information on their background and their goals. Then, a computer goes through all these questionnaires and tries to match up people who might be compatible. In this way, the odds of someone finding a partner who is "right" for them is greatly increased – because they have been pre-selected. This type of preselection also takes place in the secondary lymphoid organs. These organs are compartmentalized, with separate areas for naive T cells and B cells. As the billions of Th cells pass through the T cell areas of the secondary lymphoid organs, only a tiny fraction of these cells will be activated – those whose cognate antigens are displayed by the antigen presenting cells that also populate the T cell areas. The Th cells that do not find their antigens leave the secondary lymphoid organs and continue to circulate. Only those lucky Th cells which are activated in the T cell area will proliferate and then travel to a developing germinal center to provide help to B cells. This makes perfect sense: Allowing useless, non-activated Th cells to enter B cell areas would just clutter things up, and would decrease the chances that Th and B cells which are "right" for each other might get together.

Likewise, many B cells enter the B cell areas of secondary lymphoid organs looking for their cognate antigen displayed by follicular dendritic cells. Most just pass on through without finding the antigen their receptors recognize. Those rare B cells which do find their "mates" are retained in the secondary lymphoid organs, and are allowed to interact with activated Th cells. Consequently, **the "preselection" of lymphocytes in their respective areas of secondary lymphoid organs insures that when Th cells and B cells eventually do meet, they will have the maximum chance of finding their "mates"** – just as with a dating service.

LYMPHOCYTE TRAFFICKING

So far, we've talked about the secondary lymphoid organs in which B and T cells meet to do their activation thing, but I haven't said much about how these cells know to go there. Immunologists call this process **lymphocyte trafficking.** In a human, about 500 billion lymphocytes circulate each day through the various secondary lymphoid organs, but these cells don't just wander around. No, they follow well-defined traffic patterns which maximize their chances of encountering an invader. Importantly, **the traffic patterns of virgin and experienced lymphocytes are different.** Let's look first at the travels of a virgin T cell.

T cells begin life in the bone marrow and are educated in the thymus (lots more on that subject in Lecture 9). When they emerge from the thymus, virgin T cells express a mixture of cellular adhesion molecules on their surface. These function as “passports” for travel to any of the secondary lymphoid organs. For example, virgin T cells have a molecule called L-selectin on their surface that can bind to its adhesion partner, GlyCAM-1, which is found on the high endothelial venules of lymph nodes. This is their “lymph node passport.” Virgin T cells also express an integrin molecule, $\alpha 4\beta 7$, whose adhesion partner, MadCAM-1, is found on the high endothelial venules of Peyer’s patches and the lymph nodes that drain the tissues around the intestines (the mesenteric lymph nodes). So this integrin is their passport to the gut region. Equipped with an array of different adhesion molecules, inexperienced T cells circulate through all of the secondary lymphoid organs. This makes sense: The genes for a T cell’s receptors are assembled by randomly selecting gene segments – so there is no telling where in the body a given naive T cell will encounter its cognate antigen.

In the secondary lymphoid organs, virgin T cells pass through fields of antigen presenting cells in the T cell areas. There these T cells check the billboards on several hundred dendritic cells. If they do not see their cognate antigens advertised, they re-enter the blood either via the lymph or directly (in the case of the spleen) and continue to recirculate. On average, naive T cells make this loop about once a day, spending only about thirty minutes in the blood on each circuit. A naive T cell can continue doing this circulation thing for quite some time, but after about six weeks, if the T cell has not encountered its cognate antigen presented by an MHC molecule, it will die by apoptosis, lonely and unsatisfied. In contrast, those lucky T cells that do find their antigen are activated in the secondary lymphoid organs. These are now “experienced” T cells.

Experienced T cells also carry passports, but they are “restricted passports,” because, during activation, expression of certain adhesion molecules on the T cell surface is increased, whereas expression of others is decreased. This modulation of cellular adhesion molecule expression is not random. There’s a plan here. In fact, **the cellular adhesion molecules that activated T cells express depend on where these T cells were activated. In this way, T cells are imprinted with a memory of where they came from.** For example, DCs in Peyer’s patches produce retinoic acid which induces T cells activated there to express high levels of $\alpha 4\beta 7$ (the gut-specific integrin). As a result, T cells activated in Peyer’s patches tend to return to Peyer’s patches. Likewise, T cells activated in lymph nodes that drain the

skin upregulate expression of receptors that encourage them to return to skin-draining lymph nodes. Thus, **when activated T cells recirculate, they usually exit the blood and re-enter the same type of secondary lymphoid organ in which they originally encountered antigen.** This restricted traffic pattern is quite logical. After all, there is no use having experienced helper T cells recirculate to the lymph node behind your knee if your intestines have been invaded. Certainly not. You want those experienced helper T cells to get right back to the tissues that underlie your intestines to be restimulated and provide help. **Equipping activated T cells with restricted passports insures that these cells will go back to where they are most likely to re-encounter their cognate antigens – be it in a Peyer’s patch, a lymph node, or a tonsil.**

Now, of course, you don’t want T cells to just go round and round. You also want them to exit the blood at sites of infection. That way CTLs can kill pathogen-infected cells and Th cells can provide cytokines that amplify the immune response and recruit even more warriors from the blood. To make this happen, **experienced T cells also carry “combat passports” (adhesion molecules) which direct them to exit the blood at places where invaders have started an infection.** These T cells employ the same “roll, sniff, stop, exit” technique that neutrophils use to leave the blood and enter inflamed tissues. For instance, T cells that gained their experience in the mucosa express an integrin molecule, $\alpha E\beta 7$, which has as its adhesion partner an addressin molecule that is expressed on inflamed mucosal blood vessels. As a result, T cells that have the right “training” to deal with mucosal invaders will seek out mucosal tissues which have been infected. In these tissues, chemokines given off by the soldiers on the front lines help direct T cells to the battle by binding to the chemokine receptors that were expressed on the surface of the T cells during activation. And when T cells recognize their cognate antigen out in the tissues, they receive “stop” signals which tell them to cease migrating and start defending.

In summary, **naive T cells have passports that allow them to visit all the secondary lymphoid organs, but not sites of inflammation. As a consequence, the entire collection of virgin T cells travels through the secondary lymphoid organs, and greatly increases the probability that these T cells will be activated.** The reason that virgin T cells don’t carry passports to battle sites is that they couldn’t do anything there anyway – they must be activated first.

In contrast to virgin T cells, experienced T cells have restricted passports that encourage them to return to the same type of secondary lymphoid organ as the one in

which they gained their experience. By recirculating preferentially to these organs, T cells are more likely to be restimulated or to find CTLs and B cells that have encountered the same invader and need their help.

And, of course, experienced T cells also have passports that allow them to exit the blood at sites of infection, enabling CTLs to kill infected cells, and Th cells to provide appropriate cytokines to direct the battle. This marvelous “postal system,” made up of cellular adhesion molecules and chemokines, insures delivery of the right weapons to the sites where they are needed.

B cell trafficking is roughly similar to T cell trafficking. Like virgin T cells, virgin B cells also have passports that admit them to the complete range of secondary lymphoid organs. However, experienced B cells are not as migratory as experienced T cells. Most just settle down in secondary lymphoid organs or in the bone marrow, produce antibodies, and let these antibodies do the traveling.

WHY MOTHERS KISS THEIR BABIES

Have you ever wondered why mothers kiss their babies? It's something they all do, you know. Most of the barnyard animals also kiss their babies, although in that case we call it licking. I'm going to tell you why they do it.

The immune system of a newborn human is not very well developed. In fact, production of IgG antibodies doesn't begin until a few months after birth. Fortunately, IgG antibodies from the mother's blood can cross the placenta into the fetus's blood, so a newborn has this “passive immunity” from mother to help tide him over. The newborn

can also receive another type of passive immunity: IgA antibodies from mother's milk. Production of IgA also doesn't begin until several months after birth, and only reaches adult levels when the infant is about three years old. During lactation, plasma B cells migrate to a mother's mammary glands and produce IgA antibodies that are secreted into the milk. This works great, because many of the pathogens a baby encounters enter through his mouth or nose, travel to his intestines, and cause diarrhea. By drinking mother's milk that is rich in IgA antibodies, the baby's digestive tract becomes coated with antibodies. This antibody “barrier” can act as a first line of defense by intercepting pathogens the baby ingests.

When you think about it, however, a mother has been exposed to many different pathogens during her life, and the antibodies she makes to most of these will not be of any use to the infant. For example, it is likely that the mother has antibodies which recognize the Epstein–Barr virus that causes mononucleosis, but her child probably won't be exposed to this virus until he is a teenager. So wouldn't it be great if a mother could somehow provide antibodies that recognize the particular pathogens that her baby is encountering – and not provide antibodies that the baby has no use for? Well, that's exactly what happens.

When a mother kisses her baby, she “samples” those pathogens that are on the baby's face – the ones the baby is about to ingest. These samples are taken up by the mother's secondary lymphoid organs (e.g., her tonsils), and memory B cells specific for those pathogens are reactivated. These B cells then traffic to the mother's breasts where they produce a ton of antibodies – the very antibodies the baby needs for protection!

REVIEW

In this lecture, we visited three secondary lymphoid organs: a lymph node, a Peyer's patch, and the spleen. Secondary lymphoid organs are strategically situated to intercept invaders that breach the physical barriers and enter the tissues and the blood. Because of their locations, secondary lymphoid organs play critical roles in immunity by creating an environment in which antigen, antigen presenting cells, and lymphocytes can gather to initiate an immune response. To help make this happen, the secondary lymphoid organs are compartmentalized, with special areas where T cells or B cells are preselected before they are allowed to meet.

B and T cells gain access to a lymph node either from the blood (by passing between specialized high endothelial

cells) or via the lymph. Antigen, carried by lymph drained from the tissues, can enter the lymph node via the subcapsular sinus. Within the sinus, macrophages are strategically positioned to gobble up pathogens when they first enter the node. Consequently, this organ functions as a lymph filter designed to intercept invaders. Antigen can also be carried to a lymph node as cargo aboard an antigen presenting cell, and dendritic cells in the subcapsular sinus can capture antigen from the lymph for presentation.

Within a lymph node, the movements of lymphocytes and dendritic cells are carefully choreographed through the use of cellular adhesion molecules which are up- or downregulated as the cells travel within the node. As a

result, helper T cells, which were activated in the T cell areas, move to the boundary of the B cells area to meet with B cells which have recognized their cognate antigen displayed by follicular dendritic cells. At the boundary, T and B cells do a “dance,” during which the helper T cells mature to become follicular helper T cells (Tfh cells) and B cells become fully activated. B cells and Tfh cells can then enter the lymphoid follicle where, with the help of Tfh cells, B cells can proliferate and undergo somatic hypermutation and class switching.

Antigen is transported into Peyer’s patches through specialized M cells that sample antigen from the intestine. This antigen can interact with B and T cells that have entered the Peyer’s patch via high endothelial venules, or it can travel with the lymph to the lymph nodes that drain the Peyer’s patch. Thus, a Peyer’s patch is a secondary lymphoid organ designed to deal with pathogens which breach the intestinal mucosal barrier.

Finally, we talked about the spleen, a secondary lymphoid organ that is quite different from either a lymph node or a Peyer’s patch in that it has no incoming lymphatics and no high endothelial venules. As a result of this “plumbing,” antigen and lymphocytes must enter the spleen via the blood. This construction makes the spleen an ideal blood filter that intercepts blood-borne pathogens.

Virgin helper T cells travel through the blood and enter the secondary lymphoid organs. If a Th cell does not encounter its cognate antigen displayed by an APC in the T cell zone, it exits the organ via the lymph or blood (depending on the organ), and visits other secondary lymphoid organs in search of its cognate antigen. On the other hand, if, during its visit to a secondary lymphoid organ, a Th cell does find its cognate antigen displayed by class II MHC molecules on a dendritic cell, it becomes activated and proliferates. Most of the progeny then exit the secondary lymphoid organ and travel again through the lymph and the blood. These “experienced” Th cells have adhesion molecules on their surface that encourage them to re-enter the same type of secondary lymphoid organ in which they were activated (e.g., a Peyer’s patch or a peripheral lymph node). This restricted recirculation

following initial activation and proliferation spreads activated Th cells around to those secondary lymphoid organs in which B cells or CTLs are likely to be waiting for their help. Recirculating Th cells also can exit the blood vessels that run through sites of inflammation. There, Th cells provide cytokines which strengthen the reaction of the innate and adaptive systems to the attack, and which help recruit even more immune system cells from the blood.

Virgin killer T cells also circulate through the blood, lymph, and secondary lymphoid organs. They can be activated if they encounter their cognate antigen displayed by class I MHC molecules on the surface of antigen presenting cells in the T cell zones of the secondary lymphoid organs. Like experienced Th cells, experienced CTLs can proliferate and recirculate to secondary lymphoid organs to be restimulated, or they can leave the circulation and enter inflamed tissues to kill cells infected with viruses or other pathogens (e.g., intracellular bacteria).

Virgin B cells also travel to secondary lymphoid organs, looking for their cognate antigens. If they are unsuccessful, they continue circulating through the blood, lymph, and secondary lymphoid organs until they either find their mates or die of neglect. In the lymphoid follicles of the secondary lymphoid organs, a lucky B cell that finds the antigen to which its receptors can bind will migrate to the border of the lymphoid follicle. There, if it receives the required co-stimulation from an activated helper T cell, the B cell will be activated, and will proliferate to produce many more B cells that recognize the same antigen. All this activity converts a primary lymphoid follicle, which is just a loose collection of FDCs and B cells, into a germinal center in which B cells proliferate and mature. In a germinal center, B cells may class switch to produce IgA, IgG, or IgE antibodies, and they may undergo somatic hypermutation to increase the average affinity of their receptors for antigen. These two “upgrades” usually require the ligation of CD40 on the maturing B cells by CD40L proteins on Tfh cells. Most of these B cells then become plasma cells and travel to the bone marrow or secondary lymphoid organs where they produce antibodies. Others remain in the germinal center and undergo further rounds of proliferation and selection.

KNOWN UNKNOWNS

1. Conduits within lymph nodes deliver antigen directly to lymphoid follicles. What other functions do these conduits perform?
2. How are marginal zone B cells in the spleen activated without T cell help?
3. Which occurs first in the lymphoid follicle, class switching or somatic hypermutation?
4. During lactation, how do plasma cells know to travel to mammary glands to produce antibodies?

THOUGHT QUESTIONS

1. What are the functions of the various secondary lymphoid organs?
2. Make a table for each of the secondary lymphoid organs that we discussed (lymph node, Peyer's patch, and spleen) which lists how antigen, B cells, and T cells enter and leave these organs.
3. Why do naive T cells and B cells congregate in separate areas in the secondary lymphoid organs?
4. In the T cell areas of secondary lymphoid organs, activated dendritic cells and Th cells interact. What goes on during this "dance"?
5. At the boundary of the lymphoid follicles of secondary lymphoid organs, B cells and Th cells interact. What goes on during that "dance"?
6. What is the advantage of having virgin B and T cells circulate through all the secondary lymphoid organs?
7. What is the advantage of having experienced B and T cells circulate through selected secondary lymphoid organs?

Restraining the Immune System

HEADS UP!

In some situations, a vigorous immune response is not desirable, and the immune system must be restrained so that it does not become overly exuberant. Also, after the immune system has vanquished an intruder, production of the weapons used to defend against that invader must be stopped, and most of those weapons must be destroyed.

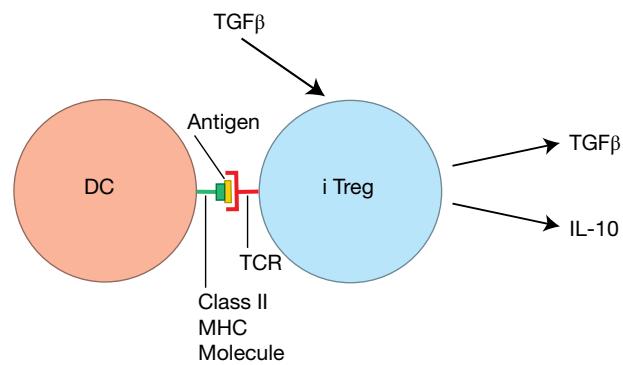
INTRODUCTION

The immune system evolved to provide a rapid and overwhelming response to invading pathogens. After all, most attacks by viruses or bacteria result in acute infections which either are quickly dealt with by the immune system (in a matter of days or weeks) or overwhelm the immune system and kill you. Built into this system are positive feedback loops in which various immune system players work together to get each other fired up. However, once an invasion has been repulsed, these feedback loops must be broken, and the system must be turned off. In addition, there are times when a vigorous response to an invasion is simply not appropriate, and in those situations, the immune system must be restrained in order to prevent irreparable damage to our bodies.

Until recently, immunologists spent most of their effort trying to understand how the immune system gets turned on, and great progress has been made in that area. Now, however, many immunologists are focusing on the equally important question of how the system is restrained.

ATTENUATING THE IMMUNE RESPONSE

We generally think of helper T cells as being important in activating the immune system. However, **another type of CD4+ T cell has been discovered which actually can dampen the immune response: the inducible regulatory T cell (iTreg)**. These T cells are termed “inducible” because, just as naive helper T cells can be encouraged to become Th1, Th2, or Th17 cells, **naive Th cells activated in an environment that is rich in TGF β can be “induced” to become iTregs**. Inducible regulatory T cells are called “regulatory” because, instead of secreting cytokines such as TNF and IFN- γ , which activate the immune system, iTregs produce cytokines such as IL-10 and TGF β that help restrain the system.



iTregs which have been activated by seeing their cognate antigen expressed by an APC exert their “calming influence” in multiple ways. When the IL-10 which iTregs produce binds to its receptors on antigen presenting cells, it reduces the expression of the APC’s pattern-recognition receptors, making it more difficult for these APCs to be activated. In addition, IL-10 binding to an APC’s receptors reduces the levels of the B7 co-stimulatory molecules that

are expressed on the APC's surface. This makes it harder for the APC to activate T cells. iTregs also express a high-affinity IL-2 receptor on their surface, so iTregs can function as an IL-2 sink, soaking up the IL-2 which T cells need to proliferate. Finally, the TGF β produced by iTregs reduces the proliferation rate of T cells, and also makes killer T cells less vicious killers. The net result is that **iTregs use multiple mechanisms to attenuate the immune response and prevent excessive immune activation.**

One area of our body where preventing immune over-exuberance is extremely important is in the tissues that underlie the intestines. Our intestines are home to trillions of harmless bacteria, and inducible regulatory T cells play a major role in keeping the warriors that guard the intestines from overreacting to these bacteria. Intestinal immunity is the subject of Lecture 11.

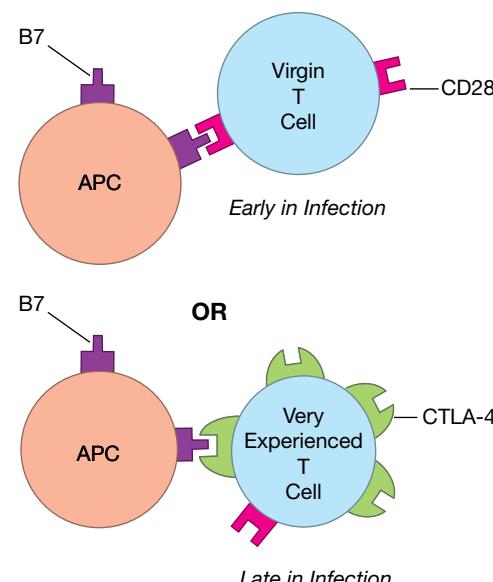
It also is believed that iTregs are important in protecting us against allergies caused by an overreaction of the immune system to common environmental antigens. In this case, iTregs are thought to act, at least in part, by inhibiting mast cell degranulation – an event which is central to the allergic reaction. We will talk more about allergies in Lecture 12.

DEACTIVATING THE SYSTEM

Even in situations in which it is appropriate for the immune system to react strongly against invaders, immune warriors must still be restrained once the battle has been won. During an invasion, as the immune system gains the upper hand and the intruders are destroyed, there will be less and less “invading antigen” present. Consequently, fewer innate system cells will be activated, and fewer dendritic cells will mature and travel to secondary lymphoid organs with their cargo of battle antigens. So **as foreign antigen is eliminated, the level of activation of both the innate and the adaptive system decreases.** This is the first step in turning off the immune system.

Although the removal of foreign antigen is very important, other mechanisms also help decrease the level of activation as the battle winds down. In Lecture 4 we discussed the B7 co-stimulator protein. Activation of a T cell requires that, in addition to ligation of its T cell receptors, B7 proteins on the surface of the APC must plug into CD28 molecules on the surface of the T cell. This co-stimulatory signal greatly increases the efficiency of T cell activation. However, **in addition to engaging stimulatory CD28 molecules on T cells, B7 proteins on APCs also can plug into other receptor proteins on T cells called CTLA-4.** Although most human T cells continuously display CD28 on their surface, the bulk of a naive T cell’s CTLA-4 is stored inside the cell.

Then, beginning about two days after a virgin T cell is first activated, more and more CTLA-4 is moved from these intracellular reservoirs to the cell surface. Importantly, B7 on antigen presenting cells binds to CTLA-4 with an affinity thousands of times higher than its affinity for CD28. Consequently, as time goes on, the CTLA-4 molecules out-compete CD28 for B7 binding. As a result, **early in an infection B7 proteins on an APC bind to CD28 on T cells and provide co-stimulation. Then, after the battle has been raging for a while, the limited number of B7 proteins on an APC bind preferentially to CTLA-4, not CD28. This makes it harder for these T cells to be reactivated and helps shut down the adaptive immune response.**



Another molecule, **programmed death 1 (PD-1)**, (what a great name!) can also help deactivate T cells. Like CTLA-4, expression of PD-1 on the surface of T cells increases after activation. The ligand for PD-1, **PD-L1**, appears on the surface of many different cell types in tissues that are under attack (inflamed tissues). When the PD-L1 protein on inflamed tissues binds to PD-1 on T cells that have been at work for a while, the T cells become “lethargic” – so that they don’t function well. This helps minimize the “collateral damage” that might occur if T cells were not restrained once an infection has been dealt with.

In summary, **late in an infection, CTLA-4 “soaks up” B7 co-stimulatory proteins on APCs and makes reactivation of T cells less efficient. Ligation of PD-1 inhibits the function of previously activated T cells. Together, CTLA-4 and PD-1 function as checkpoint proteins which help “decommission” T cells as the battle winds down.** These checkpoint proteins probably should have been called “negative immune regulator” proteins – because that’s really what they are.

LIFE IS SHORT

As a consequence of the removal of foreign antigen and the subsequent cessation of activation, the immune system will stop producing those weapons which can defend against a banished invader. Nevertheless, many of the weapons made during the struggle will remain at the battle site, and these stockpiles of obsolete weapons must somehow be eliminated. Fortunately, this problem is partly solved by making many of these weapons short-lived.

During a major invasion, huge numbers of neutrophils are recruited from the blood, but these cells are programmed to die after a few days. Likewise, natural killer cells have a half-life of only about a week. Consequently, once recruitment ceases, the stockpiles of neutrophils and NK cells are quickly depleted. Moreover, because natural killer cells supply IFN- γ to help keep macrophages fired up, when NK cells die off, macrophages tend to go back to a resting state.

Dendritic cells, once they reach a lymph node, only live about a week, and plasma B cells die after about five days of hard labor. Consequently, as the activation of Th and B cells wanes, the number of plasma B cells specific for an invader declines. In addition, the antibodies which plasma cells produce have short lifetimes, with the longest lived (the IgG class) having a half-life of only about three weeks. As a result, once plasma B cells stop being produced, the number of invader-specific antibodies drops rapidly.

EXHAUSTION

Although many immune system weapons are short-lived, T cells are an important exception to this rule. In contrast to cells such as neutrophils, which are programmed to self-destruct after a short time on the job, T cells are designed to

live a long time. The reason for this is that naive T cells must circulate again and again through the secondary lymphoid organs, looking for their particular antigen on display. Consequently, it would be extremely wasteful if T cells were short-lived. On the other hand, once T cells have been activated, have proliferated in response to an attack, and have defeated the invader, the longevity of T cells could be a major problem. Indeed, at the height of some viral infections, more than 10% of all our T cells recognize that particular virus. If most of these cells were not eliminated, our bodies would soon fill up with obsolete T cells that could only defend us against invaders from the past. Fortunately, this problem is solved by **activation-induced cell death (AICD)** – a way of eliminating obsolete T cells after they have been restimulated many times in the course of a battle. Here's how this works.

CTLs have proteins called **Fas ligand** that are prominently displayed on their surface, and one way they kill is by plugging this protein into its binding partner, **Fas**, which is present on the surface of target cells. When these proteins connect, the target is triggered to commit suicide by apoptosis. Virgin T cells are “wired” so that they are insensitive to ligation of their own Fas proteins. However, when T cells are activated and then reactivated many times during an attack, their internal wiring changes. During this process, they become increasingly sensitive to ligation of their Fas proteins by their own Fas ligand proteins or by FasL on other T cells. This feature makes these “exhausted” T cells targets for Fas-mediated killing – either by suicide or homicide. By this mechanism, **activation-induced cell death eliminates T cells which have been repeatedly activated, and makes room for new T cells that can protect us from the next microbes which might try to do us harm.** In fact, once an invader has been vanquished, more than 90% of the T cells which responded to the attack usually die off.

REVIEW

Inducible regulatory T cells (iTregs) are helper T cells which secrete cytokines designed to keep the immune system “calm” when we are not threatened by dangerous invaders. And after a real threat has been dealt with, it is important to turn the immune system off and dispose of obsolete weapons. Continued activation of the system depends on the presence of foreign antigen, so as invaders are destroyed, the activation level of the system decreases. Moreover, T cells that have been repeatedly reactivated express checkpoint

proteins on their surface. These “negative regulators” make it more difficult to reactivate T cells (CTLA-4) or make T cells function less well (PD-1). In addition, the short lifetimes of many immune warriors help reduce the stockpiles of weapons that are no longer needed, and T cells that are “exhausted” from their efforts are eliminated by activation-induced cell death. All of these mechanisms combine to “reset” the system after each infection, so that it will be ready to deal with the next attack.

KNOWN UNKNOWNS

1. How important are iTregs in preventing allergies?

THOUGHT QUESTIONS

1. How do inducible T regulatory cells (iTregs) function to dampen the immune response?
2. Why doesn't the interaction between B7 proteins on APCs and CTLA-4 proteins on naive T cells prevent activation of these T cells?
3. Why do the CTLA-4 and PD-1 checkpoint systems work well in combination to help turn off the adaptive immune system late in an infection?
4. Can you imagine why one might want to block the interaction between CTLA-4 and B7 or PD-1 and its ligand to help T cells destroy a cancer?

Self Tolerance and MHC Restriction

HEADS UP!

T cells must be “restricted” to recognize self MHC molecules, so that the attention of these cells will be focused on MHC-peptide complexes, not on unrepresented antigen. In addition, B cells and T cells must be screened to eliminate those which might lead an attack on our own bodies. The safeguards that protect against autoimmunity are multilayered, with each layer designed to catch potentially self-reactive cells that “slip through the cracks” in the layers above. Natural killer cells are also tested to be sure they do not cause autoimmune disease.

thymus has no incoming lymphatics, so cells enter the thymus from the blood. However, in contrast to the spleen, which welcomes anything that is in the blood, entry of cells into the thymus is quite restricted. It is believed that immature T cells from the bone marrow enter the thymus in waves, somewhere in the middle of this organ. However, exactly how this happens is not understood, because the high endothelial cells that allow lymphocytes to exit the blood into secondary lymphoid organs are missing from the thymus.

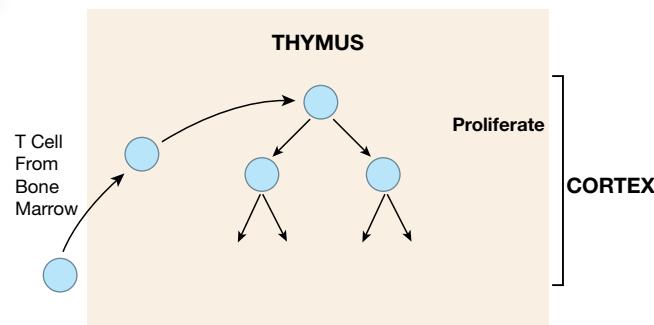
What is known is that the T cells enter the thymus from the bone marrow “in the nude”: They don’t express CD4, CD8, or a TCR. After entry, these cells migrate to the outer region of the thymus (the **cortex**) and begin to proliferate.

INTRODUCTION

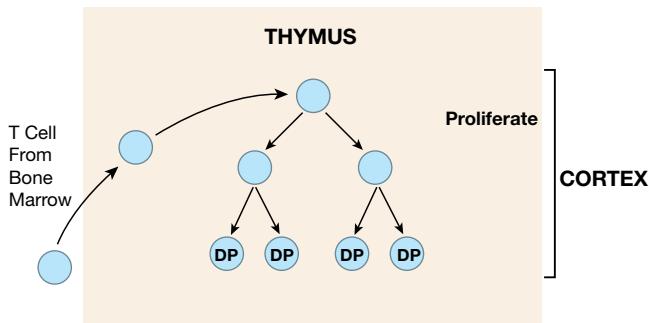
The subject of this lecture is one of the most exciting in all of immunology. Part of that excitement arises because, although a huge amount of research has been done on tolerance of self and MHC restriction, there are still many unanswered questions. But what really makes this topic so interesting is that it is of critical importance. B cells and T cells must learn not to recognize our own antigens as dangerous. Otherwise, we would all die of autoimmune disease.

THE THYMUS

T cells first learn tolerance of self in the thymus, a small organ located just below the neck. This process usually is called **central tolerance induction**. Like the spleen, the



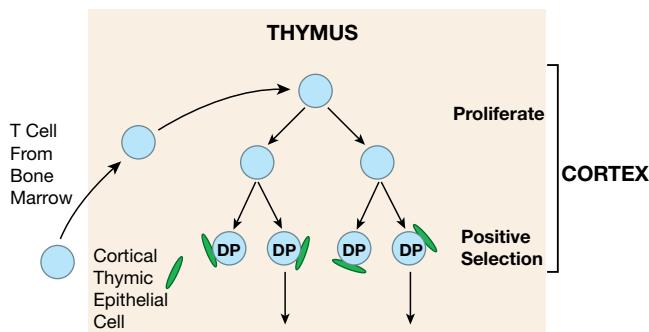
About this time, some of the T cells start to rearrange the gene segments that encode the α and β chains of the TCR. If these rearrangements are successful, a T cell begins to express low levels of the T cell receptor (including the CD3 protein complex) as well as both the CD4 and the CD8 co-receptors. As a result, the formerly nude T cells soon are “dressed” with CD4, CD8, and TCR molecules on their surface. Because these T cells express both CD4 and the CD8, they are called **double-positive (DP)** cells.



During this “reverse striptease,” another important change takes place. When the T cell was naked, it was resistant to death by apoptosis because it expressed little or no Fas antigen (which can trigger cell death when ligated) and because it expressed high levels of Bcl-2 (a cellular protein that protects against apoptosis). In contrast, a “fully dressed” T cell of the thymic cortex **expresses high levels of Fas on its surface and produces very little Bcl-2. Consequently, it is exquisitely sensitive to signals that can trigger death by apoptosis. It is in this highly vulnerable condition that a T cell is tested for MHC restriction and tolerance of self. If it fails either test, it will die a horrible death!**

MHC RESTRICTION

The process of testing T cells for MHC restriction is usually referred to as positive selection. The “examiners” here are epithelial cells in the cortical region of the thymus, and the question a cortical thymic epithelial cell (cTEC) asks of a T cell is: Do you have receptors that recognize one of the self MHC molecules which I am expressing on my surface? The correct answer is, “Yes, I do!” for if its TCRs do not recognize any of these self MHC molecules, the T cell dies.



When I say “self” MHC, I simply mean those MHC molecules which are expressed by the person (or mouse)

who “owns” this thymus. Yes, that does seem like a no-brainer – that my T cells would be tested in my thymus on my MHC molecules – but immunologists like to emphasize this point by saying “self MHC.”

The MHC molecules on the surface of the cortical thymic epithelial cells are actually loaded with peptides, so **what a TCR really recognizes is the combination of a self MHC molecule and its associated peptide**. The peptides presented by the cTEC’s class I MHC molecules represent a sampling of the proteins that are being made inside the cell. This is normal class I presentation. Cortical thymic epithelial cells use their class II MHC molecules to present fragments of proteins which they have taken up from the environment within the thymus. This is normal class II MHC presentation. However, immunologists have recently discovered that cTECs can also employ their class II MHC molecules to present many peptides which come from inside, not from outside these cells. Here’s how this works.

Cells have evolved several mechanisms to help them deal with times of famine – situations when the raw materials required for the synthesis of cellular components are limiting. One such survival tool is a process called **autophagy** (literally “self eating”). When cells are starving, they can enclose portions of their cytoplasm in membranes, which then fuse with lysosomes. The cytoplasmic components (e.g., proteins) are then disassembled by lysosomal enzymes so that they can be reused. Remarkably, **cortical thymic epithelial cells can also employ autophagy to capture their own intracellular proteins, digest them into short peptides, and display them on their surface using class II MHC molecules**. Of course, class II MHC molecules are supposed to present peptides from proteins taken in from outside of the cell. So displaying peptides derived from intracellular proteins certainly is abnormal. However, by using this intracellular digestive system, cortical thymic epithelial cells can greatly increase the universe of self peptides they can present to T cells in the thymus. Presumably, this makes it more likely that a T cell will see a combination of a class II MHC molecule and a peptide to which it can bind – and therefore be positively selected for survival.

THE LOGIC OF MHC RESTRICTION

Let’s pause for a moment between exams to ask an important question: Why do T cells need to be tested to be sure that they can recognize peptides presented by self MHC molecules? After all, most humans complete their

lifetimes without ever seeing “foreign” MHC molecules (e.g., on a transplanted organ), so MHC restriction can’t be about discriminating between your MHC molecules and mine. No, **MHC restriction has nothing to do with foreign versus self – it’s all about focus.** As we discussed in Lecture 4, we want the system to be set up so that T cells focus on antigens that are presented by MHC molecules. Like a B cell’s receptors, a T cell’s receptors are made by mixing and matching gene segments, so they are incredibly diverse. As a result, it is certain that in the collection of TCRs expressed on T cells, there will be many which recognize unpreserved antigens, just as a B cell’s receptors do. These T cells must be eliminated. Otherwise the wonderful system of antigen presentation by MHC molecules won’t work. So **the reason positive selection (MHC restriction) is so important is that it sets up a system in which all mature T cells will have TCRs that recognize antigen presented by self MHC molecules.**

THYMIC TESTING FOR TOLERANCE OF SELF

During or slightly after positive selection takes place in the cortex of the thymus, T cells stop displaying either one or the other of the co-receptor molecules, CD4 or CD8. As you’d predict, these cells are then called **single-positive (SP)** cells. The exact mechanism by which a T cell “chooses” between displaying CD4 or CD8 co-receptors is still being explored. However, the emerging picture is that the choice of co-receptor depends on whether a particular T cell recognizes its cognate antigen displayed by either the class I or class II MHC molecules on a cortical thymic epithelial cell. For example, if a T cell’s receptors recognize an antigen displayed by class I MHC molecules, CD8 co-receptors on the T cell surface will “join the party” and clip onto the MHC molecule. When this happens, the expression of CD4 molecules on that T cell is downregulated. And similarly, a T cell whose receptors recognize a peptide displayed by class II molecules will become a CD4 T cell, and expression of CD8 co-receptors on that cell will be turned off. This strategy works because **CD8 co-receptors only bind to class I MHC molecules, and CD4 co-receptors only bind to class II MHC molecules.**

Those lucky T cells whose TCRs recognize self MHC plus peptide begin to express the CCR7 chemokine receptor on their surface. This influences them to proceed from the thymic cortex to the central region of the

thymus called the **medulla**, where the ligand for this receptor is abundant. **It is in the thymic medulla that the second test is administered: the test for tolerance of self. This exam is frequently referred to as negative selection. The exam question asked of T cells during negative selection is: Do you recognize any of the self peptides displayed by the MHC molecules on my surface?** The correct answer is, “No way!” because T cells with receptors that do recognize the combination of MHC molecules and self peptides are deleted. This second test, which eliminates T cells that could react against our own antigens, is crucial, because if such self-reactive T cells were not deleted, autoimmune disease could result. For example, Th cells that recognize self antigens could help B cells make antibodies that would tag our own molecules (e.g., the insulin proteins in our blood) for destruction – or CTLs could be produced that would attack our own cells.

Medullary thymic epithelial cells

There are two types of cells that screen for tolerance of self antigens (negative selection), and both cell types are different from the cortical thymic epithelial cells that tested T cells for MHC restriction (positive selection). **One cell type involved in testing T cells for tolerance of self is the medullary thymic epithelial cell (mTEC).** These cells are cousins of the cortical thymic epithelial cells that test for MHC restriction. They have two properties which make them especially suited as “tolerance testers.” First, like cTECs, **mTECs use autophagy to digest their own “innards” and process these proteins for presentation by class II MHC molecules.** This rule-breaking presentation, in which proteins made within the cell are displayed by class II MHC molecules, provides a diverse source of self antigens that can be used to eliminate most self-reactive helper T cells during negative selection.

However, there still is a problem. In addition to the “shared” proteins which all cells produce, there are many proteins (estimates suggest several thousand) that are tissue-specific. These **tissue-specific proteins** are the ones which give each organ or tissue type its identity. For example, there are proteins produced by the cells that make up your heart which are unique to that organ. Also, there are proteins made by kidney cells that are kidney-specific. So for tolerance testing in the thymus to be complete, tissue-specific proteins would need to be included in the “material” on which student

T cells are examined. Otherwise, when killer T cells leave the thymus, some of them would surely encounter tissue-specific proteins to which they were not tolerant – and set about destroying your liver, your heart, or your kidneys. Not good.

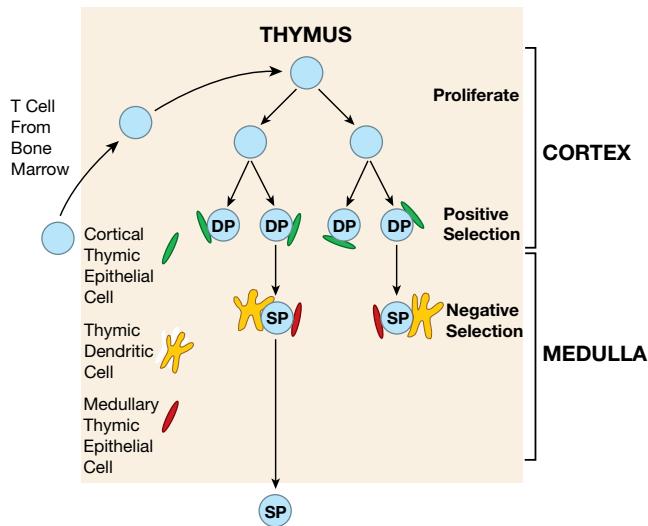
Fortunately, **medullary thymic epithelial cells produce a transcription factor called AIRE that drives expression of many tissue-specific antigens. Consequently, mTECs produce, in addition to the usual shared proteins, many tissue-specific proteins.** Although each individual mTEC expresses only about 2% of the total tissue-specific antigens, altogether the AIRE-expressing cells in the thymus can present about 3,000 different tissue-specific antigens. This helps solve the problem of eliminating T cells with receptors that might recognize tissue-specific proteins. However, while it is believed that the mTEC collection expresses most of the tissue-specific proteins found in the body, they probably do not express all of them.

Thymic dendritic cells

There is a second cell type which has been implicated in testing for tolerance of self antigens in the thymus: the thymic dendritic cell (TDC). Although thymic DCs have a characteristic starfish-like shape, they are different from the migratory dendritic cells we have discussed previously. The medullary TDCs are “residents” of the thymic medulla and develop there from bone-marrow-derived precursors. What is interesting about TDCs is that in addition to acquiring antigens in the usual way from the thymic environment, some of the antigens they present are “given” to them by mTECs. Indeed, it appears that MHC-peptide complexes from mTECs are somehow “handed off” to thymic dendritic cells for them to use to test CD4⁺ and CD8⁺ cells for tolerance of self. How this handoff is accomplished, and why it is important remains a mystery. Clearly, there is still a lot still to be discovered about negative selection in the thymus!

GRADUATION

The final result of all this testing in the thymus is a collection of T cells that has receptors which do recognize self MHC-peptide complexes presented by cortical thymic epithelial cells, but which do not recognize self antigens presented by MHC molecules on thymic dendritic cells or medullary thymic epithelial cells.



The “thymic graduates” that pass these tests express high levels (i.e., many molecules) of the T cell receptor on their surface, plus either the CD4 or CD8 co-receptor, but not both. Each day in the thymus of a young person, about 60 million double-positive cells are tested, but only about two million single-positive cells exit the thymus. The rest die by apoptosis, and are quickly eaten by macrophages in the thymus. Most students are not too thrilled about exams that last more than an hour, so I thought you might like to know that these tests take about two weeks! We’re talking major exams here, where the life of each T cell hangs in the balance. Interestingly, immunologists still aren’t certain how these graduates leave the thymus, but it is thought that they exit near the corticomedullary junction via the blood.

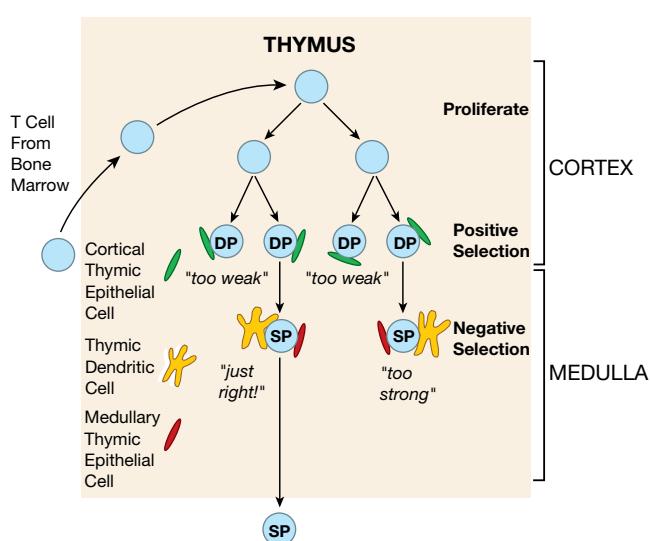
THE RIDDLE OF MHC RESTRICTION AND TOLERANCE INDUCTION

Now, if you’ve been paying close attention, you may be wondering how any T cells could possibly pass both exams. After all, to pass the test for MHC restriction, their TCRs must recognize MHC plus self peptide. Yet to pass the tolerance exam, their TCRs must not be able to recognize MHC plus self peptide. Doesn’t it seem that the two exams would cancel each other out, allowing no T cells to pass? It certainly does, and this is the essence of the riddle of self tolerance: How can ligation of a T cell receptor possibly result in both positive selection (MHC restriction) and negative selection (tolerance induction)? In fact, it is

even more complicated than that, because once a T cell has passed both tests in the thymus, its TCRs must be able to signal activation when they encounter invader-derived peptides presented by self MHC molecules.

The “Goldilocks” hypothesis

It is known that the events leading to MHC restriction and tolerance induction are similar to those involved in the activation of T cells: cell–cell adhesion, TCR clustering, and co-stimulation. However, the question that vexes immunologists is: **How does the same TCR, when it engages MHC-peptide complexes, signal three very different outcomes – positive selection, negative selection, or activation?** Most immunologists favor the “affinity model” – which is usually called the Goldilocks hypothesis. This hypothesis states that to survive both positive and negative selection in the thymus, T cells must have receptors that are “just right.” Indeed, it is hypothesized that in the thymus, **positive selection (survival) of T cells results from a relatively weak interaction between TCRs and MHC-self peptide displayed on cortical thymic epithelial cells** – an interaction that is strong enough to insure that the TCRs are focused on presented antigen. Then, **the interaction between TCRs and MHC-self peptide expressed on medullary thymic epithelial cells or thymic dendritic cells must not be too strong or cell death (negative selection) will result.** And finally, **after T cells leave the thymus, the interaction between their TCRs and MHC-peptide displayed by professional antigen presenting cells must be strong enough to trigger activation.**



Of course, since the TCR is the same in all three situations, the question is what makes the effect of these three interactions of MHC–peptide with a T cell receptor so different: life, death, or activation? One key element appears to be the properties of the cell that “sends” the signals. In the case of MHC restriction, this is a cortical thymic epithelial cell. For tolerance induction, the cell is a bone marrow-derived dendritic cell or a medullary thymic epithelial cell. And for activation, the sender is a specialized antigen presenting cell. These sender cells are very different. For example, the proteasomes of cortical thymic epithelial cells – the machines that chop up proteins to make peptides for class I display – are subtly different from the proteasomes of the cells that are responsible for negative selection. This could affect which self peptides are presented on class I MHC molecules by these examiner cells. Moreover, some of the enzymes that cTECs use to prepare peptides for presentation on class II MHC molecules are different from the corresponding enzymes employed by the examining cells in the thymic medulla.

It is also likely that the various sender cells differ in the cellular adhesion molecules they express and in the number or type of MHC-peptide complexes they display on their surface. Such differences could dramatically influence the strength of the signal that is sent through the T cell receptor. In addition, the different types of sender cells are likely to express different mixtures of co-stimulatory molecules – and co-stimulatory signals could change the meaning of the signal that results from TCR–MHC–peptide engagements.

Not only are the cells that send the signals different, the “receiver” (the T cell) also may change between exams. Cytokines found in various parts of the thymus are different, and these cytokines can change the level of expression of T cell receptors and alter the threshold level for selection. Indeed, it is known that the number of TCRs on the surface of the T cell increases as the cell is tested, and it is also possible that the “wiring” within the T cell changes as the T cell matures. These differences in TCR density and signal processing could influence the interpretation of signals generated by the various types of sender cells.

The Goldilocks hypothesis may be correct. However, many of the details of the MHC restriction/tolerance induction riddle remain to be worked out, and more experiments will need to be done before this amazing process is fully understood.

TOLERANCE BY IGNORANCE

Thankfully, most T cells with receptors which could recognize our own proteins are eliminated in the thymus. However, central tolerance induction in the thymus is not foolproof. If it were, every single T cell would have to be tested on every possible self antigen – and that's a lot to ask. The probability is great that T cells with receptors which have a high affinity for those self antigens that are abundant in the thymus will be deleted there. However, T cells whose receptors have a low affinity for self antigens, or which recognize self antigens that are rare in the thymus, are less likely to be negatively selected. They may just “slip through the cracks” of central tolerance induction. Fortunately, the system has been set up to deal with this possibility.

Virgin T cells circulate through the secondary lymphoid organs, but are not allowed out into the tissues. This traffic pattern takes these virgins to the areas of the body where they are most likely to encounter APCs and be activated. However, the travel restriction that keeps virgin T cells out of the tissues also is important in maintaining self tolerance. The reason is that, as a rule, those self antigens which are abundant in the secondary lymphoid organs, where virgin lymphocytes are activated, are also abundant in the thymus, where T cells are tolerized. Therefore, **as a result of the traffic pattern followed by virgin T cells, most T cells that could be activated by an abundant self antigen in the secondary lymphoid organs will already have been eliminated by seeing that same, abundant self antigen in the thymus.**

Conversely, T cells whose receptors recognize self antigens that are relatively rare in the thymus may escape deletion there. However, these same antigens usually exist at such low concentrations in the secondary lymphoid organs that they do not activate potentially self-reactive T cells. Thus, **although rare self antigens are present in the secondary lymphoid organs, and although T cells do have receptors which can recognize them, these T cells usually remain functionally “ignorant” of their presence – because the self antigens are too rare to trigger activation. So lymphocyte traffic patterns play a key role not only in insuring the efficient activation of the adaptive immune system, but also in preserving tolerance of self antigens.**

TOLERANCE INDUCTION IN SECONDARY LYMPHOID ORGANS

Although the restricted traffic pattern of naive T cells usually protects them from exposure to self antigens which might activate them, this barrier to activation is not absolute. Occasionally, self antigens that are too rare in the thymus to cause deletion of potentially autoreactive T cells, are released into the blood and lymphatic systems (e.g., as the result of an injury which causes tissue damage) in concentrations sufficient to activate previously ignorant T cells. But again, the immune system has a way to deal with this potential problem.

Until recently, it was thought that the only role of the thymus in preventing autoimmunity was the elimination of potentially self-reactive T cells. However, it now is clear that there is an additional thymic function which helps protect us from autoimmune disease – the generation of **natural regulatory T cells (nTregs)**. In the thymus, a subset of CD4⁺ T cells is selected to become natural regulatory T cells. This selection takes place in the thymic medulla and requires the action of mTECs and TDCs. The current thinking is that CD4⁺ T cells whose receptors have a strong affinity for self antigens presented by these cells are eliminated. T cells whose receptors have a weak affinity for self antigens presented by mTECs or TDCs are selected to survive as helper T cells. And CD4⁺ T cells with an “intermediate” affinity for self antigens are “induced” to become natural regulatory T cells. However, exactly what “intermediate” means in this context and the details of how these T cells are induced are not known.

One thing that is known about the selection of CD4⁺ T cells to become nTregs is that these cells are induced to express a gene called **Foxp3**, which is instrumental in conferring upon nTreg cells their regulatory properties. After they are generated in the thymus, natural Tregs receive passports (adhesion molecules) which allow them to enter lymph nodes and other secondary lymphoid organs. Indeed, about 5% of all the CD4⁺ T cells in circulation are regulatory T cells. If, in a secondary lymphoid organ, a natural Treg encounters its cognate self antigen presented by an antigen presenting cell, it can be activated. Once activated, nTreg cells are able to suppress the activation of potentially self-reactive T cells.

How nTregs accomplish this suppression is incompletely understood. One likely mechanism is that when an Treg cell recognizes its cognate antigen displayed by an antigen presenting cell, the nTreg cell acts to reduce expression of co-stimulatory molecules on that APC. nTregs express high levels of CTLA-4 proteins on their surface, and it has been proposed that when CTLA-4 plugs into the B7 co-stimulator protein on an APC, the nTreg “plucks” B7 proteins from the surface of the APC. The resulting paucity of B7 proteins on the APC surface makes it more difficult for the APC to activate potentially self-reactive effector T cells.

In the last lecture, you met another type of regulatory T cell: the inducible regulatory T cell. Both inducible and natural regulatory T cells express the Foxp3 protein, but the targets of their suppressive activities appear to be different. **Whereas the role of natural regulatory T cells is to provide protection against T cells which have the potential to react against self antigens and cause autoimmunity, the main function of inducible regulatory T cells is to keep the immune system from overreacting to foreign invaders.**

Although there is a lot to be discovered about natural Tregs, it is clear that they play an important role in protecting us from autoimmune disease. Indeed, humans who have mutations that compromise the function of the Foxp3 protein suffer from aggressive autoimmune disease and die at an early age.

PERIPHERAL TOLERANCE INDUCTION

Of course, virgin T cells aren't perfect, and some do stray from the prescribed traffic pattern and venture out into the tissues. Indeed, potentially self-reactive T cells are found in the tissues of every normal human. There these “lawbreakers” may encounter self antigens that were too rare in the thymus to trigger deletion, but which are abundant enough in the tissues to activate these T cells. To deal with this situation, there is another level of protection against autoimmunity: **peripheral tolerance induction**.

Because of the two-key requirement for T cell activation, virgin T cells must not only encounter enough presented antigen to cluster their receptors, they must also receive co-stimulatory signals from the cell that is presenting the antigen. That's where activated antigen presenting cells come in. These special cells have lots of MHC molecules on their surface to present antigen, and they also express co-stimulatory molecules such as

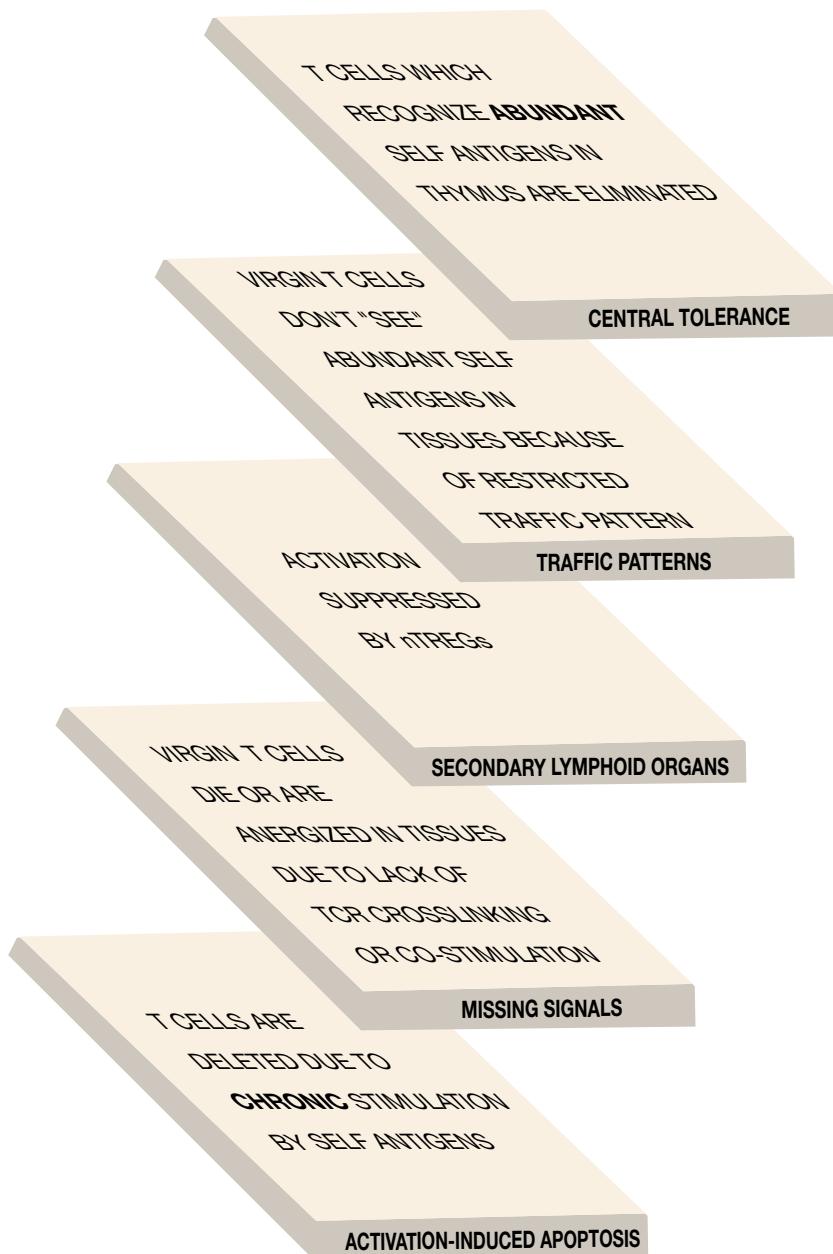
B7. In contrast, ordinary cells such as heart or kidney cells generally don't express high levels of MHC proteins or don't express co-stimulatory molecules, or both. As a result, a virgin T cell with receptors that recognize a kidney antigen could probably go right up to a kidney cell and not be activated by it. In fact, it's even better than that. **When a virgin T cell recognizes its cognate antigen presented on a cell, but does not receive the required co-stimulation, that T cell is “neutered.” It looks like a T cell, but it can no longer perform. Immunologists say the cell is anergized. In many cases, cells that are anergized eventually die, so peripheral tolerance induction can result in either anergy or death. Consequently, the requirement for the second, co-stimulatory “key” during T cell activation protects us against virgin T cells that venture outside their normal traffic pattern.**

TOLERANCE DUE TO ACTIVATION-INDUCED CELL DEATH

Okay, so what if a T cell escapes deletion in the thymus, breaks the traffic laws, and ventures out into the tissues. And suppose that this T cell just happens to find its cognate antigen displayed by MHC molecules at a high enough density to crosslink its receptors on a cell that just happens to be able to provide the co-stimulation required to activate the T cell. What then? Well, all is not lost, because there is yet another layer of tolerance induction that can protect us in this unlikely situation.

In the last lecture, we discussed activation-induced cell death (AICD) as one way T cells are eliminated when an invader has been vanquished. This same mechanism also helps protect against virgin T cells that break the traffic rules and are activated by self antigens out in the tissues. T cells in this situation are stimulated over and over by the ever-present self antigens, and when this happens, the self-reactive T cells are usually eliminated by activation-induced cell death. It is as if the immune system senses that this continual reactivation “ain't natural,” and does away with the offending, self-reactive T cells.

So **T cell tolerance induction is a multilayered process. Instead of trying to test every single T cell for self-reactivity, the immune system employs at least five tolerance-inducing mechanisms. This multilayered approach insures that, for most humans, autoimmune disease never happens.**



B CELL TOLERANCE

Immunologists once thought that it might not be necessary to delete B cells whose receptors recognize self antigens. The idea was that the T cells which were needed to help activate potentially self-reactive B cells would already have been killed or anergized. Consequently, B cell tolerance might be "covered" by T cell tolerance. However, it is now clear that mechanisms also exist for tolerizing those B cells which have the potential to be self-reactive.

Most B cells are tolerized where they are born – in the bone marrow, and the antigens that developing B cells encounter in the bone marrow are almost exclusively self

antigens. This testing for tolerance of self is the rough equivalent of thymic tolerance induction for T cells. After B cells mix and match gene segments to construct the genes for their receptors, they are tested to see if these receptors recognize antigens that are present in the bone marrow. If its receptors do recognize a self antigen, a B cell is given another chance to rearrange its light chain genes and come up with new receptors that don't bind to a self antigen. This attempt at "redemption" is called **receptor editing**, and, in mice, at least 25% of all B cells take advantage of this second chance. Nevertheless, even when they try again to produce acceptable receptors, only about 10% of all B cells pass the tolerance test. The rest die in the bone marrow.

After testing, B cells with receptors that do not bind to self antigens that are abundant in the bone marrow are released to circulate with the blood and lymph. Of course, induction of B cell tolerance in the bone marrow has the same problems as T cell tolerance induction in the thymus: B cells that have receptors which recognize self antigens that are rare in the marrow can slip through the cracks. Fortunately, bone marrow contains mostly the same abundant self antigens that are found in the secondary lymphoid organs where virgin B cells will be activated. Consequently, **self antigens that are too rare to efficiently delete B cells in the bone marrow are usually too rare to activate these B cells in the secondary lymphoid organs.** So **the traffic pattern of virgin B cells, which restricts them to circulating through the secondary lymphoid organs, helps protect them from encountering abundant self antigens that are not present in the bone marrow.**

There also are mechanisms which can tolerize B cells that break these traffic laws. For example, **virgin B cells that venture into the tissues can be anergized or deleted if they recognize their cognate antigen, but do not receive T cell help.** Thus, B cells are subject to mechanisms which enforce self tolerance out in the tissues that are similar, but not identical, to those which tolerize T cells.

MAINTENANCE OF B CELL TOLERANCE IN GERMINAL CENTERS

In contrast to T cells, which are stuck with the same receptors they express when they are tested in the thymus, B cells have a chance, after they have been activated in the secondary lymphoid organs, to modify their receptors through somatic hypermutation. So you may be wondering whether B cells undergoing somatic hypermutation might end up with receptors that can recognize self antigens. If so, these B cells might produce antibodies that could cause autoimmune disease. Fortunately, it turns out that this usually doesn't happen. Here's why.

If a B cell hypermutates in a germinal center so that its receptors recognize a self antigen, it is very unlikely to find and be stimulated by that self antigen advertised on follicular dendritic cells. After all, FDCs only display antigens that have been opsonized – and self antigens usually aren't opsonized. So the first difficulty that potentially self-reactive B cells face in a germinal center is the lack of opsonized self antigen on follicular dendritic cells. But they have another problem – lack of co-stimulation.

After follicular helper T cells have been activated in the T cell zones of secondary lymphoid organs, they move to the lymphoid follicles to give help to B cells. This help takes

place during a dance in which follicular helper T cells (Tfh cells) and B cells stimulate each other. The B cells that participate in this dance have internalized the antigen to which their receptors bind and they use their class II MHC molecules to present this antigen to Tfh cells. The B cells also provide the co-stimulation (e.g., B7) required for the Tfh cell to remain active. In return, the Tfh cell provides the B cell with the co-stimulation (e.g., CD40L) it needs. The important point here is that **for this bidirectional stimulation to work, the Tfh cell's receptors and the B cell's receptors must recognize the same antigen – or more precisely, parts of the same antigen.** So if a B cell hypermutates so that its BCRs bind to, internalize, and present a self antigen, that new antigen will not be recognized by the "needy" Tfh cell's receptors. As a result, the B and T cells will not be able to collaborate to stimulate each other. They will have lost their "common interest." And because B cells require Tfh cell help to survive in the germinal center, the interdependence of B and Tfh cells helps keep B cells "on track" as they undergo somatic hypermutation. So **self tolerance is preserved during B cell hypermutation for two reasons: the lack of opsonized self antigen required for efficient BCR signaling and the lack of germinal center Tfh cells which can provide help for B cells that recognize self antigen.**

THE EDUCATION OF NATURAL KILLER CELLS

Many viruses try to evade the immune system by down-regulating expression of class I MHC molecules on infected cells. This dirty trick is designed to prevent killer T cells from "looking into" these cells and determining that they are infected. To counter this ploy, natural killer cells survey the cells they come in contact with, and destroy those which do not display class I MHC molecules on their surface – a process called **missing self recognition.** This works because NK cells have **inhibitory receptors** on their surface which can recognize class I MHC molecules on healthy cells, and convey a "don't kill" signal so that the target cell is spared. But there is a potential problem. MHC molecules are extremely polymorphic (i.e., each MHC gene has many slightly different forms in the human population). Consequently, it is possible that the inhibitory receptors on my NK cells might not recognize my own class I MHC molecules. And if that happened, my NK cells might think that my normal cells were virus-infected and kill them. Not good.

I suppose one solution to this problem would be to co-express each class I MHC molecule with its matching NK inhibitory receptor – but that turns out not to be the way it is done. Rather, every human has multiple genes

for inhibitory NK receptors, and these genes also are quite polymorphic. As a result, every person inherits a collection of inhibitory receptor genes, and these are usually different from person to person. Moreover, because these genes seem to be selected at random for expression, the array of different inhibitory receptors actually differs from NK cell to NK cell within the same person.

The current thinking is that before NK cells can be fully functional (i.e., deadly), they must be “licensed to kill.” To get this license, our NK cells must have inhibitory receptors that can recognize at least one of the class I MHC molecules on our cells. Those NK cells which do not have inhibitory receptors that bind to self MHC molecules are anergized so that they cannot function. In this way, NK

cells are screened to help avoid NK cell-mediated autoimmunity. NK cells usually receive this part of their education in the bone marrow.

In addition to inhibitory receptors, NK cells also are equipped with **activating receptors**. These receptors are designed to respond to signals which indicate that a cell has been infected and should be destroyed. For example, there are activating receptors which recognize molecules that appear on the surface of human cells when they are “stressed” by a viral infection. It is believed that the final decision on whether to kill a target cell is made by balancing the strengths of the signals delivered by the NK cell’s inhibitory and activating receptors. How, when, and where NK cells are educated so that the proper balance is achieved is still a mystery.

REVIEW

In this lecture, we discussed one of the most important riddles in immunology: How can the same T cell receptor mediate positive selection (MHC restriction), negative selection (tolerance induction), and activation? The current thinking is that in the thymus, positive selection (survival) of a T cell results from a relatively weak interaction between the cell’s TCRs and MHC-self peptides displayed on cortical thymic epithelial cells. This “test” is intended to focus the attention of T cells on antigen presented by MHC molecules, insuring that recognition is restricted to presented antigen, not “native” antigen. Negative selection (death) of a T cell in the thymus is caused by a strong interaction between the cell’s TCRs and MHC-self peptides expressed on medullary thymic epithelial cells or thymic dendritic cells. This “exam” is designed to eliminate T cells which might cause autoimmune disease. Finally, after it leaves the thymus, the T cell can be activated to defend us against disease through a strong interaction between its TCRs and MHC-peptides displayed by professional antigen presenting cells.

Although thymic (central) tolerance induction is pretty good, it isn’t perfect. One way of dealing with T cells that escape deletion in the thymus is to restrict the trafficking of virgin T cells to blood, lymph, and secondary lymphoid organs. T cells with receptors which recognize antigens that are abundant in the secondary lymphoid organs are usually efficiently deleted in the thymus – where the same antigens are also abundant. Conversely, self antigens that are rare enough in the thymus to allow self-reactive T cells to escape deletion are usually also too rare to activate

virgin T cells in the secondary lymphoid organs. Thus, because of their restricted traffic pattern, virgin T cells normally remain functionally ignorant of self antigens that are rare in the thymus.

Natural regulatory T cells in the secondary lymphoid organs also provide protection against autoimmunity, probably by interfering with the activation of potentially self-reactive T cells. And in those cases where virgin T cells do venture outside the blood–lymph–secondary lymphoid organ system, they generally encounter self antigens in a context that leads to anergy or death, not activation. Moreover, those rare T cells that are activated by recognizing self antigens in the tissues usually die from chronic restimulation.

Whereas T cells have a separate organ, the thymus, in which central tolerance is induced, B cells with receptors that recognize abundant self antigens are eliminated where they are born – in the bone marrow. During this screening, self-reactive B cells are given a second chance to “edit” their receptors in an attempt to come up with BCRs that do not recognize self antigens.

As with T cells, tolerance induction in B cells is multi-layered. Virgin B cells mainly travel through the blood, lymph, and secondary lymphoid organs. So like T cells, the traffic pattern of naive B cells usually protects them from contact with abundant self antigens on which they were not tested during tolerance induction in the bone marrow. Naive B cells that wander out of the blood/lymph traffic pattern don’t usually encounter sufficient self antigen in a form that can crosslink their BCRs. In addition,

virgin B cells whose receptors are crosslinked by self antigen in tissues don't usually receive the co-stimulatory signals required for activation – and crosslinking without co-stimulation can anergize or kill B cells.

When B cells mature in germinal centers, they can undergo somatic hypermutation to refine the affinity of their receptors. This process creates the possibility that the mutated BCRs might recognize a self antigen. Fortunately, this isn't usually a problem. In order for B cells to proliferate in germinal centers, their receptors must recognize opsonized antigen displayed by follicular dendritic cells – and self antigens are not normally opsonized. Even more importantly, follicular helper T cells in the germinal center will not recognize the self antigen which the mutated BCRs now recognize and present. And B cells count on help from Tfh cells for survival.

The picture you should have is that none of the mechanisms for tolerizing B or T cells is foolproof – they all are a little “leaky.” However, because there are multiple layers of tolerance-inducing mechanisms to catch potentially self-reactive cells, the whole system works very well and relatively few humans suffer from serious autoimmune disease.

Natural killer cells also are tested to avoid autoreactivity. If an NK cell does not have inhibitory receptors that recognize at least one of a person's class I MHC molecules, that NK cell is rendered nonfunctional. NK cells also have activating receptors on their surface that help identify cells which have been infected and should be destroyed. It is the balance between the signals sent by inhibitory and activating receptors which determines the fate of the potential target cell.

KNOWN UNKNOWNS

1. In the thymus, how do cells “choose” to become CD4 or CD8 T cells?
2. How are natural regulatory T cells (nTregs) generated in the thymus?
3. How are MHC-peptide complexes from mTECs handed off to thymic dendritic cells to use to test for tolerance of self?
4. How are B cells educated to be tolerant of tissue-specific self antigens?
5. How are the signals from inhibitory and activating receptors on NK cells evaluated, so that infected cells are destroyed and healthy cells are spared?

THOUGHT QUESTIONS

1. Why is it important that T cells be tested to be sure they can recognize self MHC molecules? Wouldn't it be a lot simpler just to eliminate this exam?
2. For T cells being tested in the thymus, what is the functional definition of self (i.e., what do these T cells consider to be self peptides)?
3. What is the underlying difficulty in a T cell satisfying both the requirement for MHC restriction (positive selection) and the requirement for tolerance of self (negative selection)?
4. Why are mechanisms needed that can tolerize T cells once they leave the thymus?
5. Explain why the traffic pattern of virgin T cells plays a role in maintaining tolerance of self.
6. Why is it important that B cells also be screened for tolerance of self?
7. So far, we have encountered four types of dendritic cells: plasmacytoid DCs, antigen presenting DCs, follicular DCs, and thymic DCs. As a way to review, explain the function of each of these cell types.

HEADS UP!

The innate immune system has a “hard-wired” memory which allows it to remember encounters with invaders from the ancient past. Some innate system cells can be “trained” to respond more strongly to a subsequent threat. The adaptive immune system has an “updatable” memory which remembers the specific invaders we have encountered during our lifetime. Memory B and T cells have received “upgrades,” and are better able to deal with a second attack than are the B and T cells which responded to the initial invasion.

component). Moreover, these receptor genes are passed down from generation to generation, and do not change during the lifetime of a human. This ancient memory allows an immediate and robust response to invaders that have been attacking humans for a very long time. Importantly, although the innate immune memory is “tuned” to past invaders, the innate immune system also can protect us against new invaders (for example, viruses that enter the human population from wild animals) if these novel pathogens have structural features in common with ancient invaders.

Some cells of the innate system (e.g., macrophages and NK cells) can be “trained” by a first exposure to a pathogen to respond more quickly and powerfully to a subsequent invasion. The hyperactivation of a macrophage is an example of such training. Although the rules that govern this **trained immunity** are still being worked out, in humans this type of memory usually seems to be nonspecific. That is, the initial defense against one pathogen can enhance the response of innate system cells to a subsequent attack by the same or a different pathogen. In this way, trained immunity can help provide broad, nonspecific protection against future microbial attacks. Trained immunity is usually short-lived, lasting only for weeks or months. And it is local. Only the innate cells in the area of the original infection can be trained. In trained immunity, a previous exposure to a pathogen results in an altered pattern of gene expression that is driven and maintained by **epigenetic modifications** (e.g., histone acetylation or DNA methylation).

There is also some experimental evidence that natural killer cells which respond to an infection by the human cytomegalovirus can be trained to respond specifically to a subsequent attack by this virus. Of course, the human cytomegalovirus is older than dirt. It has been infecting humans for a very long time. Consequently, we shouldn’t be surprised if this virus appears in the NK cell’s “list” of

INTRODUCTION

One of the most important attributes of the immune system is that it remembers past encounters with attackers. These memories help protect against future challenges. Both the innate and the adaptive systems have memories, but what these two systems remember is quite different.

INNATE MEMORY

The innate immune system has a “hard-wired” memory which is extremely important in defending us against everyday invaders. This memory is the result of millions of years of experience, during which the innate system slowly evolved genes for receptors that can detect the signatures of common invaders. These receptors (e.g., Toll-like receptors) usually detect molecular structures which are essential for an invader’s lifestyle, and which are characteristic of broad classes of microbial pathogens (e.g., all bacteria that have LPS as a cell wall

ancient invaders. So far, however, the importance of trained NK cells in defending against a human cytomegalovirus infection is unknown.

ADAPTIVE MEMORY

The innate immune system uses hard-wired receptors to “remember” broad classes of pathogens that also plagued our ancestors. In contrast, **the adaptive immune system is set up to remember the specific attackers we encounter during our lifetime**. Although B and T cells have a diverse collection of receptors that can recognize essentially any invader, there are relatively few naive B or T cells with receptors that can recognize any particular attacker – not enough to mount an immediate defense. So in practical terms, **B and T cells really begin life with a blank memory**. During an initial attack, pathogen-specific B or T cells proliferate to build up their numbers. Then, when the invader has been subdued, most of these cells die off, but some (typically a few percent) remain as memory B or T cells. Memory cells retain knowledge of the initial infection, and are able to mount a robust response to a subsequent attack by the same invader.

B cell memory

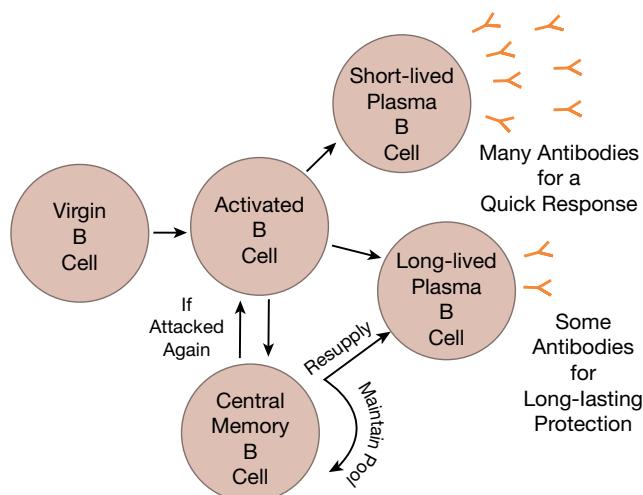
It is clear that B cells and the antibodies they produce can confer life-long immunity to infection. For example, in 1781, Swedish traders brought the measles virus to the isolated Faroe Islands. In 1846, when another ship carrying sailors infected with measles visited the islands, most people who were older than 64 years did not contract the disease – because they still had antibodies against the measles virus. Even the longest-lived antibodies (IgG) have a half-life of less than a month, so antibodies would have to be made continuously over a period of many years to provide this long-lasting protection.

During the initial response to an invader, short-lived plasma B cells are rapidly activated in the secondary lymphoid organs. There they proliferate and produce huge quantities of antibodies that are specific for the attacker. Because short-lived plasma cells are activated very quickly, most have not undergone somatic hypermutation or switched from producing IgM to another class of antibody. Although they only live for a few days, and the antibodies they produce are not very “sophisticated,” the antibodies made by short-lived plasma B cells are extremely important in protecting us against an enemy that the adaptive immune system has never encountered before.

In addition to short-lived plasma cells, which are generated rapidly after infection, other activated B cells enter germinal centers where they proliferate and undergo rounds of somatic hypermutation and selection. These “upgraded” B cells, many of which have switched class, then begin to produce antibodies that are sharply focused on the invader.

After the battle has been won, most upgraded B cells die off, but some become long-lived plasma cells. These are memory cells which take up residence in the bone marrow where a supportive environment allows them to survive for a long time. Importantly, long-lived plasma cells continually produce antibodies – antibodies that can provide life-long immunity to subsequent infections. So together, short-lived and long-lived plasma B cells provide both immediate and long-term antibody protection against attacks.

There is a second type of memory B cell: the central memory B cell. These cells are produced early in an infection and circulate throughout the body with the lymph or take up residence in the secondary lymphoid organs. **Central memory B cells function as memory “stem cells” which proliferate slowly to maintain a pool of central memory B cells and to replace long-lived plasma cells that have died of old age.** If the pathogen attacks again, central memory B cells are strategically positioned so that they can be quickly reactivated, proliferate, and produce pathogen-specific antibodies. Importantly, the generation of both types of memory cells – long-lived plasma cells and central memory B cells – requires T cell help.



This strategy, which involves B cells that function in four different ways, provides overlapping layers of defense. When an invader first attacks, antibodies need to be made quickly to tag invaders for destruction. That's what

short-lived plasma B cells do. Meanwhile, upgraded B cells are produced which make antibodies that have high affinity for the pathogen. These B cells continue to be produced for the duration of the infection. Then, after the battle is over, it is important to keep invader-specific antibodies on hand which can provide an immediate defense in case of

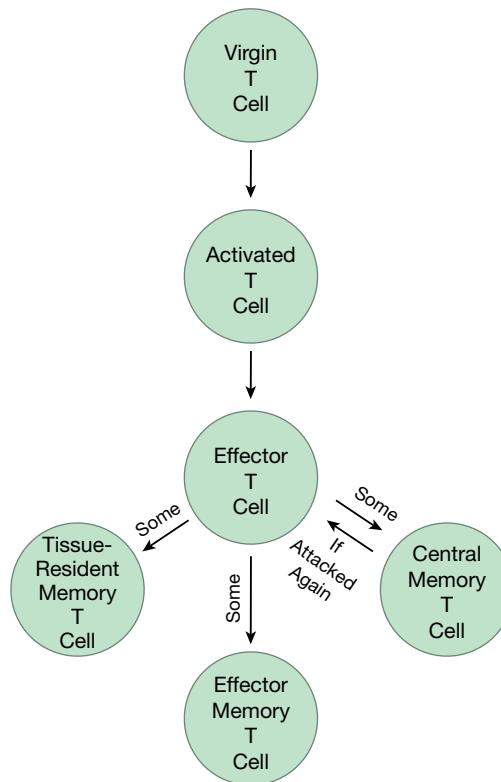
reinfection. That's the job of long-lived plasma B cells. And between attacks, readiness is maintained by central memory B cells. These memory cells replenish supplies of long-lived plasma cells, and also stand ready to respond to reinfection by quickly reactivating and producing large quantities of invader-specific antibodies.

B CELLS					
TYPE	FUNCTION	LIFETIME	CLASS SWITCH	SOMATIC HYPERMUTATION	WHERE RESIDE
Short-lived plasma (SLP)	Immediate antibody production	Days	Some	Limited	Secondary lymphoid organ
Upgraded B cells	Make high-affinity antibodies	Duration of infection	Most	Yes	Secondary lymphoid organ
Long-lived plasma (LLP)	Continuously produce antibodies	Months to years	Most	Most	Bone marrow/lymph
Central memory	Proliferate slowly Replace LLP Reactivate quickly	Years	Some	Limited	Secondary lymphoid organ

T cell memory

T cells also are able to remember a previous encounter with an invader. Although T cells can be activated either with or without assistance from helper T cells, only Th-dependent activation of T cells generates memory T cells.

T cell memory is similar, but not identical, to B cell memory. **After naive T cells have been activated in response to an initial attack and have proliferated to build up their numbers as much as 10,000-fold, many of them are given passports to travel out to the tissues to do battle with the enemy. These are the effector T cells.** After the attack has been repulsed, about 90% of the effector T cells die by apoptosis, but some of them, the **tissue-resident memory T cells**, remain in the tissues near the site of the original encounter with the pathogen. There they wait for a subsequent infection in which the same pathogen breaches the barrier defenses and enters the tissues. If reinfection occurs, they rapidly reactivate, proliferate, and begin to destroy the invaders they remember. **Other T cells that responded to the initial infection become effector memory T cells.** These cells circulate through the blood and lymph and are "on guard" in case there is a subsequent attack anywhere in the body. Finally, some memory T cells remain in the secondary lymphoid organs. These are the **central memory T cells**. During reinfection, central memory T cells activate quickly. After a brief period of proliferation, most mature into effector cells, which join effector memory T cells at the battle scene.



This three-pronged strategy works well. If invaders return to infect the same area of the body, the tissue-resident memory T cells are there to greet them. Effector memory cells, which are providing surveillance throughout the body, can be recruited as reinforcements by

tissue-resident memory cells, or they can mount a defense if the invaders return to attack a different part of the body. And central memory T cells are standing by in the secondary lymphoid organs to provide backup. Exactly how long each type of memory T cell persists after an attack probably depends on the pathogen which is attacking. However, it is known that T cell memory can last for years.

In this drawing, T cells are depicted as first becoming effector cells before some of them become memory cells. And most recent experiments suggest that this is true. However, there also are experiments which show that after they have been activated, T cells can “choose” to become memory cells – without ever becoming effector cells.

Th1, Th2, and Th17 cells, which function to turn on the immune system, have long memories. In contrast, iTreg cells, which turn the immune system off once the battle has been won, have very short memories. This is a good thing. Long-lived memory iTregs could keep the immune system “turned off,” preventing it from springing into action during a subsequent infection.

T CELLS

TYPE	FUNCTION	LIFETIME	WHERE RESIDE
Effector	Immediate protection	Days	Tissues
Tissue-resident memory	On-site for second attack	?	Tissues
Effector memory	Surveillance	Probably years	Blood and lymph
Central memory	Activate quickly in second attack Become effector cells	Years	Secondary lymphoid organ

PROPERTIES OF ADAPTIVE MEMORY CELLS

The adaptive immune system remembers specific invaders so well and reacts so powerfully during a subsequent infection that we usually don’t even know we have been reinfected. There are a number of reasons why memory cells are better able to deal with a second attack than were the inexperienced B and T cells which responded to the original invasion. First, there are many more of them. Indeed, when we are attacked for the first time, there is usually only about one B or T cell in a million which can recognize that invader. In contrast, by the time the battle is over, the memory pool of pathogen-specific cells will have expanded so that usually about one in a thousand of all the B or T cells

will recognize the attacker. Consequently, **the adaptive immune system’s response to a subsequent attack is much more robust than the initial response – in part because there are so many more invader-specific cells “on duty.”**

In addition to being more numerous than their inexperienced predecessors, **memory B and T cells are easier to activate.** For example, memory T cells can be activated by MHC-peptide concentrations that are as much as fifty-fold lower than those required to activate virgin T cells. Also, during the reactivation of memory cells, recognition of cognate antigen still is required, but at least in some cases, co-stimulation is not essential.

Now why would it be advantageous to have a system in which it is difficult to activate B and T cells the first time, but relatively easy to reactivate them? Clearly, we want activation of virgin cells to be tightly controlled – because we only want to engage the adaptive immune system when there is a real threat. Consequently, a fail-safe activation requirement for virgin B and T cells is important. On the other hand, once these cells have been through the stringent, two-key selection for primary activation, we want them to respond quickly to a subsequent attack by the same invader. So making it easier for them to be reactivated is a great idea.

There is a third reason why memory B cells are better defenders than are naive B cells: **Long-lived plasma B cells are “upgraded” versions of the original, virgin B cells.** These upgrades are of two types. First, **during the course of an attack, B cells can switch the class of antibody they make from the “compromise” antibody class, IgM, to one of the other classes (IgG, IgA, or IgE) which specializes in dealing with that particular kind of invader. This class switch is imprinted on the memory of the B cells that remain after an attack. As a result, long-lived plasma B cells are able to produce the antibody class which is just right to protect against the invader they remember.** Interestingly, B cells which have class switched to produce IgE antibodies seldom become memory cells. It is thought that this helps protect against long-lasting allergic reactions.

Also, **during an attack, B cells can use somatic hypermutation to fine-tune both their receptors and the antibodies they manufacture.** Long-lived plasma cells have usually undergone multiple rounds of somatic hypermutation. This results in upgraded B cells with receptors that can detect small amounts of foreign antigen early in a subsequent attack. Consequently, long-lived plasma cells are narrowly focused on the current invader. In contrast, the receptors of central memory B cells are not usually highly mutated. As a consequence, they can still produce a diverse collection of antibodies. This “breadth of focus” allows

central memory B cells to provide protection during future attacks by “variants” – pathogens that have undergone mutations which make them less recognizable by the antibodies produced by long-lived plasma cells. Moreover, when central memory B cells are reactivated in response to a subsequent attack, they can reenter germinal centers and undergo rounds of somatic hypermutation – which can focus their receptors on the mutated pathogen.

As you would expect, the gene expression profile of memory cells differs from that of naive cells or effector cells. Memory-specific gene expression is maintained by epigenetic modifications which can be “erased” when memory cells are reactivated in response to reinfection. Exactly how this is accomplished is unknown.

COMPARING B AND T CELL MEMORIES

B and T cell memories are similar in that both systems center around stem-cell-like central memory cells. These central memory cells reside in the secondary lymphoid organs, where they are strategically located to intercept invaders as they enter the body. Memory B and T cells are more potent weapons than are naive cells because there are more of them and because they are easier to activate than are virgin B and T cells.

Other aspects of B cell and T cell memory, however, are different. **B cells can fine-tune their receptors through somatic hypermutation. T cells cannot.** Moreover, **there is no T cell equivalent of the long-lived plasma B cell.** Once we have been exposed to a pathogen, long-lived plasma B cells continue to produce protective antibodies, sometimes for a lifetime. Consequently, **the weapons made by B cells (the antibody molecules) continue to be deployed even after an invasion has been repulsed.** This works well because antibodies are very specific and rather benign. Only when they tag an invader is the rest of the immune system alerted to take action. So if the invader they recognize doesn’t attack again, the antibodies produced by long-lived plasma B cells do nothing and cause no trouble.

In contrast, activated T cells produce cytokines and other chemicals that are nonspecific, and which can cause severe damage to normal tissues. Consequently, it would be very dangerous to have T cells remain in action once an invasion has been repulsed. So instead of continuing to function after the enemy has been defeated, as long-lived plasma cells do, tissue-resident memory T cells and effector memory T cells go “dormant.” If the attacker does not return, they cause no trouble. But if the enemy attacks again, these cells quickly reactivate and spring into action.

INNATE VERSUS ADAPTIVE MEMORY

Although both innate and adaptive immune systems remember, it is important to understand how these memories differ. **The innate system remembers invaders that its hard-wired receptors recognize. Consequently, the innate memory is a static memory: It is not updatable** – at least not on the time scale of a human lifetime. Although there will be slight genetic differences from person to person, **all humans have essentially the same innate memory**, which reflects the experience of the human race with common invaders that have been plaguing us for millions of years.

In contrast, **the adaptive immune system has an expandable memory that can remember any specific invader to which we have been exposed, be it common or rare.** Moreover, **the adaptive immune system’s memory is personal: Each of us has a different adaptive memory, depending on the particular invaders we have encountered during our lifetime.** Not only do we have different “lists” of invaders we have encountered, but even when two people have been attacked by the same microbe, their adaptive memories of that attack will be different – because the receptors on the collection of invader-specific B and T cells will differ from person to person. Indeed, because B and T cell receptors are made by a mix-and-match mechanism, no two humans will have the same adaptive memory.

REVIEW

Both the innate system and the adaptive systems are able to remember past invaders. The innate immune system’s memory is hard-wired, and depends on pattern-recognition receptors that have evolved over millions

of years to identify common invaders. These receptors recognize signatures which are shared by classes of invaders, and focus on molecular structures that are not easily mutated. In contrast, B and T cells of the adaptive immune

system have updatable memories which can remember the individual invaders we have encountered during our lifetimes, both common and rare. Consequently, adaptive memory is personal in the sense that every person has a different adaptive memory.

Memory B and T cells are better able to deal with a second attack because they are much more numerous than before the first invasion, and because they are more easily activated than are virgin B and T cells. Moreover, long-lived plasma B cells have receptors that have been fine-tuned by somatic hypermutation, and these memory cells usually have class switched to produce the type of antibody molecule which is most appropriate for the invader they remember. As a result of these upgrades, long-lived plasma B cells are more efficient at dealing with repeat offenders than were their virgin predecessors. After a first attack, long-lived plasma B cells, which reside in the bone marrow, continuously produce pathogen-specific antibodies which provide immediate protection if we are reinfected.

The pool of long-lived plasma cells is replenished by central memory B cells, which proliferate slowly in the

secondary lymphoid organs between invasions. If we are reinfected by the same pathogen, these central memory B cells quickly activate, proliferate, and produce large quantities of pathogen-specific antibodies.

Tissue-resident memory T cells remain at the scene of the original battle and wait to “pounce” if we are attacked again in the same area of the body. Meanwhile, effector memory T cells circulate through the blood and lymphatic systems, patrolling for invaders which might pay a return visit at a different site. And central memory T cells persist in the secondary lymphoid organs following an attack. These cells proliferate slowly to maintain a pool of invader-specific T cells. Central memory T cells can react quickly to a second attack by proliferating and maturing into effector T cells – which can travel to the site of the invasion, and destroy the enemy.

Some innate immune cells can be trained to respond more quickly and vigorously to a subsequent attack. This trained memory is the result of epigenetic reprogramming. In humans, trained immunity is usually nonspecific, local, and not very long-lasting.

KNOWN UNKNOWNS

1. How do B cells “decide” whether to become short-lived plasma cells, long-lived plasma cells, or central memory cells?
2. Where does class switching take place in secondary lymphoid organs? At the B cell–T cell boundary? Within the lymphoid follicles?
3. Do T cells first become effector cells and then stick around as memory cells, or do T cells “choose” to be either one or the other – a memory cell or an effector cell? Perhaps both are true?
4. Are trained NK cells important in defending against a human cytomegalovirus infection?

THOUGHT QUESTIONS

1. What are the basic differences between innate system memory and adaptive system memory?
2. What properties of memory B and T cells make them “better, stronger, faster” than the cells which responded to the initial infection?
3. Three kinds of memory T cells have been identified: central memory T cells, effector memory T cells, and tissue-resident memory T cells. What role does each type of memory T cell play, and why is it useful to have all three types?
4. What are the differences between the strategies B and T memory cells use to be sure we are “covered” against a future invasion by the pathogen they remember? Why are these differences important?
5. How does an innate cell’s trained immunity differ from T and B cell memory?
6. Why is it that some people appear to have a “good” immune system (i.e., they never get sick), whereas others seem to catch every bug that comes along? Asked another way: Which components of the immune system can differ between individuals?

The Intestinal Immune System

HEADS UP!

The intestines are home to trillions of bacteria, some of which “leak” into the surrounding tissues. If the intestinal immune system which protects these tissues reacts too strongly to these bacteria, intestinal disorders can result. On the other hand, if the immune response is too weak, there is the likelihood of a severe bacterial infection. How does the intestinal immune system know whether to respond gently or forcefully?

INTRODUCTION

Now we come to the fun part! Lectures 1–10 were meant to introduce you to basic immunological concepts. In the next seven lectures, we will review what you’ve learned by examining real-world examples of the immune system at work in health and disease. I think you’ll be amazed by how much you understand.

The gastrointestinal system and its role in human health is currently a hot topic in multiple disciplines. This is because it is recognized that many diseases, such as diabetes, allergies, obesity, some cancers, and inflammatory bowel disease (ulcerative colitis and Crohn’s disease), result, at least in part, from an imbalance in the number or type of microbes present in our intestines – or from the immune system’s misguided response to these microbes. The collection of all the microbes (bacteria, viruses, fungi, and parasites) that inhabit our intestines is called the **intestinal microbiota**. By far the most numerous constituents of the intestinal microbiota are the bacteria. Most of the research done to try to understand the interaction between the microbiota and the immune

system involves bacteria, so we will focus on these microbes in this lecture.

Our intestines are home to about 100 trillion bacteria of at least 1,000 different types. Most of these are **commensal bacteria** (from the Latin, meaning roughly “to eat at the same table”). Commensals are important for our digestion because they produce enzymes that can break down complex carbohydrates in the food we eat – carbohydrates which cannot be dismantled by enzymes made by human cells. Some commensal bacteria also produce vitamins that we require for survival. Moreover, because these “friendly” bacteria are so well adapted to live in our intestines, they help protect us from pathogenic bacteria by out-competing the bad guys for available resources and physical niches. In a sense, the commensals are our microbial “partners.”

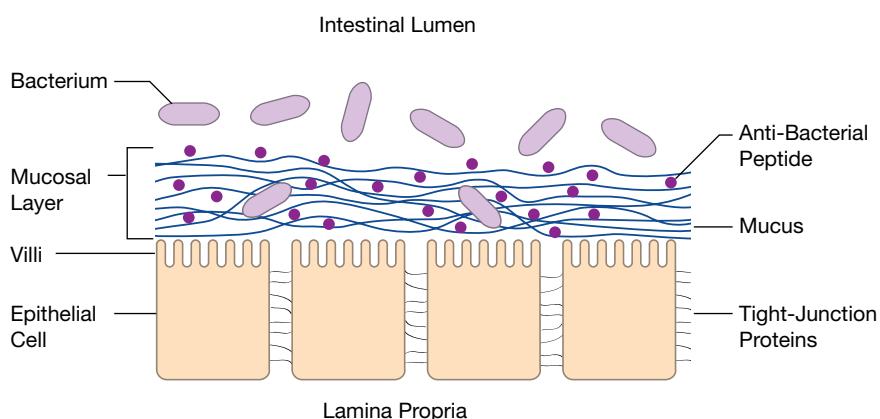
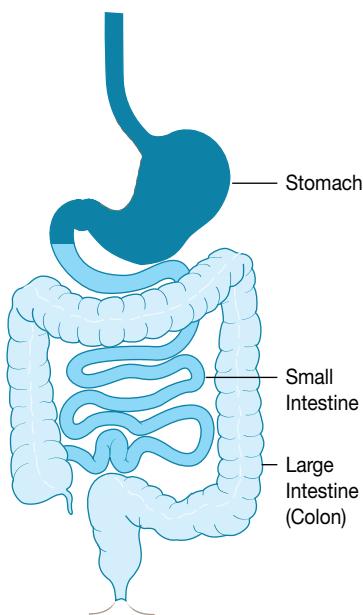
Although commensal bacteria can have a beneficial, symbiotic relationship with their human host, they also can pose a problem. The single layer of epithelial cells which separates them from the tissues that surround the intestines is so thin, its area so vast, and the bacteria so numerous that, even under normal conditions, some of the intestinal bacteria will breach this barrier and enter the tissues. In fact, the epithelial “barrier” actually inhibits, but does not prevent, microbes from entering the tissues that underlie the intestines.

This situation poses a real dilemma. If the intestinal immune system were to react too strongly to commensals, the tissues surrounding your intestines would be in a constant state of inflammation – which would cause diarrhea and all sorts of other problems. However, if these errant commensal bacteria were simply ignored, they might enter the blood stream and cause a life-threatening systemic infection. So **the intestinal immune system cannot just ignore commensal bacteria**. Moreover, pathogenic bacteria, which are not so friendly, also can breach the

intestinal barrier. In those situations, the immune system must respond appropriately against these dangerous invaders. What this means is that the intestinal immune system has a unique challenge: **It must deal gently with intestinal bacteria that are not inherently dangerous, but harshly with those bacteria which can do us serious harm.** How the immune system tells friend from foe and avoids over-reaction is currently the subject of intense investigation.

INTESTINAL ARCHITECTURE

To appreciate what the intestinal immune system is up against, we need to have a clear picture of the digestive system and how it works. It is important to note that topologically, our gastrointestinal tract is actually part of the “outside environment.” It is essentially a tube that runs through our body from “top to bottom.” Here is a schematic representation which shows the basic layout.



Most of the action, so far as the immune system is concerned, takes place below the stomach in the **small intestine** and the **large intestine (colon)**. The primary function of the small intestine is digestion, and the requirement for absorption of nutrients dictates that it must have a large area. Indeed, the small intestine of a human is about six meters in length, and its epithelial surface includes millions of finger-like projections called **villi**, which expand the total surface area of the small intestine to nearly 200 square meters. In contrast, the large intestine is only about 1.5 meters long, has no villi, and plays almost no role in digestion. Its primary function is the absorption of water and salt from the intestinal contents. Importantly, the large intestine is home to the vast majority of the commensal bacteria that inhabit the digestive tract.

A single layer of epithelial cells surrounds the **lumen** (i.e., the inside) of both large and small intestines. These cells stand shoulder-to-shoulder, are joined together by tight-junction proteins, and are coated with protective **mucus** which is generated by goblet cells that are part of the epithelium. The epithelial cell layer is renewed every four or five days, and it separates the contents of the intestines from the tissues that surround the intestines called the **lamina propria**.

In the small intestine there is just a single layer of protective mucus, and it is rather porous – which is important for the efficient uptake of nutrients. Fortunately, the food and bacteria we ingest move rapidly through the small intestine, so bacteria have to work fast if they are going to get a foothold there. Moreover, the mucus is rich in antibacterial proteins such as lysozyme, which are secreted by cells in the epithelium, and which can attack the membranes that surround some bacteria. Here is a diagram that shows important features of the small intestine.

The epithelium of the large intestine is protected by two layers of mucus. The inner layer is firmly attached to the epithelium, and is rather like a pad of steel wool. This layer of mucus is relatively bacteria-free and is rich in antimicrobial peptides (e.g., α -defensins). On top of this dense inner pad is another layer of mucus which, like the single layer in the small intestine, is less dense and more like a slimy net.

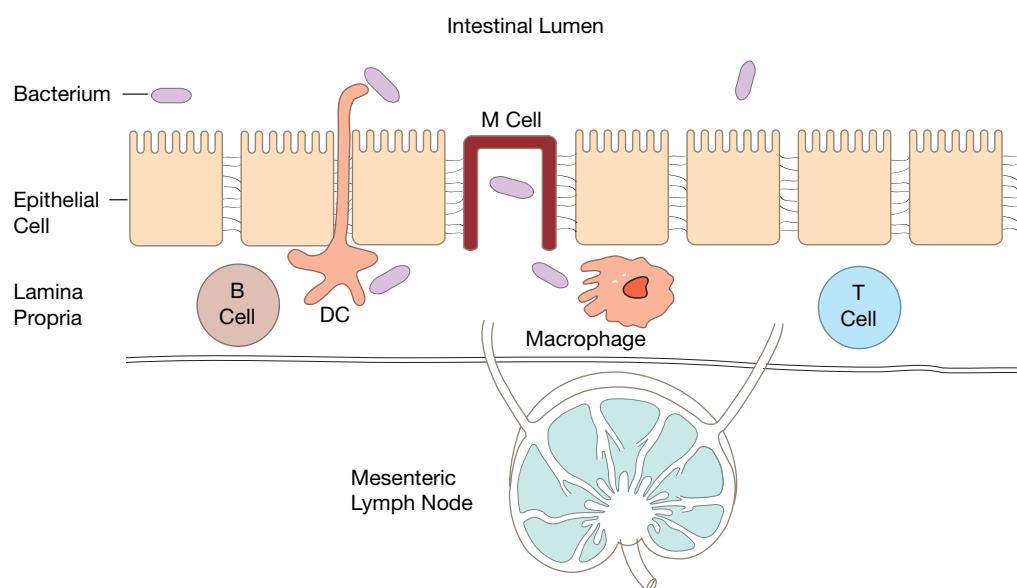
The intestinal mucus has several important functions. It acts as a diffusion barrier which denies most of the bacteria in the lumen access to the epithelium. The mucus also concentrates antimicrobial proteins near the epithelial surface – antimicrobials which can destroy bacteria that might try to breach this barrier. These features are important because **intestinal infections usually begin when invaders adhere to the epithelial cells that line the intestine**. The goblet cells which produce the mucus are hard workers, and the mucus is replaced in a matter of hours. As a consequence, bacteria that are trapped in the mucus are rapidly shown out the “back door” – if you know what I mean.

The mucin proteins that make up the mucus are highly glycosylated. Commensal bacteria feast on these attached carbohydrates, and convert them into short-chain fatty acids such as butyrate and acetate. These molecules easily diffuse through the mucus, and provide an important energy source for the cells of the epithelium.

CHALLENGES FACED BY THE INTESTINAL IMMUNE SYSTEM

Now that we have an understanding of the architecture of the intestines, we can discuss how the immune system deals with bacteria which “wander” out of the intestinal lumen and into the tissues. One of the defining characteristics of commensal bacteria is that although they may adhere to the epithelium, they do not actively cross this intestinal barrier. Nevertheless, commensals do make their way into the lamina propria as a result of small breaks in the epithelial barrier (no barrier is perfect), and this happens almost continuously. Moreover, after they adhere to the epithelium, some pathogenic bacteria produce virulence factors which allow them to cross the barrier and enter the lamina propria. So the picture you should have is that **the intestinal immune system is under constant attack by bacteria and other invaders**.

Commensal or pathogenic bacteria which breach the epithelial barrier are usually intercepted by resident macrophages – the most abundant immune system cell in the lamina propria. Invading bacteria can also be transported to nearby mesenteric lymph nodes by the lymphatic vessels that drain the lamina propria. And during an intestinal invasion, dendritic cells which reside in the tissues that surround the intestines can travel via the lymphatic route to mesenteric lymph nodes. There they can activate T cells which are specific for the invader.



Now if this were all there was to the intestinal immune system, we'd be in big trouble. Commensals are continually breaching the epithelial barrier, so our intestines would be in a state of constant war. Instead of that single splinter in your big toe, this situation would be the rough equivalent of having bacteria-laden splinters piercing the skin all over your body, all the time. It would be awful – and lethal!

RESPONDING GENTLY TO LIMITED THREATS

Clearly, there must be special features of the intestinal immune system which are different from the “systemic” immune system that protects the rest of our body. Let's see what they might be.

An anti-inflammatory environment

In contrast to the systemic immune system, where inflammation is the game, the “default option” for the intestinal immune system is anti-inflammatory. Indeed, under normal conditions, the environment surrounding the intestines is heavily biased toward producing a gentle reaction. In Lecture 8, we discussed inducible regulatory T cells – special Th cells whose job is to limit inflammation. It turns out that the lamina propria is home to a large number of these cells. The reason for this is that healthy intestinal epithelial cells produce TGF β , a cytokine which encourages Th cells that are activated in the intestinal environment to become iTregs. These T cells then give off cytokines such as TGF β and IL-10, which help “calm down” the mucosal immune system. In addition, many CTLA-4 checkpoint proteins are expressed on the surface of iTreg cells. These CTLA-4 proteins can bind to the B7 proteins on antigen presenting cells in the lamina propria, thereby decreasing the APC's ability to activate effector T cells.

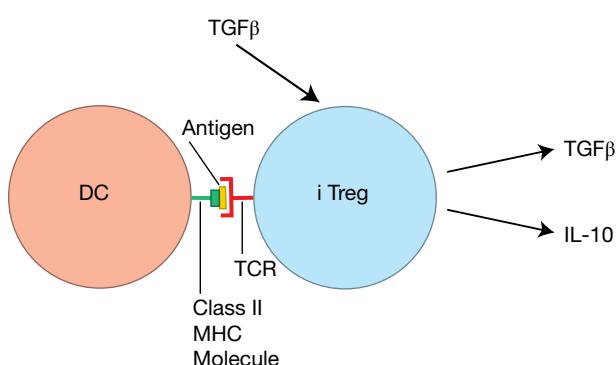
In some cases, commensal bacteria contribute directly to help maintain the normally immunosuppressive environment of the lamina propria. For example, as part of their normal metabolism, some commensal bacteria produce butyrate. This short-chain fatty acid influences Th cells in the lamina propria to become regulatory T cells, which secrete “calming” cytokines. Likewise, *Bacteroides fragilis*, a commensal bacterium, produces a molecule called polysaccharide A. When Toll-like receptors on helper T cells in the lamina propria detect this polysaccharide, those T cells are instructed to produce IL-10, which dampens inflammation. *Bifidobacterium* is a commensal which is a common constituent of the probiotics many people take to “promote intestinal health.” When the Toll-like receptors of intestinal dendritic cells detect the presence of *Bifidobacterium breve*, those DCs produce IL-10 to calm the intestines.

Non-inflammatory macrophages

In response to an infection, the normal job of a macrophage is to cause inflammation. For instance, when the tissues beneath the skin are infected by bacteria, macrophages not only phagocytose these invaders, they also secrete cytokines which alert other immune warriors, and summon neutrophils from the blood to join in the battle. The result is inflamed tissues at the site of the invasion. Fortunately, the IL-10 produced by iTregs in the lamina propria encourages macrophages that patrol this area to be “non-inflammatory.” What this means is that although these macrophages continue to be highly phagocytic, they don't give off cytokines which would signal a full-blown attack and cause inflammation. In addition, the butyrate produced by commensal bacteria influences lamina propria macrophages to increase their production of antimicrobial peptides, which can kill bacteria without causing inflammation. The result is that **non-inflammatory macrophages can deal gently either with the small number of commensals which continually “leak” from the intestines into the lamina propria or with a small attack by pathogenic bacteria.**

IgA antibodies

IgA is the major antibody class produced by B cells in the lamina propria. In fact, **IgA is an antibody which evolved especially for the protection of mucosal surfaces.** This antibody class helps protect us against bacteria, viruses, and toxins. Some of the IgA antibodies produced by lamina propria B cells are transported through the epithelial cells (are transcytosed) and are released into the lumen of the intestines. This “secretory” IgA binds to microbes there and prevents them from adhering to the epithelial cells that line the intestine. Indeed, most bacteria in the colon are coated with IgA antibodies. And because the



intestinal mucus is renewed frequently, clumps of IgA-bound microbes can be rapidly eliminated with the feces. So **the main task of secretory IgA is exclusion.**

In addition to helping prevent luminal bacteria from crossing the epithelial barrier, IgA antibodies made by lamina propria B cells can also intercept invaders once they have breached the intestinal barrier and have entered the lamina propria. **IgA antibodies in the lamina propria can bind to invaders, transcytose epithelial cells with their cargo, and usher the intruders back out into the intestine for disposal. Importantly, secretory IgA does not cause inflammation.** This is because the Fc portion of this antibody cannot bind to receptors on immune system cells to trigger an inflammatory response – as IgG antibodies would do. Consequently, **IgA antibodies can deal gently with intestinal invaders without causing inflammation.**

It is not entirely clear how B cells in the lamina propria are influenced to make the IgA class of antibodies, and not, for example, IgG antibodies. Vitamin A in our diet is absorbed by intestinal epithelial cells and converted to retinol. Dendritic cells and macrophages then convert this to retinoic acid, which is secreted into the lamina propria. It is known that retinoic acid produced by intestinal dendritic cells can drive IgA production, and retinoic acid also imprints IgA-secreting plasma B cells with an “intestinal identity,” so that they travel back to the tissues which surround the intestines.

Usually, class switching requires the help of Th cells. This assistance involves the ligation of CD40 on the B cell surface by CD40L on the surface of a helper T cell. However, it has been discovered that in response to some pathogens, B cells of the intestinal immune system can actually switch to the production of IgA antibodies without T cell help. There is still a lot of mystery surrounding IgA-producing lamina propria B cells.

A distributed response

The systemic immune system is designed to respond locally. For example, if you have a splinter in your big toe, B and T cells activated in the lymph nodes that drain the toe will recirculate through the lymph and blood, and exit the blood stream where the battle is being waged in your toe. After all, these weapons are specific for the particular invader that has attacked your big toe today, so it wouldn't be useful to send them to your calf – or even to your little toe. There is nothing going on there. The intestinal immune response is quite different. Although B and T cells might be activated in response to bacteria that entered the lamina propria one meter down in your small intestine, those lymphocytes don't return just to that spot. In fact, they are

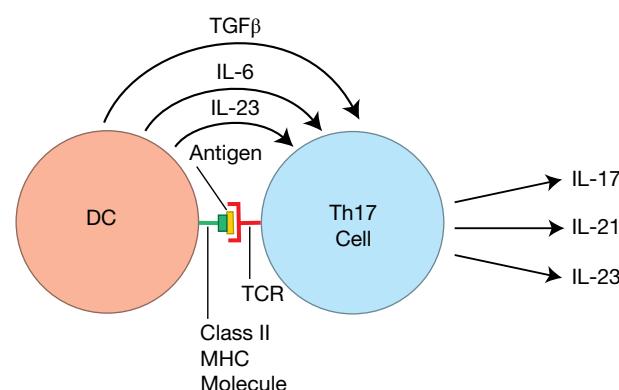
distributed throughout the lamina propria. Why is this, you may ask? Doesn't that seem wasteful?

The answer is that whereas the splinter piercing your toe is a rare event, invasions by the resident bacteria in your intestines are continual. Moreover, although the types of commensals do vary as one goes from the top of the small intestine to the anus, the same commensals are present over long stretches of the intestines. Consequently, **a distributed response, in which B and T cells specific for intestinal invaders are stationed throughout the lamina propria, makes sense.** This distributed response has another important feature. In the big toe example, it takes some time to mobilize the troops that are specific for that invader, and to deliver them to the battlefield. In contrast, **the intestinal immune system is “prepared in advance” to deal with common invaders because lymphocytes and IgA antibodies are already “on site.” The result is a lightning fast response that can deal with attackers before they can multiply in the tissues, thereby limiting the amount of inflammation.**

THE INTESTINAL IMMUNE SYSTEM'S RESPONSE TO PATHOGENS

Okay, so the intestinal immune system is set up to provide a gentle response to commensal bacteria and to small numbers of pathogens. However, in large numbers, both commensals and pathogenic bacteria can cause damaging infections. So how does the intestinal immune system deal with these dangerous situations?

In response to serious attacks, Th1 cells can be activated. These helper cells encourage the production of IgG antibodies, and Th1 cells secrete cytokines such as IFN- γ which enhance the killing power of lamina propria macrophages. Also, when helper T cells are activated in an environment that is rich in TGF β and IL-6 or TGF β and IL-23, these cells are influenced to become Th17 cells – helper T cells which play an important role in the intestinal immune defense against dangerous attacks.



Th17 cells are highly inflammatory. The “signature cytokine” they produce, IL-17, recruits huge numbers of neutrophils from the blood stream – warriors which are just the ticket for dealing with a dangerous bacterial invasion. Cytokines secreted by Th17 cells also function to increase the effectiveness of the intestinal barrier by strengthening the tight junctions between epithelial cells. In addition, Th17 cytokines stimulate antimicrobial peptide and mucus production by intestinal epithelial cells, and act to facilitate the transcytosis of IgA antibodies and their cargo out into the intestinal lumen.

Another important feature of the intestinal immune system is that it is designed to function independently of the immune system in the rest of the body. Dendritic cells that are activated in the lamina propria travel to the mesenteric lymph nodes that drain the intestinal tissues – but they do not travel any farther along the chain of lymph nodes. In addition, B and T cells activated in the mesenteric lymph nodes have strict instructions to take up residence in the lamina propria. They do not enter the normal traffic pattern of circulating lymphocytes, which would carry them to other parts of the body. So the intestinal immune system is a “private” system. What happens in the intestinal immune system usually stays in the intestinal immune system.

HOW TO RESPOND?

So the intestinal immune system can respond gently to attacks that are not serious, and it also has the tools to deal harshly with dangerous pathogens that invade via the digestive tract. But how does the intestinal immune system know to react gently to small doses of commensals or pathogens, and vigorously when there is real danger? This is the central question that immunologists who study the intestinal immune system are asking.

TGF β is a cytokine that drives helper T cells to become iTregs – which are anti-inflammatory. However, TGF β also is one of the cytokines that causes naive Th cells to become Th17 cells – cells which are skilled at orchestrating an inflammatory response to a bacterial or fungal invasion. So how does the immune system decide whether Th cells should become iTregs, and restrain the immune response, or become Th17 cells, and “let the dogs out”? The complete answer is unknown. However, as you might predict, **dendritic cells in the lamina propria are thought to play a critical role in maintaining the proper balance between a gentle or an inflammatory response.**

Dendritic cells in the Peyer’s patches of the small intestine intercept luminal antigens which have been delivered into the lamina propria by transcytosis through the M cells that crown these patches. In addition, some lamina propria DCs can extend their dendrites between the epithelial cells to make direct contact with antigens in the intestinal lumen. Using this mechanism, **DCs deliberately and continuously sample what is going on in the intestines, and use this information to decide on an appropriate course of action.**

Dendritic cells are equipped with pattern-recognition receptors that can recognize bacterial signatures. For example, some of the most pathogenic intestinal bacteria (e.g., *Salmonella*) are equipped with flagella, which help them “swim” through the mucus so they can access the intestinal epithelium. The flagellin protein, from which flagella are constructed, can be detected as a danger signal by pattern-recognition receptors called TLR5 on the surface of intestinal dendritic cells. And when their pattern-recognition receptors detect flagellin, DCs begin to produce IL-6, which instructs Th cells to become Th17 cells.

So, if there is no real danger, and things just need to be kept calm, lamina propria DCs don’t produce IL-6, and naive Th cells – under the influence of tissue-produced TGF β – become iTregs. On the other hand, if there is an invasion of pathogenic bacteria that have flagella, dendritic cells produce IL-6, which causes helper T cells to commit to becoming Th17 cells. One important feature of this iTreg to Th17 “switch” is that iTregs are very short lived. Consequently, the switch from suppression to defense can be made quickly.

It is important to note, however, that **commensals and pathogenic bacteria share many of the same molecular features, so in most cases, it is not clear how dendritic cells distinguish between pathogenic and commensal bacteria.** It may be that pathogens and commensals trigger different combinations of pattern-recognition receptors, leading to different outcomes. It also may turn out that the response to pathogens and commensals frequently is the same, and that the decision to respond gently or violently depends on the size of the invasion. In any case, **how the intestinal immune system determines the appropriate response to intestinal invaders is one of the most important unsolved mysteries in immunology.** Roughly 1.5 million Americans suffer from Crohn’s disease or ulcerative colitis – conditions that are thought to result from an inappropriate inflammatory response to commensal bacteria. It is hoped that a better understanding of the intestinal immune system’s decision-making process, and how these decisions are implemented, may lead to improved treatments, or even a cure, for these diseases.

REVIEW

Trillions of intestinal bacteria are separated from the tissues that surround the intestines by a single layer of epithelial cells covered with mucus. Most of these bacteria are commensal bacteria that have evolved a mutually beneficial relationship with their human host. However, there are also pathogenic bacteria which inhabit the intestines, and these can do us serious harm. Both types of bacteria can breach the epithelial barrier, and both must be dealt with by the intestinal immune system.

A variety of immune system defenders, including macrophages, dendritic cells, and lymphocytes, are found beneath the intestinal epithelium in the lamina propria. Under normal conditions, only small numbers of bacteria leak from the intestines into the lamina propria, and the immune warriors there operate in an environment which encourages them to deal gently with invaders. “Non-inflammatory” macrophages in the lamina propria are highly phagocytic, but they do not normally secrete battle cytokines which would “stir up” a full-blown inflammatory response. B cells in the lamina propria specialize in producing IgA antibodies, which deal passively with invaders by “quietly” transporting them back out into the intestines to be eliminated with the feces. In addition, healthy intestinal epithelial cells produce cytokines which help keep the intestinal immune system relatively

calm. These cytokines can induce helper T cells to become regulatory T cells – cells which produce cytokines that have a soothing effect on the immune warriors stationed in the lamina propria.

Dendritic cells in the lamina propria continuously evaluate the danger posed by current invaders. If there is a serious breach of the epithelial barrier, the intestinal immune system can switch rapidly from a gentle response to an aggressive reaction. Alerted dendritic cells can instruct helper T cells to become Th1 or Th17 cells. These helper T cells then orchestrate an inflammatory response in which formerly non-inflammatory macrophages become “angry,” and neutrophils are recruited from the blood to engage invaders in hand-to-hand combat. Although some pathogenic bacteria may have unique signatures that alert the intestinal immune system to danger, commensal bacteria and pathogenic bacteria share many of the same molecular features.

The weapons of the intestinal immune system are deployed over large areas of the intestines. Because of this distributed response, the intestinal immune system is prepared to deal rapidly with common invaders before they can proliferate to build up their numbers. On the other hand, the intestinal immune system is “private”: Intestinal attacks are normally dealt with locally without spilling over into the rest of the body.

KNOWN UNKNOWNS

- 1.** How does the intestinal immune system differentiate between infections that can be dealt with gently and serious infections that must be dealt with harshly?
- 2.** What are the mechanisms by which most B cells in the intestinal lamina propria are encouraged to produce IgA antibodies?
- 3.** How do Th cells in the lamina propria know to switch from being iTregs to being Th17 cells when there is an attack?

THOUGHT QUESTIONS

- 1.** Discuss several ways in which the intestinal immune system differs from the systemic immune system that protects other areas of the body.
- 2.** What special features of the immune system in the tissues which surround the intestines help avoid an overreaction to commensal bacteria?
- 3.** Why are IgA antibodies called “passive” antibodies?
- 4.** Why are inducible regulatory T cells (iTregs) important, and how do they function?
- 5.** If you were “designing” the intestinal immune system, how would YOU equip it to tell friend from foe? The correct answer to this question might win you a Nobel Prize!

The Immune System Gone Wrong

HEADS UP!

Most of the time, the immune system functions flawlessly, but occasionally it “makes mistakes.” In some situations, the immune system may mobilize weapons which are not appropriate for the situation. And in rare instances, the immune system may mistake friend for foe, and attack our own bodies.

INTRODUCTION

Thus far, we have focused on the good that the immune system does in protecting us from disease. Occasionally, however, the immune system “goes wrong” – sometimes with devastating consequences. In this lecture we will examine several situations in which the immune system plays a major role in producing the damaging effects (the pathology) of a disease.

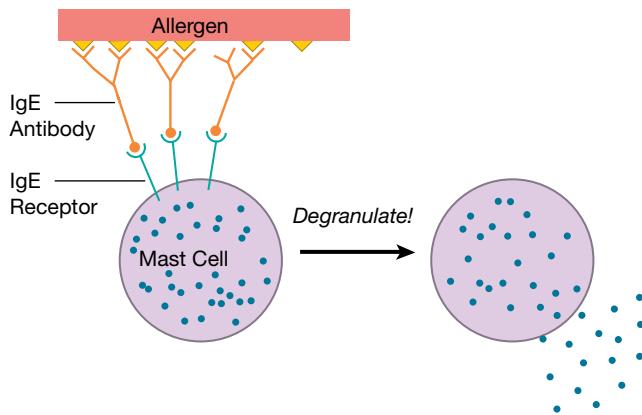
DISEASES CAUSED BY DEFECTS IN IMMUNE REGULATION

Roughly a quarter of the U.S. population suffer from **allergies** to common environmental antigens (**allergens**) that are either inhaled or ingested. Hay fever and asthma are the two most common allergic diseases of the respiratory tract. Hay fever is caused by proteins that are derived from mold spores or plant pollens. These allergens are present in the outside air, usually at certain times of the year. In contrast, the allergens that cause asthma are mostly found indoors. Dust mites, cockroaches, rodents, and household pets are major sources

of these allergy-causing proteins. In addition to allergies caused by allergens in the air we breathe, the food we eat can also cause allergies.

The immune systems of non-allergic people respond weakly to these allergens, and produce mainly antibodies of the IgG class. In striking contrast, people with allergies (called **atopic individuals**) produce large quantities of IgE antibodies. Indeed, the concentration of IgE antibodies in the blood of those with allergies can be 1,000- to 10,000-fold higher than that in the blood of non-atopic people! **It is the overproduction of IgE antibodies in response to otherwise innocuous environmental antigens that causes allergies.**

In Lecture 3, we discussed the interaction of IgE antibodies with white blood cells called **mast cells**. Because mast cell degranulation is a central event in many allergic reactions, let’s take a moment to review this concept. When atopic individuals are first exposed to an allergen (e.g., pollen) they produce large amounts of IgE antibodies which recognize that allergen. Mast cells have receptors on their surface that can bind to the Fc region of IgE antibodies. Consequently, after the initial exposure, mast cells will have many of these allergen-specific IgE molecules attached to their surface. Allergens are small proteins with a repeating structure to which the antigen binding region of IgE antibodies can bind close together. So on a second or subsequent exposure, an allergen can crosslink the IgE molecules that are bound to the mast cell surface, dragging the mast cell’s receptors together. This clustering of IgE receptors tells mast cells to **degranulate**: to release their granules, which are normally stored safely inside the mast cells, into the tissues in which they reside. Mast cell granules contain histamine and other powerful chemicals and enzymes that can cause the symptoms with which atopic individuals are intimately familiar.



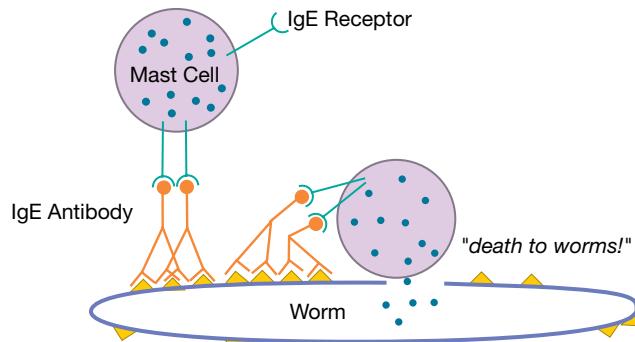
Interestingly, although IgE antibodies have a half-life of only about two days in the blood, once they are attached to mast cells, they have a half-life of weeks to months. This means that mast cells can stay “armed” and ready to degranulate for an extended period after exposure to an allergen.

Allergic reactions generally have two phases: immediate and delayed. The immediate reaction to an allergen is the work of mast cells, which are stationed out in the tissues, and **basophils**, another granule-containing white blood cell, which can be recruited from the blood by signals given off by mast cells responding to an allergen. Like mast cells, basophils have receptors for IgE antibodies, and crosslinking of these receptors can lead to basophil degranulation.

Although mast cells and basophils are responsible for the immediate reaction to an allergen, a third granule-containing white blood cell, the **eosinophil**, is usually the prominent player in chronic allergic reactions (e.g., in asthma). Before an “attack” by an allergen, there are relatively few eosinophils present in the tissues or circulating in the blood. However, once an allergic reaction has begun, helper T cells secrete cytokines such as IL-5, which can recruit many more eosinophils from the bone marrow. These eosinophils can then add their “weight” to the allergic reaction. Because eosinophils must be mobilized from the marrow, their contribution is delayed relative to that of mast cells and basophils, which can respond almost immediately.

Of course, mast cells and basophils did not evolve just to annoy atopic people. These cells, with their ability to degranulate “on command,” provide a defense against parasites (e.g., worms) that are too large to be phagocytosed by professional phagocytes. In a sense, IgE antibodies act as a guidance system for these cells, targeting their weapons to the enemy. For example, by discharging their

destructive chemicals directly onto the skin (tegument) of a parasite to which IgE antibodies have bound, mast cells can destroy these massive creatures.



What makes this defense so elegant is that in response to a parasitic infection, parasite-specific IgE antibodies are made, and mast cells and basophils are armed. However, degranulation does not take place unless these armed cells come in contact with a parasite that can cluster their IgE receptors. Consequently, you don’t get uncontrolled degranulation, wreaking havoc throughout your body. Rather, the IgE guidance system allows mast cells to zero in on parasites, causing relatively little collateral damage to our tissues.

Why do some people have allergies?

It is clear that IgE antibodies are the bad guys in allergic reactions, but what determines whether a person will make IgE or IgG antibodies in response to an allergen? You remember from Lecture 6 that helper T cells can be “instructed” by the environment in which they are stimulated to secrete various cytokine subsets (e.g., Th1, Th2, or Th17). And the cytokines given off by these T cells can then influence B cells undergoing class switching to produce IgA, IgG, or IgE antibodies. For example, a germinal center that is populated with Th1 cells usually will produce B cells that make IgG antibodies, because Th1 cells secrete IFN- γ , which drives the IgG class switch. In contrast, B cells tend to change to IgE production if class switching takes place in germinal centers which contain Th2 cells that secrete IL-4 and IL-5. Consequently, **the decision to produce either IgG or IgE antibodies in response to an allergen will depend heavily on the type of helper T cells present in the secondary lymphoid organ which intercepts the allergen**. Indeed, helper T cells from allergic individuals show a much stronger bias toward the Th2 type than do Th cells from non-atopic people.

The hygiene hypothesis

So **atopic individuals produce IgE antibodies because their allergen-specific helper T cells tend to be of the Th2 type.** But how do they get that way? The answer to this important question is not known for certain, but many immunologists believe that a bias toward Th2-type helper T cells can be established early in childhood, and in some cases, even before birth. Here's how this is thought to work.

A fetus inherits roughly half of its genetic material from its mother and half from its father. As a result, the fetus is really a "transplant" that expresses many paternal antigens to which the mother's immune system is not tolerant. Since the placenta is the interface between the mother and the fetus, measures must be taken to avoid having maternal CTLs and NK cells attack the placenta because it expresses these paternal antigens. The Th1 subset of helper cells secretes TNF, which helps activate NK cells, and Th1 cells also produce IL-2, which causes NK cells and CTLs to proliferate. So it would be advantageous for the survival of the fetus to bias maternal Th cells away from the Th1 cytokine profile. Indeed, cells of the placenta produce relatively large amounts of IL-4, which influences maternal helper T cells to become Th2 cells. Importantly, these same placental cytokines also have a strong influence on fetal helper T cells. As a result, most humans are born with helper T cells that are strongly biased toward making Th2 cytokines – cytokines which can encourage B cells to produce IgE rather than IgG antibodies.

Obviously this bias does not last a lifetime, and eventually most people end up with a more balanced population of Th1 and Th2 cells. One event that probably helps establish this balance is infection at an early age with microbes (e.g., viruses or bacteria) that normally elicit a Th1 response. Indeed, it is suspected that early microbial infections may be important in "reprogramming" a child's immune system so that a Th1 response to allergens results. Immunologists hypothesize that if a microbial infection strongly biases the immune response toward a Th1 type at the same time that the child encounters an allergen (say, a dust mite protein), the Th response to that allergen also will be deviated toward the Th1 type. Once this deviation takes place, feedback mechanisms tend to lock in the Th1 bias, and memory T cells will be generated that remember not only the allergen, but also their Th1 response to it. Once a large number of biased memory cells is built up, it is difficult to reverse this bias, so early exposure to infectious diseases may be critical in establishing a normal reaction to environmental allergens. Said another way, **the early-life "education" of the immune**

system may have a large impact on the health of an individual later in life.

The idea that childhood microbial infections or early exposure to allergens might be important in biasing our immune systems toward producing Th1 helper T cells in response to environmental allergens is called the **hygiene hypothesis**. Indeed, in Western countries, where improved personal hygiene has led to a decrease in childhood infections, and where exposure to certain allergens early in life is less frequent, the incidence of allergies to environmental allergens has increased dramatically. Some of the best data in support of the hygiene hypothesis comes from studies of families living on traditional farms. These studies have shown that children who have contact with farm animals have a significantly lower incidence of asthma and hay fever than do children from rural areas who do not live on a farm. This effect is even more pronounced if their mothers come in contact with multiple animal species and animal feed (such as hay and grain) during their pregnancy. Interestingly, the timing of exposure to animals and their feed seems to be important, with the greatest protection being observed for children who live on a farm during the first few years of life. In this regard, it is important to note that living on a farm is not "unusual" as far as the human immune system is concerned. After all, until recently, many of our ancestors lived in close contact with farm animals, and it is likely that the immune system evolved to function best – at least in terms of allergies – in that setting.

Although immunologists call it the "hygiene hypothesis," it actually should be called the "lifestyle hypothesis" – because the increased incidence of allergies is likely due to a change in lifestyle, not just to improved hygiene. For example, prior to the 1950s, when televisions became commonplace in the United States, most children came home from school and went outdoors to play. Things are very different now, with many young children spending long hours indoors playing video games or staring at a television.

After World War II, it became customary for childhood illnesses to be treated with antibiotics, which can destroy intestinal bacteria that may be helpful in setting up a balanced immune system. It is known that the composition of the intestinal microbiota – the collection of bacteria, viruses, fungi, and parasites which inhabit the intestines – develops during the first three or four years of a child's life. After that, the microbiota becomes stable and tends to persist through adulthood. So the early years are particularly vulnerable to events such as infections, antibiotic treatments, and fevers which could alter the

composition of the microbiota – and these changes could influence how the immune system responds to allergens. Indeed, studies show an increased risk of asthma in children who had been treated with multiple courses of antibiotics during their first year of life.

Heredity

In addition to environmental factors (e.g., early exposure to infectious diseases or environmental allergens), heredity clearly plays a large part in susceptibility to allergies. Indeed, if one identical twin suffers from allergies, the probability is about 50% that the second twin will also be atopic. Immunologists have noticed that people who are allergic to some allergens are more likely to have inherited certain versions of the class II MHC genes than are non-atopic people, suggesting that these particular MHC molecules may be especially efficient at presenting these allergens. Also, some atopic individuals produce mutant forms of the IgE receptor. It is hypothesized that these mutant receptors may send an unusually strong signal when crosslinked, resulting in secretion of abnormally high levels of IL-4 by mast cells – which favor the production of IgE antibodies. Unfortunately, mutations in genes that confer susceptibility to allergies have been difficult to identify – because there seem to be many of them, and because they usually differ from atopic individual to atopic individual.

The best current synthesis of this information is that **the immunological basis for allergies is a defect in immune regulation in which allergen-specific helper T cells are strongly polarized toward a Th2 cytokine profile, resulting in the production of allergen-specific IgE antibodies. The genes a person inherits can make him more or less susceptible to allergies, and exposure to environmental factors such as microbial infections may influence whether susceptible individuals become atopic.**

While many Americans may curse IgE antibodies, people in much of the rest of the world depend heavily on these antibodies to defend them against parasites. Parasitic worms still infect roughly a third of the human population.

Treatments for allergies

Although not a cure, treatment with glucocorticoid steroids can decrease allergy symptoms by blocking cytokine production by helper T cells. As a result, fewer B cells are activated (because they do not get the help they need), and the total number of antibodies made is reduced. Steroids, however, are not specific for allergies, and steroid treatment decreases the number of activated B cells of all kinds. Consequently, taking glucocorticoid

steroids for extended periods can result in increased susceptibility to infectious diseases. Recently, immunologists have produced monoclonal antibodies (e.g., omalizumab) which can grasp the Fc region of IgE antibodies and block the binding of these antibodies to mast cells. Treatment with these antibodies is quite effective in relieving allergic symptoms and decreasing the severity of asthma attacks.

So far, only one approach, **specific immunotherapy**, has been successful in curing allergies. Specific immunotherapy involves the injection of gradually increasing doses of a crude extract containing allergens until a maintenance dose is achieved. After several years of regular injections, some patients become tolerant to the allergen (or allergens) in the extract. The immediate result of these injections is that mast cells become more difficult to activate in response to IgE binding. Then, over time, these injections encourage allergen-specific B cells to switch their antibody class from IgE to one of the other antibody classes. Indeed, during specific immunotherapy, the ratio of IgG to IgE antibodies specific for the allergen being administered can increase 10- to 100-fold. Unfortunately, the mechanisms by which this immune deviation is achieved are not well understood. The latest thinking is that repeated injections of allergen extracts may generate inducible regulatory T cells which produce IL-10 and TGF β – cytokines which are known to bias antibody production away from IgE and toward IgG or IgA. Indeed, in individuals who are not atopic, iTregs represent the majority of CD4 $^{+}$ T cells that are specific for common environmental allergens. This view is also supported by the finding that beekeepers, who receive repetitive doses of bee venom (because they are stung frequently), do not suffer severe allergic reactions when stung by bees, and have elevated levels of IL-10.

AUTOIMMUNE DISEASE

The human immune system does not expend a huge amount of biological “energy” on a foolproof system in which every B and T cell is carefully checked for tolerance of self. Instead, the system relies on a multilayered strategy in which each layer includes mechanisms that should weed out most self-reactive cells, with lower layers catching cells that slip through tolerance induction in the layers above. This usually works very well, but occasionally “mistakes are made,” and instead of defending us against foreign invaders, the weapons of our immune system are turned back on us. **Autoimmune disease results when a breakdown in the mechanisms meant to preserve**

tolerance of self is severe enough to cause a pathological condition. Roughly 5% of Americans suffer from some form of autoimmune disease.

Some cases of autoimmunity result from genetic defects. For example, most autoimmune diseases are chronic disorders that involve repeated stimulation of self-reactive lymphocytes. In healthy people, this is controlled by activation-induced cell death in which chronically stimulated T cells are eliminated when Fas proteins on their surface are ligated. Humans with genetic defects in either the Fas or the Fas ligand protein lack this layer of tolerance protection, and their T cells refuse to die when chronically stimulated by self antigens. The resulting disease, **autoimmune lymphoproliferative syndrome** or **Canale-Smith syndrome**, has, as its pathological consequences, massive swelling of lymph nodes, the production of antibodies that recognize self antigens, and the accumulation of a large number of T cells in the secondary lymphoid organs.

Although some autoimmune disorders are caused by genetic defects, **the majority of autoimmune diseases occur when the layers of tolerance-inducing mechanisms fail to eliminate self-reactive cells in genetically normal individuals.** In fact, you could argue that the potential for autoimmune disease is the price we must pay for having B and T cell receptors which are so diverse that they can recognize essentially any invader.

The latest thinking is that for autoimmunity to occur, at least three conditions must be met. First, an individual must express MHC molecules that efficiently present a peptide derived from the target self antigen. This means that the MHC molecules you inherit can play a major role in determining your susceptibility to autoimmune disease. For instance, only about 0.2% of the U.S. population suffers from juvenile (type 1) diabetes, yet for Caucasian Americans who inherit two particular versions of class II MHC genes, the probability of contracting this autoimmune disease is increased about twenty-fold.

The second requirement for autoimmunity is that the affected person must produce T and, in some cases, B cells which have receptors that recognize a self antigen. Because TCRs and BCRs are made by a mix-and-match strategy, the repertoire of receptors that one individual expresses will be different from that of every other human, and will change with time as lymphocytes die and are replaced. Even the collections of TCRs and BCRs expressed by identical twins will be different. Therefore, it is largely by chance that a person will produce lymphocytes whose receptors recognize a particular self antigen.

So **for autoimmune disease to occur, a person must have MHC molecules that can present a self antigen,**

and lymphocytes with receptors that can recognize the self antigen – but this is not enough. There also must be environmental factors that lead to the breakdown of the tolerance mechanisms which are designed to eliminate self-reactive lymphocytes. For years, physicians have noticed that autoimmune diseases frequently follow bacterial or viral infections, and immunologists believe that microbial attack may be one of the key environmental factors that triggers autoimmune disease. Now clearly, a viral or bacterial infection cannot be the whole story, because for most people, these infections do not result in autoimmunity. However, in conjunction with a genetic predisposition (e.g., the type of MHC molecules inherited) and lymphocytes with potentially self-reactive receptors, a microbial infection may be the “last straw” that leads to autoimmune disease.

Molecular mimicry

Immunologists’ current favorite hypothesis to explain why infections might lead to the breakdown of self tolerance is called **molecular mimicry**. Here’s how this is thought to work.

Lymphocytes have BCRs or TCRs that recognize their cognate antigen. It turns out, however, that this is almost never a single antigen. Just as one MHC molecule can present a large number of peptides which have the same overall characteristics (length, binding motif, etc.), a TCR or a BCR can usually recognize (**cross react with**) several different antigens. Generally, a TCR or BCR will have a high affinity for one or a few of these cognate antigens, and relatively lower affinities for the others.

During a microbial invasion, lymphocytes whose receptors recognize microbial antigens will be activated. The molecular mimicry hypothesis holds that sometimes these receptors also recognize a self antigen, and if they do, an autoimmune response to that self antigen may result. It is presumed that before the microbial infection, these potentially self-reactive lymphocytes had not been activated – either because the affinity of their receptors for the self antigen was too low to trigger activation, or because the restricted traffic patterns of virgin lymphocytes never brought them into contact with the self antigen under conditions that would promote activation.

Self-reactive B cells could also be generated by molecular mimicry during somatic hypermutation. This could happen if the receptors of a B cell that originally recognized only a bona fide pathogen mutated so that they could recognize both the pathogen, making them “eligible” for Tfh help, and a self antigen, making them potentially destructive.

In these scenarios, the invading microbe substitutes for (mimics) the self antigen for activation. And once activated in response to a cross-reacting microbial antigen, these self-reactive lymphocytes can do real damage. Cross-reactive antibodies have been identified in some patients with autoimmune disease who had previously been infected by certain viruses or bacteria. For example, it is believed that **rheumatic heart disease**, which is a possible complication of a streptococcal throat infection, can result when receptors on helper T cells that recognize streptococcal antigens cross react with a protein which is present on the tissues that make up the mitral valve of the heart. These cross-reactive Th cells may then direct an inflammatory response that can severely damage this heart valve.

One reason it has been so difficult to pin down the environmental triggers for most autoimmune diseases is that TCRs which recognize self antigens can usually cross react with multiple environmental antigens. Consequently, **although viral or bacterial infections may be involved in some autoimmune disorders, it appears unlikely that any single microbe is responsible for any one autoimmune disease.**

Animal models of human autoimmune diseases have been useful for understanding which immune system players are involved, which self antigens are targets of the immune response, and which microbial antigens might be involved in the molecular mimicry that may trigger disease. Typically, these models involve animals that have been bred to be exquisitely susceptible to autoimmune disease, or animals whose genes have been altered to make them susceptible. Nevertheless, animal models frequently differ in important respects from the human disease they are meant to model. As a result, many treatments for autoimmune diseases which look promising in an animal model have turned out to be useless in humans.

Inflammation and autoimmune disease

Although molecular mimicry may result in the activation of lymphocytes that had previously been ignorant of self antigens, these self-reactive lymphocytes still face a problem once they reach the tissues where the self antigen is located: They must be reactivated before they can do any real damage. If the innate immune system is battling an infection in the tissues, inflammatory cytokines such as IFN- γ and TNF can activate APCs (e.g., macrophages) that reside in the tissues. And once activated, these APCs will express the MHC and co-stimulatory molecules required to restimulate T cells which enter the tissues to do battle. Consequently, when lymphocytes venture out

into the tissues to join a war that the innate system is already fighting, restimulation is not a problem. However, for a T cell that recognizes a self antigen which the innate system does not see as dangerous, the tissues can be a very inhospitable place – because that self-reactive lymphocyte will not usually receive the co-stimulation necessary for its survival.

What this means is that it is not enough for a microbe to activate self-reactive T cells by mimicry. There must also be an inflammatory reaction going on in the same tissues that express the self antigen. Otherwise it is unlikely that self-reactive lymphocytes would exit the blood into these tissues, or that they would survive if they did. This requirement for inflammation at the site of an autoimmune attack helps explains why, for example, a strep infection in the throat only rarely leads to rheumatic heart disease.

So one scenario that immunologists favor for the initiation of autoimmune disease is this: **A genetically susceptible individual is attacked by a microbe that activates T cells whose receptors just happen to cross react with a self antigen. Simultaneously, an inflammatory reaction takes place in the tissues where the self antigen is expressed. This inflammation could be caused either by the mimicking microbe itself, or by another, unrelated, infection or trauma. As a result of this inflammatory reaction, APCs are activated that can restimulate self-reactive T cells. In addition, cytokines generated by the inflammatory response can upregulate class I MHC expression on normal cells in the tissues, making these cells even better targets for destruction by self-reactive CTLs.**

Examples of autoimmune disease

Autoimmune diseases are usually divided into two groups: organ-specific and systemic diseases. Let's look at examples of both types, paying special attention to the self antigens against which the autoimmune response is thought to be directed, and to the environmental antigens that may be involved in molecular mimicry.

Insulin-dependent diabetes mellitus (type 1 diabetes) is an example of an organ-specific autoimmune disease. In this disease, the targets of autoimmune attack are the insulin-producing β cells of the pancreas. Although antibodies produced by self-reactive B cells may participate in the chronic inflammation that contributes to the pathology of this disease, it is currently believed that the initial attack on the β cells is mediated by CTLs.

In diabetes, destruction of β cells usually begins months or even years before the first symptoms of diabetes appear, so this disease is sometimes referred to as a "silent

killer." Indeed, by the time of diagnosis, more than 90% of a patient's β cells will usually have been destroyed. Until insulin injections became possible in the 1920s, the life expectancy of someone diagnosed with diabetes was a matter of months. Even now, with the use of supplementary insulin, this disease shortens average life expectancy by more than a decade.

Antibodies that bind to β cell antigens are produced very early in the disease. As a result, relatives of diabetic patients can be tested to determine whether they might be in the initial stages of diabetes and could be helped by early intervention. Indeed, if a child has a sibling who developed diabetes early in life, and if that child's immune system does make antibodies which recognize beta cell proteins, the probability that he will develop diabetes within the next five years is nearly 100%.

Clearly, there are genetic factors which help determine susceptibility to diabetes, since the probability that both identical twins will suffer from this autoimmune disease is about 50% if one of them has it. It is known, for example, that some individuals have a version of the gene for CTLA-4 which is associated with an increased risk of type 1 diabetes. Patients with this variant make less CTLA-4 RNA, and presumably are less able to limit the activation of self-reactive T cells that recognize β cell antigens.

Thus far, no strong candidates have emerged for environmental factors that might trigger the initial attack on β cells. However, many immunologists believe that diabetes results, at least in part, when the balance between natural regulatory T cells and potentially self-reactive CTLs is upset. Indeed, mutations in genes that compromise nTreg function can cause autoimmune disease both in humans and in mice.

Plaque psoriasis is an autoimmune disease that affects about 2% of the U.S. population. The most noticeable symptoms are the thickening and scaling of the surface of the skin. In the most severe cases, these "plaques" can cover more than 10% of the skin area. Recently, it was discovered that this disease is driven by CD8 $^{+}$ T cells that produce high levels of IL-17 (yes, killer T cells can produce cytokines!). IL-17 can bind to skin cells (keratinocytes) and set off a chain of molecular events which causes keratinocytes to proliferate to form plaques. A current molecular mimicry model is that T cells in genetically susceptible individuals (e.g., those who have certain versions of the class I MHC molecules) have receptors that recognize both a particular keratin protein and a protein made by streptococcal bacteria (which infect a large proportion of the world's population from time to time). It is hypothesized that some CTLs responding to a streptococcal infection have TCRs that cross react

with the keratin protein presented by the patient's class I MHC molecules. Once activated by the bacterial infection, these self-reactive CD8 $^{+}$ T cells produce IL-17, causing errant keratinocyte proliferation and plaque formation. These particular versions of class I MHC molecules were probably selected for during evolution because they help the immune system protect against streptococcal infections. After all, for a caveman, a streptococcal infection could be deadly, yet cavemen probably didn't care much about the appearance of their skin!

Rheumatoid arthritis is a systemic autoimmune disease that affects approximately 1% of the world's population. It is characterized by chronic inflammation of the joints. One of the presumed targets of this autoimmune reaction is a certain cartilage protein, and T cells from arthritic patients can recognize both the cartilage protein and a protein encoded by the bacterium that causes tuberculosis.

IgM antibodies that can bind to the Fc region of IgG antibodies are abundant in the joints of individuals with rheumatoid arthritis. These antibodies can form IgM-IgG antibody complexes, which can activate macrophages that have entered the joints, increasing the inflammatory reaction. Indeed, the inflammation associated with rheumatoid arthritis is caused mainly by tumor necrosis factor produced by macrophages which infiltrate the joints under the direction of self-reactive helper T cells. Interestingly, mice injected with *Mycobacterium tuberculosis* develop inflammation of the joints, suggesting, but not proving, that a TB infection may trigger rheumatoid arthritis in some patients.

Multiple sclerosis (MS) is an inflammatory disease of the central nervous system that involves both B and T cells. In multiple sclerosis, chronic inflammation destroys the myelin sheaths that are required for nerve cells in the brain to transmit electrical signals efficiently, causing defects in sensory inputs (e.g., vision) and paralysis. A recent study suggests that MS occurs almost exclusively in people who have been infected with Epstein-Barr virus, the virus which causes infectious mononucleosis. Epstein-Barr virus causes a chronic, life-long infection of B cells. Although the immune mechanism(s) which cause the disease are unknown, B cells which have receptors that can recognize certain Epstein-Barr proteins as well as myelin basic protein (a major component of the myelin sheath) have been isolated from MS patients. So molecular mimicry is likely to be involved.

More than 90% of the world's adults are infected with Epstein-Barr virus, and fewer than 1% of these people have multiple sclerosis, so exposure to microbial mimics is not the whole story. Indeed, as is true of most autoimmune

diseases, multiple sclerosis has a strong genetic component. It is about ten times more probable that identical twins will share this disease than it is for non-identical twins both to be affected, and certain class II MHC gene confers increased susceptibility to multiple sclerosis. There are also certain groups of people (e.g., Hispanic, Asian, and Native American) who have relatively low rates of this disease, presumably because of their particular genetic makeup. Environmental factors are also likely to play a role in multiple sclerosis, with large differences in the incidence of this disease observed between similar populations living in different geographical locations. If further experiments demonstrate that infection with Epstein–Barr virus is necessary but not sufficient to cause MS, a vaccine which could protect against a chronic Epstein–Barr virus infection might be able to eradicate multiple sclerosis.

Finally, ***lupus erythematosus*** is a systemic autoimmune disease that affects about 250,000 people in the United States, roughly 90% of whom are women. This disease can have multiple manifestations including a red rash on the forehead and cheeks (giving the “red wolf” appearance for which the disease was named), inflammation of the lungs, arthritis, kidney damage, hair loss, paralysis, and convulsions. Lupus is caused by a breakdown in both B and T cell tolerance that results in the production of a diverse collection of IgG antibodies which recognize a wide range of self antigens, including DNA,

DNA–protein complexes, and RNA–protein complexes. These autoantibodies can form self antigen–antibody complexes which “clog” organs in the body that contain “filters” (e.g., kidneys, joints, and the brain), causing chronic inflammation.

Non-identical twins have about a 2% probability of both having lupus if one twin has the disease. With identical twins, the probability is increased about ten-fold. This indicates a strong genetic component to the disease, and more than a dozen MHC and non-MHC genes have been identified – each of which seems to slightly increase the probability that a person will contract lupus. Although no specific microbial infection has been associated with the initiation of this autoimmune disease, mice that lack functional genes for Fas or Fas ligand exhibit lupus-like symptoms. This has led immunologists to speculate that lupus may involve a defect in activation-induced cell death, in which lymphocytes that should die due to chronic stimulation survive to cause the disease. There is also some evidence that humans with mutations which increase the sensitivity of their Toll-like receptors to RNA or DNA are lupus-prone. The idea here is that recognition of human DNA by a B cell’s receptors, together with an unusually strong signal from a mutated Toll-like receptor, could be misinterpreted as a dangerous situation. As a result, B cells could be activated without T cell help, and anti-DNA antibodies could be produced.

REVIEW

Sometimes the immune response may be misguided. Indeed, allergies result when the immune system produces IgE antibodies – which are designed to deal with a parasitic infection – in response to environmental antigens. Immunologists are not sure what causes this misguided response. Their best thought is that a defect in immune regulation causes production of a large number of allergen-specific Th2 cells. These helper T cells then orchestrate the overproduction of allergen-specific IgE antibodies. Atopic individuals frequently inherit a “genetic landscape” which predisposes them to allergies, and the timing and extent of exposure to pathogens may influence whether susceptible individuals become atopic. In fact, the hygiene hypothesis holds that if the immune system of a young child is not appropriately challenged by microbial infections, allergies may result.

Autoimmunity occurs when the mechanisms designed to enforce tolerance of self antigens don’t function properly. In some cases, this is the result of genetic defects. However, in most cases, immunologists don’t know what causes the breakdown in tolerance-inducing mechanisms. Clearly, for autoimmunity to occur, a person must have MHC molecules which can present self antigens, and lymphocytes with receptors that can recognize these antigens. So there is a genetic component. In addition, it is believed that environmental factors are involved, although such factors have been difficult to discover – probably because there are many of them. It is hypothesized that autoimmunity can be triggered when an invading microbe “mimics” a self antigen. According to this scenario, the microbe activates lymphocytes which have receptors

that recognize both a microbial antigen and a self antigen. Once activated in response to the microbial invasion, these cross-reactive lymphocytes can lead an attack on both the invader and the cells or proteins

belonging to the infected individual. Inflammation also is believed to play a role in molecular mimicry by providing the signals required to attract cross-reactive lymphocytes and keep them activated.

KNOWN UNKNOWNS

1. What are the immunological factors that underlie the dramatic increase in the incidence of allergies in developed countries?
2. How does specific immunotherapy cure allergies?
3. What causes the breakdown in self tolerance which results in various autoimmune diseases?

THOUGHT QUESTIONS

1. Describe the events that lead to the degranulation of mast cells during an allergic reaction.
2. Why do some people have allergies, whereas others do not?
3. What events likely are required to initiate autoimmunity?
4. How do immunologists know that a microbial infection alone is not sufficient to cause autoimmune disease?

HEADS UP!

Because the immune system is highly interconnected, a genetic defect which cripples one of the players can have a major effect on the functioning of the overall system. Moreover, drugs or illnesses which weaken the immune system can leave us vulnerable to infections – infections which would not be a problem for an immune system operating at full strength.

INTRODUCTION

Serious disease may result when our immune system is compromised. Some immunodeficiencies are caused by genetic defects that disable parts of the immune network. Others are “acquired” as the consequence of malnutrition, deliberate immunosuppression (e.g., during organ transplantation or chemotherapy for cancer), or disease (e.g., AIDS).

GENETIC DEFECTS LEADING TO IMMUNODEFICIENCY

A genetic defect in which a single gene is mutated can lead to immune system weakness. For example, individuals who are born with nonfunctional CD40 or CD40L proteins are unable to mount a T cell-dependent antibody response – either because T cells cannot deliver or because B cells cannot receive this all-important, co-stimulatory signal. Both class switching and somatic hypermutation

usually require co-stimulation by CD40L, so one result of the CD40–CD40L defect is that B cells secrete mainly IgM antibodies which have not affinity matured. Other genetic deficiencies affect the formation of the thymus. In one such disease, DiGeorge syndrome, essentially all thymic tissue is missing. People with this disorder are susceptible to life-threatening infections because they lack functional T cells.

Genetic defects also can knock out both B and T cells. This group of diseases is called **severe combined immunodeficiency syndrome (SCIDS)** – where the “combined” label indicates that neither B nor T cells function properly. It was this disease that forced David Vetter, the famous “bubble boy,” to live for twelve years in a pathogen-free, plastic bubble. Although a number of different mutations can result in SCIDS, the best-studied mutation causes a defect in a protein that initiates the gene splicing required to produce B and T cell receptors. Without their receptors, B and T cells are totally useless.

Immunodeficiencies also can result from genetic defects in the innate immune system. For instance, people who are born with mutations in important complement proteins (e.g., C3) have lymph nodes with no germinal centers and B cells that produce mainly IgM antibodies.

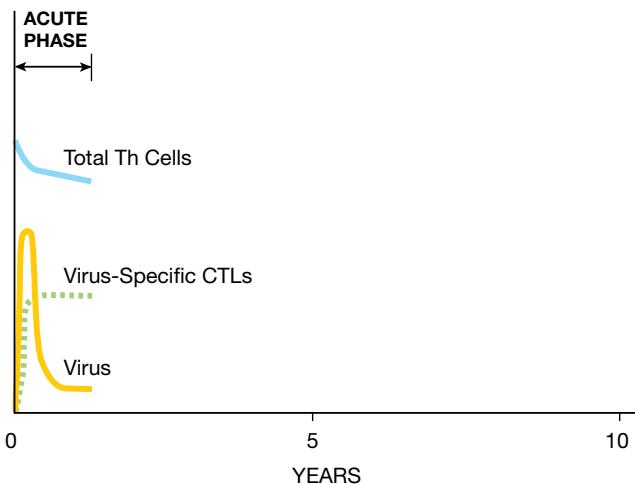
Given the large number of different proteins involved in making the innate and adaptive immune systems work effectively, it’s pretty amazing that mutations leading to immunodeficiency are so rare. In fact, inherited immunodeficiencies affect only about one in 10,000 newborns. It is likely, however, that many other cases of genetic immunodeficiency go undetected because our functionally redundant immune system has evolved to provide “backups” when elements of the main system are disabled.

AIDS

Although genetic immunodeficiencies are relatively rare, millions of people suffer from immunodeficiencies that are acquired. A large group of immunodeficient humans acquired their deficiency when they were infected with the AIDS virus, HIV-1, a virus that currently infects about forty million people worldwide, and has resulted in more than thirty million deaths. The AIDS symptoms which originally alerted physicians to the fact that they were dealing with a disease which had immunodeficiency as its basis were the high incidences of infections (e.g., *Pneumocystis carinii* pneumonia) or cancers (e.g., Kaposi sarcoma) that were usually seen only in immunosuppressed individuals. Soon, the virus that caused this immunodeficiency was isolated and named the **human immunodeficiency virus number one (HIV-1)**. This is one of the world's most intensely studied viruses, with nearly a billion dollars being spent annually to try to discover its secrets.

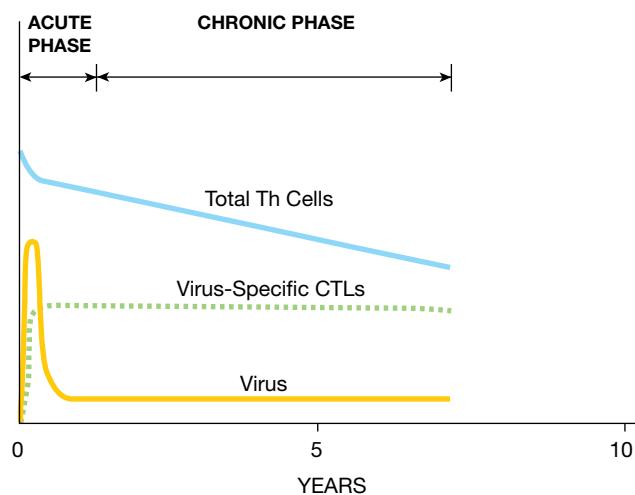
An HIV-1 infection

The early events in a human HIV-1 infection are not well characterized because the infection typically is not diagnosed until weeks or months after exposure to the virus. However, the emerging picture is that these infections typically begin when the virus penetrates the rectal or vaginal mucosa and infects helper T cells which lie beneath these protective surfaces. The virus uses these cells' biosynthetic machinery to make many more copies of itself, and the newly made viruses then infect other cells. So in the early stages of infection, the virus multiplies relatively unchecked while the innate system gives it its best shot, and the adaptive system is being mobilized. After a week or so, the adaptive system starts to kick in, and virus-specific B cells, helper T cells, and CTLs are activated, proliferate, and begin to do their thing. During this early, **acute phase** of the infection, there is a dramatic rise in the number of viruses in the body (the **viral load**) as the virus multiplies in infected cells. The viral load peaks three to four weeks post infection, and this peak is followed by a marked decrease in the viral load as virus-specific CTLs go to work.

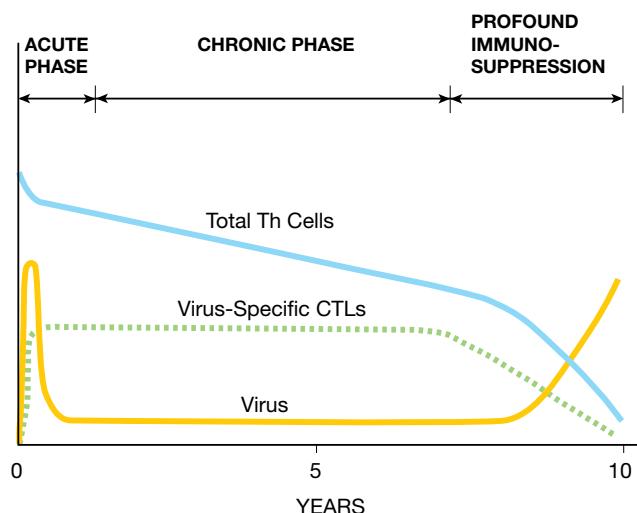


With many viruses (e.g., smallpox), the end result of the acute phase of a viral infection is **sterilization**: The immune system destroys all the invading viruses, and memory B and T cells are produced to protect against a subsequent infection by the same virus. In contrast, a full-blown HIV-1 infection always leads to a **chronic phase** that can last for ten or more years. During this phase, a fierce struggle goes on between the immune system and HIV-1 – a battle which, if untreated, the virus almost always wins.

During the chronic phase of infection, viral loads decrease to low levels compared with those reached during the height of the acute phase, but the number of virus-specific CTLs and Th cells remains high – a sign that the immune system is still trying hard to defeat the virus.



However, as the chronic phase progresses, the total number of helper T cells slowly decreases, because these cells are killed as a consequence of the viral infection. Eventually there are not enough Th cells left to provide the help needed by virus-specific CTLs. When this happens, the number of CTLs also begins to decline, and the viral load increases – because there are too few CTLs left to cope with newly infected cells.



In the end, the immune defenses are overwhelmed, and the resulting profound state of immunosuppression leaves the person open to unchecked infections by pathogens that normally would not be the slightest problem for someone with an intact immune system. Sadly, these **opportunistic infections** can be lethal.

HIV-1 versus the immune system

Why is HIV-1 able to defeat an immune system that is so successful in protecting us from most other pathogens? There are two parts to this answer. The first has to do with the nature of the virus itself. All viruses are basically pieces of genetic information (either DNA or RNA) with a protective coat. For HIV-1, this genetic information is in the form of RNA which, after the virus enters its target cell, is copied by a viral enzyme (reverse transcriptase) to make a piece of “complementary” DNA (cDNA). Next, the DNA of the cell is cut by another enzyme carried by the virus, and the viral cDNA is inserted into the gap made in the cellular DNA. Now comes the nasty part. Once the viral DNA has been

inserted into a cell’s DNA, it can just sit there, and while the virus is in this “latent” state, the infected cell cannot be detected by CTLs. Importantly, it only takes a few days for HIV-1 to initiate a **latent infection** and establish a **stealth reservoir of virus** in these “sanctuary” cells. Sometime later, in response to signals that are not fully understood, the latent virus can be “reactivated,” additional copies of the virus can be produced, and more cells can be infected by these newly minted viruses.

The fact that a reservoir of virus which is invisible to the immune system can be established within a week of infection is a serious problem. After all, a week into the infection, the adaptive immune system is still being activated. Consequently, the major responsibility for stopping the virus before it can get a foothold falls to the innate system. And the innate immune system is not usually up to the task.

So the ability to quickly establish a latent infection which cannot be detected by CTLs is one property of HIV-1 that makes this virus such a problem for the immune system. But it gets worse. The reverse transcriptase enzyme used to copy the HIV-1 RNA is very error-prone: It makes a mistake almost every time it copies a piece of viral RNA. This means that most of the new viruses produced by an infected cell are mutated versions of the virus which originally infected that cell. And some of these mutations may enable the newly made viruses to evade the immune system. For example, the virus can mutate so that a viral peptide that was formerly targeted by a CTL can no longer be recognized, or can no longer be presented by the MHC molecule that the CTL was trained to focus on. In fact, it has been shown that it only takes about ten days for these **escape mutants** to arise. When such mutations occur, the original CTL will be useless against cells infected with the mutant virus, and new CTLs which recognize a different viral peptide will need to be activated. Meanwhile, the virus that has escaped from surveillance by the obsolete CTLs is replicating like crazy, and every time it infects a new cell, it mutates again. Consequently, the mutation rate of HIV-1 is so high that it can usually stay one step ahead of CTLs or antibodies directed against it.

So two of the properties of HIV-1 that make it especially deadly are its ability to establish an undetectable, latent infection and its high mutation rate. But that’s only half the story. The other part has to do with the cells HIV-1 infects.

This virus specifically targets cells of the immune system: helper T cells, macrophages, and dendritic cells. The “docking” protein that HIV-1 binds to when it infects a cell is CD4, the co-receptor protein found in large numbers on the surface of helper T cells. This protein is also expressed on macrophages and dendritic cells, although they have fewer CD4 molecules on their surface. By attacking these cells, HIV-1 either disrupts their function, kills the cells, or makes them targets for killing by CTLs that recognize them as being virus-infected. So **the very cells that are needed to activate CTLs and to provide them with help are damaged or destroyed by the virus.**

Even more insidiously, **HIV-1 can turn the immune system against itself by using processes which are essential for immune function to spread and maintain the viral infection.** For instance, HIV-1 can attach to the surface of dendritic cells and be transported by these cells from the tissues, where there are relatively few CD4⁺ cells, into the lymph nodes, where huge numbers of CD4⁺ T cells are congregated. Not only are helper T cells within easy reach in the lymph nodes, but many of these cells are proliferating, making them ideal candidates to be infected and become HIV-1 “factories.”

Also, viruses that have been opsonized either by antibodies or by complement are retained in lymph nodes by follicular dendritic cells. This display is intended to help activate B cells. However, CD4⁺ T cells also pass through these forests of follicular dendritic cells, and as they do, they can be infected by the opsonized viruses. And because virus particles typically remain bound to follicular dendritic cells for months, lymph nodes actually become reservoirs of HIV-1. The net result is that HIV-1 takes advantage of the normal trafficking of immune system cells through lymph nodes, and turns these secondary lymphoid organs into its own playground.

In summary, **the pathological consequences of an HIV-1 infection are the result of the virus’ ability to slowly destroy the immune system of the patient, leading to a state of profound immunosuppression which makes the individual an inviting host for life-threatening infections. The virus is able to do this because it can rapidly establish a latent, “stealth” infection, because it has a high mutation rate, because it preferentially infects and disables the immune system cells that normally would defend against it, and because it uses the immune system itself to facilitate its spread throughout the body.**

Living with AIDS

Untreated, most people infected with HIV-1 die within ten years. Fortunately, **anti-retroviral treatment (ART)** is now available, and worldwide, roughly thirty million people

receive these drugs. This chemotherapy targets specific aspects of the viral replication cycle, and can lengthen the life of an AIDS patient by many years. ART treatment can also decrease the chance of transmission. Nevertheless, ART does not eliminate the virus from the body of the patient – because it cannot eradicate the reservoir of latent virus “hiding” in infected CD4⁺ cells. In most cases, life-long ART is required to control the disease, and this type of chemotherapy is not without side effects. Indeed, for those on ART, there is an increased risk for cancer and cognitive disorders, as well as kidney, liver, bone, and heart disease.

Interestingly, for a very small fraction of untreated individuals infected with HIV-1 (roughly 0.5%), their immune system is able to control the infection for a relatively long period of time. In fact, some of these **elite controllers** have almost undetectable levels of virus and have remained symptom-free for as long as thirty years. As you might expect, immunologists are very interested in understanding how the immune system of an elite controller deals with a viral infection that is deadly for most other humans. Although the story is far from complete, there are some clues.

One consistent finding is that the innate and adaptive defenses of elite controllers seem to fire up more quickly after the initial infection than does the immune system of “ordinary” humans. Several possible reasons for this quick response have been discovered. For example, the pattern-recognition receptors of some elite controllers trigger unusually vigorous secretion of IFN- α and IFN- β by cells of the innate immune system. IFN- α and IFN- β activate genes within HIV-1-infected cells which encode proteins that limit the efficiency of replication of the virus. In addition, these warning cytokines can cause infected cells to die by apoptosis, destroying the viruses that are replicating inside them.

In Lecture 4, I noted that one reason MHC molecules are so polymorphic is to increase the probability that at least some individuals in the population will have MHC molecules that can bind to and present an invader’s peptides. This idea is supported by the finding that certain class I MHC molecules are found much more often in elite controllers than in the general population. The thinking here is that because these MHC molecules efficiently present HIV-1 peptides, killer T cells will be activated earlier in an infection when the number of infected cells is still small. In addition, when CTLs from elite controllers are tested in the laboratory, they tend to be more vicious killers than CTLs from patients who cannot control the infection. This seems to be due to the ability of these “super CTLs” to mobilize the killing enzyme granzyme B, and deliver it into its target cells. Again, the thinking is that these CTLs kill faster, and can control the infection before it gets out of hand.

Another observation about elite controllers is the importance of CTLs in dealing with their infection. A lot of attention has been focused on the antibody response to HIV-1, in part because antibody function is easier to measure than CTL function. But it is important to remember that killer T cells evolved to deal with virus infections. These immune system cells are designed to destroy virus-infected cells before thousands of new viruses can be produced. The most useful antibodies are neutralizing antibodies which can prevent the virus from entering its target cells. However, it is relatively easy for the virus to mutate so that its shape changes slightly to avoid antibody recognition. The change of a single amino acid can suffice to alter the shape of the viral protein so dramatically that existing antibodies no longer can bind to the virus and neutralize it. In contrast, mutational evasion of CTLs is more difficult. The collection of T cell receptors recognizes a variety of short viral peptides, each of which would have to be specifically mutated so that it cannot be presented by class I MHC molecules or cannot be recognized by T cell receptors. The importance of CTLs in controlling an HIV-1 infection is the reason why most immunologists

believe that an effective HIV vaccine will need to produce memory T cells, not just memory B cells.

Of course, the hope is that if the unique features of the immune system of elite controllers can be understood in more detail, this information may be helpful in devising new treatments for persons infected with HIV-1. It is important to understand, however, that elite controllers are still infected: Their immune system has not defeated the virus. It has just controlled the viral infection for an extended period of time, and these individuals continue to have reservoirs of latently infected CD4⁺ T cells.

So far, there are only two documented cases of an AIDS patient who appears to have been treated and cured of the disease. One of them was the so-called "Berlin patient," Timothy Ray Brown. After he was infected with HIV-1, Mr. Brown developed acute myelogenous leukemia. When he was treated for that disease, he twice had his immune system destroyed by chemicals or radiation and reconstituted with stem cell transplants. The second patient went through a similar treatment. Importantly, the stem cell donor in both procedures had deletions in the genes for CCR5, the most common co-receptor for HIV-1. Sadly, Timothy Brown died of leukemia in 2020.

REVIEW

Mutations that are inherited or that arise spontaneously can cause the immune system to function suboptimally. Other immunodeficiencies arise when the immune system is suppressed by drugs or disease. Today, millions of humans are immunodeficient as a result of infection with HIV-1. Untreated, most AIDS patients succumb to infections which the immune system of a healthy individual could easily defeat. HIV-1 goes at the immune system "head on" by infecting and destroying the very immune warriors which might otherwise defend against the attack. The virus uses the immune system to facilitate its spread

throughout the body, and it can establish a "hidden" reservoir of virus within the immune system cells of an infected individual. In addition, because the virus mutates rapidly, antibodies which can bind to the virus to prevent infection and killer T cells which can recognize and kill infected cells, quickly become "obsolete," allowing the virus to stay one step ahead of the immune defenses. Anti-retroviral treatment, a form of chemotherapy, can be used to extend the life of patients infected with HIV-1. Some "elite controllers" are chronically infected with the virus, but remain asymptomatic for long periods of time.

KNOWN UNKNOWNS

1. Why are some people who have been infected with HIV-1 able to control the infection for extended periods without treatment?
2. What are the earliest steps in a human HIV-1 infection?
3. Can treatments be devised that will destroy HIV-1-infected cells which harbor latent viruses?

THOUGHT QUESTIONS

1. Describe what happens to a patient's immune system during the course of an HIV-1 infection.
2. Discuss the features of an HIV-1 infection that make it so difficult for the immune system to deal with.
3. In the past, when the human immune system has been confronted with new dangers, it has evolved to meet these challenges. Given enough time, what evolutionary changes would you predict that our immune system might make to defend us against HIV-1?

HEADS UP!

The purpose of a vaccine is to “trick” the immune system into making memory B and T cells which can defend against a future attack by the real thing. The requirements for generating memory helper T and B cells are different from those for generating memory CTLs.

INTRODUCTION

During many “natural” infections, memory B and T cells are generated which can provide protection against a subsequent attack. However, a natural infection can be quite devastating – even lethal. If there was a safe way to trick the immune system into thinking it had been attacked, and to get it to produce memory B and T cells that are appropriate to defend against the anticipated attacker, then a person could be protected against a real infection. That, of course, is what a vaccination does.

A vaccination is the immunological equivalent of the war games our armed forces use to prepare troops for combat. The goal of these games is to give soldiers as realistic a simulation of battle conditions as is possible without putting them in danger. Likewise, a vaccination is intended to prepare the immune system for battle by giving the system as close a look at the real thing as is possible without exposing the vaccine recipient to undue risks. Indeed, the generals who plan war games and the scientists who develop vaccines have a common aim: maximum realism with minimum danger.

Vaccines have been extremely useful in controlling infectious diseases. For example, before a diphtheria vaccine was available, the number of new cases of diphtheria in the United States reached over 350,000 per year. Now, as

a result of widespread vaccination against diphtheria, usually fewer than five cases are reported annually.

GENERATING MEMORY HELPER T AND B CELLS

When we are first exposed to a pathogen, dendritic cells at the battle site ingest the attacker or fragments of the attacker and travel to nearby lymph nodes. There they use class II MHC molecules to present peptides derived from the invader’s proteins. If a helper T cell has receptors which recognize these peptides, it can be triggered to proliferate. Eventually, some of these helper T cells become memory cells which can help protect against a subsequent attack. So for memory helper T cells to be generated, all that is required is for dendritic cells to collect “debris” from the battle scene (e.g., viral coat proteins or part of a bacterial cell membrane) and present peptides derived from this debris to helper T cells.

Likewise, when a B cell’s receptors recognize an attacker or a fragment of an attacker which has been transported to the secondary lymphoid organs by the lymph or the blood, that B cell can be activated. After a period of proliferation, if T cell help is available, some of the resulting B cells will become memory cells. So as with helper T cells, even a bit of battle debris is enough to activate a B cell and generate memory B cells. The important point here is that **memory B and helper T cells can be produced efficiently even when no immune system cells have been infected by the attacker.**

GENERATING MEMORY KILLER T CELLS

Memory killer T cells can also be produced during a microbial attack, but for this to happen, the microbe must infect an antigen presenting cell. For example, if a virus

infests a dendritic cell, that virus will commandeer the cell's biosynthetic machinery and use it to make viral proteins as part of its reproductive strategy. Some of these proteins will be chopped up into peptides and loaded onto class I MHC molecules. As a result, killer T cells whose receptors recognize the virus's peptides will be activated, and if assistance is available from helper T cells, memory killer T cells will be produced.

So the requirements for generating memory helper T and B cells are different from those for generating memory CTLs. Memory helper T cells and B cells can be produced even when an invader does not infect an APC. In contrast, **for memory killer T cells to be made, the attacker must infect an APC.**

Under certain experimental conditions, it has been demonstrated that antigen presenting cells can use class I MHC molecules to present antigens taken up from outside the cell – antigens that normally would be presented by class II MHC molecules. This phenomenon is termed cross-presentation, and it might allow virus-specific memory CTLs to be generated – even when the virus does not infect APCs. It is possible that cross-presentation may eventually be used to produce a vaccine which can generate CTL memory and protect humans from disease. So far, however, the rule seems to be that APCs must be infected in order for a vaccine to efficiently generate memory CTLs. In this lecture, we'll stick to that rule.

STRATEGIES FOR VACCINE DEVELOPMENT

A number of different approaches have been employed to develop the vaccines currently used to protect against microbial infections. In addition, innovative, new vaccine designs are being tested. One important feature of a vaccination is that its efficacy does not depend on the recipient's level of hygiene or lifestyle. Consequently, many believe that a vaccine against HIV-1 – a virus that currently infects thousands of people per day – may be the best way to stop the spread of HIV-1. Because this disease is such an important health issue, as we discuss different types of vaccines, we will ask whether any of them might be suitable to use as a vaccine that would protect against an HIV-1 infection. In the end, I think you will agree that designing a safe and effective AIDS vaccine is a difficult challenge.

One major obstacle to producing an AIDS vaccine is that it isn't certain which types of memory cells are needed. The results of trials with vaccines that only produce memory B cells and antibodies have not been very impressive. Moreover, individuals who are infected with

HIV-1, but whose immune systems resist the virus for long periods of time, have usually inherited particular class I MHC molecules. This suggests that presentation of antigens to killer T cells is important for resistance. Consequently, **most immunologists believe that an effective AIDS vaccine must generate memory killer T cells.** Unfortunately, the production of memory CTLs requires that the agent used as a vaccine be capable of infecting antigen presenting cells – and this puts severe restrictions on the types of AIDS vaccines that might be safe to use.

Non-infectious vaccines

Many vaccines are designed not to infect the vaccine recipient. The Salk vaccine for polio is an example of such a "non-infectious" vaccine. To make his vaccine, Dr. Jonas Salk treated poliovirus with formaldehyde to "kill" the virus. Formaldehyde acts by gluing proteins together, and the result of this treatment is that the virus looks to the immune system very much like a live poliovirus – but it cannot infect cells because its proteins are nonfunctional. This treatment is the molecular equivalent of the parking police applying a "boot" to the wheel of a car. The car may look quite normal, but because the wheels can't turn, the vehicle is disabled. The common flu vaccine is also a killed virus vaccine, and a similar strategy has been used to make vaccines against disease-causing bacteria. For example, the typhoid vaccine is prepared from bacteria that have been grown in the lab and then treated with chemicals such as formaldehyde.

Although the chemicals used to kill these microbes will certainly incapacitate most of them, the procedure is not guaranteed to be 100% effective and some of them may survive. Now, if a vaccine is intended to protect against a virus like influenza, which otherwise will infect a large fraction of the population, the presence of a few live viruses in the vaccine preparation is not a major concern – because without vaccination, many more people would contract the disease. In contrast, if the goal is to protect against a virus such as HIV-1, in which infection is usually preventable (at least for adults in developed countries where blood supplies are carefully screened), a vaccine that has even a small probability of causing the disease could not be used to vaccinate the general public.

Some bacteria produce proteins called toxins that actually cause the symptoms associated with the bacterial infection. In a few cases, these toxins have been used as non-infectious vaccines. To prepare such a vaccine, the toxin is purified and then treated with aluminum salts to produce a weakened form of the toxin called a **toxoid**. When injected into a recipient, the toxoid mobilizes B cells

that produce antibodies which can bind to and inactivate the harmful toxin during a real attack. Vaccines made from diphtheria or tetanus toxins are examples of this type of non-infectious vaccine.

Some non-infectious vaccines use only certain parts of a pathogen. The idea here is to retain the portions that the immune system needs to see for protection, while discarding the parts that cause unpleasant or dangerous side effects. An “acellular” vaccine for pertussis is made in this way. The original pertussis vaccine was prepared from whole, killed pertussis bacteria, and about half of the infants inoculated with that vaccine had an adverse reaction to it. Fortunately, almost all these side effects were mild when compared with the life-threatening possibility of contracting whooping cough. The acellular vaccine, which has a much lower rate of adverse reactions than the original pertussis vaccine, is made by growing the pertussis bacteria in culture and then purifying several of the bacterial proteins away from the rest of the bacterial components. Although the side effects associated with this acellular vaccine are minimal, studies have shown that protection against pertussis wains much more quickly with the acellular vaccine than with the vaccine made from whole bacteria.

Viral proteins produced by genetic engineering also can be used as non-infectious **subunit vaccines**. The highly effective vaccines against hepatitis B virus and the human papillomavirus are both made in this way. Because only one or a few “synthetic” viral proteins are used to make a subunit vaccine, there is no possibility that the vaccine will cause the infection it is designed to protect against. Interestingly, both the hepatitis B vaccine and the papillomavirus vaccine are **nanoparticles**. These nanoparticles are made in the lab by allowing many copies of the synthetic viral coat proteins to self-assemble into empty virus-like particles, which present the immune system with a mimic of what the real virus looks like.

A potential drawback of all non-infectious vaccines is that although they will generate memory helper T cells and B cells (which can make protective antibodies), memory killer T cells will not be made – because antigen presenting cells will not be infected. Of course, many pathogens (e.g., extracellular bacteria) do not infect human cells at all. Consequently, the lack of memory CTLs (which kill infected cells) is not an issue in designing vaccines to protect against these microbes. In addition, antibodies produced by memory B cells are sufficient to protect against some viruses which do infect human cells. Indeed, both poliovirus and hepatitis B virus infect human cells. Nevertheless, the non-infectious Salk polio-virus vaccine and the hepatitis B virus subunit vaccine

work very well, even though neither vaccine generates memory killer T cells. So whether memory CTLs are required for protection depends on the particular microbe and its lifestyle.

Another disadvantage of non-infectious vaccines is that the protection they confer is not generally as long-lasting as the protection produced by vaccination with a live microbe. That’s why, for example, the tetanus toxoid vaccine must be “boosted” about every ten years to be effective.

Attenuated vaccines

Another strategy for producing a vaccine is to use a weakened or “attenuated” form of the microbe. Virologists noticed that when a virus is grown in the laboratory in a cell type which is not its normal host, the virus sometimes accumulates mutations which weaken it. For example, poliovirus normally reproduces in human nerve cells. So to make his polio vaccine, Dr. Albert Sabin grew polioviruses in monkey kidney cells. This strategy resulted in viruses that were still infectious, but which, in their weakened condition, could not cause the disease in healthy individuals. Most children in the United States receive attenuated virus vaccines for measles, rubella, and mumps. **Attenuated virus vaccines usually provide long-lasting immunity because they replicate to a limited extent in the host, thereby mimicking a natural infection.**

An attenuated vaccine can be tested on animals to get a general idea of whether the attenuation procedure has worked. However, to be certain a crippled microbe can stimulate the production of memory cells, yet not cause disease, it must be tested on humans – usually volunteers who expect to be at risk for contracting the disease. In this regard, it is interesting to note that by the time Dr. Sabin was ready to test his attenuated virus vaccine, most people in the United States had already received the Salk polio vaccine. So, from about 1955 to 1960, at the height of the Cold War, Dr. Sabin took his vaccine to Russia and tested it there. Polio was such a dreaded disease that the Russians were delighted to be “guinea pigs” for Dr. Sabin’s made-in-the-USA vaccine.

One important feature of attenuated virus vaccines is that they can produce memory killer T cells. This is because the crippled virus can infect antigen presenting cells and can stimulate the production of CTLs before the immune system has had a chance to destroy the weakened “invaders.” However, because an attenuated vaccine contains a microbe that is infectious, there are safety issues. When a person has recently been vaccinated with an attenuated virus vaccine, they may produce enough

virus to infect some of the people with whom they come in contact. This can be an advantage if those people are healthy, because it “spreads the immunization around,” helping produce what immunologists call **herd immunity**. However, a person whose immune system is weakened (e.g., by chemotherapy for cancer) may not be able to subdue the attenuated virus. After all, the attenuated microbe in the vaccine isn’t dead. It’s just weak. So for those who are immunosuppressed, this type of gratuitous vaccination can have serious consequences.

A second potential safety concern with an attenuated virus vaccine is that before the recipient’s immune system subdues the weakened virus, the virus may mutate, and these mutations may restore the strength of the virus. Although this is not a very likely scenario, some healthy people who received the Sabin vaccine contracted polio – because the weakened virus mutated and regained its ability to cause disease.

Carrier vaccines

Some newer vaccine preparations use genetic engineering to introduce a gene (or genes) from a pathogenic microbe into a virus that doesn’t cause disease. This engineered virus can then be employed as a “Trojan Horse” to carry the gene of the pathogenic microbe into human cells. The idea here is that if the carrier infects the vaccine recipient’s antigen presenting cells, these cells will produce the pathogenic microbe’s protein in addition to the carrier’s own proteins. As a result, **inoculation with a carrier vaccine should generate memory killer T cells that can help protect against a future attack by the real pathogen. Importantly, there is no chance that this vaccine will cause the disease it is designed to protect against – because only one or a few of the pathogen’s many genes is “carried” by the vaccine.**

One example of a carrier vaccine is the ERVEBO vaccine against Ebola virus. This vaccine uses vesicular stomatitis virus as a “vector” to carry the gene for the Ebola envelope glycoprotein into the cells of vaccine recipients. The Johnson & Johnson COVID-19 vaccine is also a carrier vaccine. In this vaccine, a human adenovirus carries the gene for the SARS-CoV-2 spike protein.

It might seem that this approach would be perfect to use to prepare an AIDS vaccine, and vaccines of this type are being tested. A vaccine trial in Thailand used a canary-pox virus (a cousin of Jenner’s cowpox virus) as a Trojan Horse to carry in several genes for HIV-1 proteins. This carrier virus vaccination was then boosted by vaccinating the same individuals with a subunit vaccine containing a synthetic version of one of the same HIV-1 proteins produced by the carrier virus. The people receiving these

vaccinations, plus roughly an equal number of individuals who received a placebo vaccination, were followed for a period of three years to determine how many in each group subsequently became infected with HIV-1 as a result of risky sexual behavior. Although the authors claimed that the trial “showed a significant, though modest, reduction in the rate of HIV-1 infection,” the data is not very convincing. During the study period, 56 people who received the authentic vaccine contracted HIV-1, whereas 76 members of the group which received the sham vaccine became infected with the virus. These are very small numbers on which to base a meaningful conclusion. Moreover, HIV-specific T cells could only be detected in about 17% of the people who received the vaccine. Finally, when the people who became infected were tested, there was no significant difference in the amount of virus in the blood of individuals who had received the vaccine and those who had received the placebo. This would suggest that the vaccination had little effect on the ability of infected individuals to resist the viral infection – not what you would expect from an effective vaccine.

Nucleic acid vaccines

Vaccines can also be made by packaging pieces of microbial DNA or RNA within a carrier vehicle (e.g., a nanoparticle). The idea here is that the packaged nucleic acid can be taken up by antigen presenting cells. These cells can then produce the proteins encoded by the DNA or RNA. Because the proteins are made by the APC, they can be displayed by the APC’s class I MHC molecules, and can activate CTLs.

The most famous example of this technology is the mRNA platform currently used to produce vaccines against SARS-CoV-2, the virus that causes COVID-19. We will discuss this type of vaccine in some detail in Lecture 17. Whether this strategy will be useful in producing an AIDS vaccine is currently unknown.

Recently, a SARS-CoV-2 DNA vaccine was given emergency approval for use in India. DNA has been used to vaccinate animals against various diseases, but this is the first DNA vaccine authorized for use on humans. A DNA vaccine faces at least two major obstacles. First, the DNA (usually plasmid DNA) must be injected in such a way as to enter antigen presenting cells. The Indian vaccine, ZyCov-D, uses a needle-free injection device in which a pressurized jet of liquid punctures the skin and delivers the vaccine. The requirement for such a high-tech device is one drawback for widespread vaccination with ZyCov-D. In addition, for the vaccine to work, the DNA must not only enter the APC, but must somehow find its way to the nucleus,

where it can be transcribed into mRNA. Exactly how this happens is still a mystery. Time will tell how useful DNA will be for vaccinating humans.

WILL THERE BE AN AIDS VACCINE?

Most immunologists believe that to be effective, an AIDS vaccine must generate memory killer T cells. If this is true, non-infectious vaccines, which have been used to protect against many other pathogens, will be of little use against HIV-1. In principle, a weakened form of HIV-1 could be used as a vaccine that would produce memory CTLs. However, because the virus has an extremely high mutation rate, there is great concern that an attenuated form of HIV-1 might mutate to become lethal again. A carrier vaccine could generate memory killer T cells without putting the vaccine recipient at risk for AIDS, but this strategy has yet to yield a vaccine which elicits a strong, protective immune response against HIV-1.

Even if a safe vaccine could be devised which would produce HIV-1-specific CTLs, the high mutation rate of the AIDS virus makes it an elusive target. On average, each virus produced by an infected cell differs from the original infecting virus by at least one mutation. Consequently, the body of someone infected with HIV-1 contains not just "the" virus, but a huge collection of slightly different HIV-1 strains. Moreover, if this person infects another person, that individual will not usually be infected by just a single virus, but rather by a whole "swarm" of different viral strains. What this means is that the memory cells produced by a vaccination might protect very well against the particular strain of HIV-1 used to prepare the vaccine, yet be totally useless against the mutant versions of the virus which arise in a real infection. Indeed, the virus's ability to mutate rapidly may prove to be the most difficult problem of all to solve in making an effective AIDS vaccine.

Despite all these difficulties, immunologists are working hard to produce an AIDS vaccine that can be used to protect the public – because such a vaccine is viewed as the current best hope for controlling the spread of the AIDS virus. Recently, antibodies have been discovered in rare AIDS patients which can neutralize many different HIV-1 variants. If a vaccine could be made which would elicit these **broadly neutralizing antibodies** in healthy individuals, such a "universal" vaccine might be able to protect against infection – at least by many of the common HIV-1 strains. Unfortunately, broadly neutralizing antibodies against HIV-1 usually arise years after the initial infection, and result from many rounds of somatic hypermutation which produce "improbable mutations" not normally seen in antibody molecules. This finding raises the

question of whether a vaccine can be invented which elicits broadly neutralizing antibodies without having to wait for extensive somatic hypermutation to take place. And, of course, it may turn out that even broadly neutralizing antibodies are not enough, and that virus-specific CTLs really are required for protection against an HIV-1 infection.

It is important to note that HIV-1 is not the only microbe for which there is no effective vaccine. Roughly a million people die every year from malaria, yet there is no vaccine which has been shown to provide strong protection against this disease. Likewise, immunologists have not been able to devise an effective vaccine against tuberculosis, a bacterial infection which kills more than one million humans each year. And roughly one third of all the people on Earth are infected with herpes simplex virus, yet we do not have a vaccine that protects against infection with this virus.

VACCINATION TO PREVENT VIRUS-ASSOCIATED CANCER

Vaccines can be used to prevent certain types of cancer. For example, a chronic infection with **hepatitis B virus** increases one's risk of getting liver cancer about 200-fold, and roughly 20% of long-term hepatitis B carriers eventually develop this disease. Moreover, hepatitis B virus ranks as one of the most infectious of all viruses: Transfer of a fraction of a drop of blood is sufficient to spread the virus from one human to another. Fortunately, vaccines that protect against infection by hepatitis B virus have been available in the United States since 1982, and the current vaccine is administered not only to healthcare professionals who routinely come into contact with blood and blood products, but also to children. This subunit vaccine gives the immune system a "preview" of a real hepatitis B infection, allowing ample time for memory B cells and the antibodies they produce to be mobilized. If infection does occur, the prepared immune system can quickly eradicate the virus, effectively preventing hepatitis B-associated liver cancer.

Infection with certain "oncogenic" types of the **human papillomavirus (HPV)** can increase the risk of cervical cancer. These viruses are spread by sexual contact and there are now so many women infected with this virus that cervical carcinoma has become the fourth most common cancer in women world-wide, resulting in about 300,000 deaths per year. There are about a dozen slightly different types of HPV. A vaccine (Gardasil 9) has been developed which can protect against the seven types of HPV that are most frequently associated with cervical cancer. This is a subunit vaccine which is prepared using proteins that make up the protective coats of these viruses. It is estimated

that world-wide use of this new vaccine could prevent about 90% of all cervical cancer – providing that most sexually active young women could be vaccinated. Unfortunately, many of the cases of cervical cancer occur in less developed parts of the world where immunization via injection is problematic. Interestingly, the Gardasil 9 vaccine also includes coat proteins from two other HPV types which cause genital warts in both men and women. The thinking in including these two “extras” is that preventing genital warts might encourage boys and men to be vaccinated, since they might otherwise be reluctant to be vaccinated to prevent a disease (cervical cancer) they cannot get. HPV has also been implicated in oral, head and neck, penile, and anal cancers – so vaccinating boys as well as girls against human papillomavirus makes good sense.

VACCINE ADJUVANTS

In order for a vaccine to mimic the invasion of a pathogenic microbe, the immune system must view the vaccine as both foreign and dangerous. This is not a problem for a vaccine

which uses a crippled virus – because a crippled virus naturally provides both signals. However, for vaccines composed of only one or a few microbial proteins, providing the requisite danger signal is an important concern. Indeed, if a foreign protein is injected into a human, the immune system generally just ignores it – because it poses no danger.

Because of the requirement for a danger signal, it is common practice to combine vaccines with an **adjuvant** (derived from a Latin word meaning “help”). In fact, most of the vaccinations you have received probably contained aluminum hydroxide or “alum,” which functions, at least in part, by providing that important danger signal. Other, more powerful adjuvants are now being approved for use. For example, the Shingrix vaccine, which can protect against shingles, includes MPL, a modified version of the bacterial surface protein LPS as an adjuvant. In this subunit vaccine, lab-grown viral coat proteins provide the first signal – specific recognition of something foreign – and MPL alerts the immune system that there is danger associated with these viral proteins. Adding an adjuvant to a vaccine can greatly increase its potency, and can reduce the dose of vaccine which must be administered.

REVIEW

Vaccinations take advantage of the ability of B and T cells to remember invaders we have previously encountered. By introducing the immune system to a “safe” version of a microbe, vaccination prepares these adaptable weapons to respond rapidly and powerfully if a real attack occurs at some future time. The production of memory B and helper T cells does not require that an antigen presenting cell be infected. Consequently, non-infectious vaccines that elicit protective antibodies have been made from dead viruses or even a single viral protein. However, non-infectious vaccines do not produce memory killer T cells, and the protection conferred by non-infectious vaccines is not generally as long-lasting as the protection elicited by infectious vaccines.

Most immunologists believe that to protect against AIDS a vaccine will need to elicit memory killer T cells. To do this, a vaccine must be able to infect antigen presenting cells. Attenuated vaccines have been produced using a weakened version of a microbe that can still infect APCs, but cannot cause disease. However, a vaccine intended to protect the general population against AIDS must have no possibility of causing the disease. And because HIV-1 has a very high mutation rate, there are no guarantees that an

attenuated AIDS virus will not reactivate. Consequently, an attenuated form of the virus probably cannot be used to protect the public against an HIV-1 infection.

Another approach to making a vaccine that will elicit killer T cell memory is to insert one or more of a microbe’s genes into the genome of a benign carrier. Then, when the carrier infects antigen presenting cells, the microbe’s proteins will be produced. These proteins can be displayed by class I MHC molecules and can activate CTLs. So far, however, this approach has not produced a generally useful AIDS vaccine.

Vaccines made from DNA or RNA have been produced and used in humans, and mRNA vaccines have been quite successful in protecting against disease caused by a SARS-CoV-2 infection. The development of DNA vaccines lags behind mRNA vaccine development, and it is still not clear how useful DNA vaccines will be against human disease. So far, neither platform (mRNA or DNA) has been used to produce an AIDS vaccine.

Several “anticancer” vaccines are now on the market. These subunit vaccines can reduce the risk of contracting either hepatitis B virus or the human papillomavirus.

Infection with these viruses greatly increases the probability that a person will suffer from liver cancer (hepatitis B virus) or cancer of the uterine cervix (human papillomavirus). The potency of a vaccine can be increased by combining

the specific antigen that a B or T cell recognizes together with an adjuvant. The purpose of an adjuvant is to get the attention of the immune system by providing the danger signal required for activation.

KNOWN UNKNOWNS

1. Will the mRNA vaccine platform be useful in producing an AIDS vaccine?
2. Do DNA vaccines have special features that will make them the vaccines of choice for certain human diseases?
3. Why does intramuscular vaccination work? Muscle is not rich in antigen presenting cells.

THOUGHT QUESTIONS

1. Describe the series of events required to produce memory B cells.
2. Describe the series of events required to produce memory CTLs.
3. Discuss the strengths and weaknesses of killed virus vaccines, subunit vaccines, attenuated virus vaccines, and carrier virus vaccines.
4. What are the major obstacles to producing an AIDS vaccine that is both safe and effective?

Cancer and the Immune System

HEADS UP!

The immune system has limited ability to protect us against cancer cells in the early stages of tumor growth. First, there is a built-in conflict between providing surveillance against cancer cells and guarding against autoimmunity. Second, cancer cells mutate rapidly, making them a “moving target.” And third, tumors can create a “self-protective” environment in which immune surveillance is compromised.

INTRODUCTION

In this lecture, we are going to discuss how the immune system deals with cancer. Because you may not have had a cancer course, I will begin by discussing some general properties of cancer cells. After all, it’s important to know the enemy.

CANCER IS A CONTROL SYSTEM PROBLEM

Cancer arises when multiple control systems within a single cell are corrupted. These are of two basic types: systems that promote cell growth (proliferation) and safeguard systems that protect against “irresponsible” cell growth. Properly controlled, cell proliferation is a good thing. After all, an adult human is made up of trillions of cells, so a lot of proliferation must take place between the time we are a single fertilized egg and the time we are full-grown. However, once a human reaches adulthood, most cell proliferation ceases. For example,

when the cells in your kidney have proliferated to make that organ exactly the right size, kidney cells stop proliferating. On the other hand, skin cells and cells that line our body cavities (e.g., our intestines) must proliferate almost continuously to replenish cells that are lost as these surfaces are eroded by normal wear and tear. All this cell proliferation, from cradle to grave, must be carefully controlled to insure that the right amount of proliferation occurs at the right places in the body – and at the right time.

Usually, the growth-promoting systems within our cells work just fine. However, occasionally one of these systems may malfunction, and a cell may begin to proliferate inappropriately. When this happens, that cell has taken the first step toward becoming a cancer cell. Because these growth-promoting systems are made up of proteins, malfunctions occur when gene expression is altered, usually as a result of a mutation. **A gene which, when mutated, can cause a cell to proliferate inappropriately is called a proto-oncogene. And the mutated version of such a gene is called an oncogene.** The important point here is that **uncontrolled cell growth can result when a normal cellular gene is mutated.**

To protect against malfunctions in the control systems that promote cell proliferation, our cells are equipped with internal safeguard systems. These safeguards are of two general types: systems that help prevent mutations and systems that deal with mutations once they occur. Cells have multiple repair systems that can fix damaged DNA, helping safeguard against mutations. These DNA repair systems are especially important, because mutations occur continuously in the DNA of all our cells. In fact, it is estimated that, on average, each of our cells suffers about 25,000 mutational events every day. Fortunately, repair systems work nonstop, and if the DNA

damage is relatively small, it can be repaired immediately as part of the “maintenance” repair program.

Sometimes, however, the maintenance repair systems may miss a mutation, especially when there are many mutations and the repair systems are overwhelmed. When this happens, a second safeguard system comes into play – one that monitors unrepaired mutations. If the mutations are not extensive, this safeguard system stops the cell from proliferating to give the repair systems more time to do their thing. However, if the genetic damage is severe, the safeguard system will trigger the cell to commit suicide, eliminating the possibility that it will become a cancer cell. One of the important components of such a safeguard system is a protein called p53. **Proteins like p53, which help safeguard against uncontrolled cell growth, are called tumor suppressors, and the genes that encode them are called anti-oncogenes or tumor suppressor genes.** Mutations in the gene for p53 have been detected in the majority of human tumors, and scientists have created mice with mutant p53 genes. In contrast to normal mice, which rarely get cancer, mice that lack functional p53 proteins usually die of cancer before they are seven months old. So if you are ever asked to give up one gene, don’t pick p53!

The take-home lesson is that every normal cell has both proto-oncogenes and tumor suppressor genes. Where things get dangerous is when proto-oncogenes are mutated, so that the cell proliferates inappropriately, and tumor suppressor genes are mutated, so that the cell can’t defend itself against proto-oncogenes “gone wrong.” Indeed, **cancer results when multiple control systems, both growth-promoting and safeguard, are corrupted within a single cell.** It is estimated that between four and seven such mutations are required to produce most common cancers. This is the reason why cancer is a disease which generally strikes later in life: It usually takes a long time to accumulate the multiple mutations required to inappropriately activate growth-promoting systems and to disable safeguard systems.

Mutations that affect growth-promoting systems and safeguard systems can occur in any order. However, one type of mutation that is especially insidious is a genetic alteration which disrupts a safeguard system involved in repairing mutated DNA. When this happens, the mutation rate in a cell can soar, making it much more likely that the cell will accrue the multiple mutations required to turn it into a cancer cell. This type of mutation-accelerating defect is found in most (perhaps all) cancer cells. Indeed, **one of the hallmarks of a cancer cell is a genetically unstable condition in which cellular genes are constantly mutating.**

CLASSIFICATION OF CANCER CELLS

Cancer cells can be grouped into two general categories: non-blood-cell cancers (usually referred to as solid tumors) and blood cell cancers. Solid tumors are further classified according to the cell type from which they arise. **Carcinomas, the most common tumors in humans, are cancers of epithelial cells, and include lung, breast, colon, and cervical cancer.** These cancers generally kill by metastasizing to a vital organ, where they grow and crowd the organ until it no longer can function properly. **Humans also get cancers of the connective and structural tissues, although these sarcomas are relatively rare compared to carcinomas.** Perhaps the best known example of a sarcoma is bone cancer (osteosarcoma).

Blood cell cancers make up the other class of human cancers, and the most frequent of these are leukemias and lymphomas. Blood cell cancers arise when descendants of blood stem cells, which normally should mature into lymphocytes or myeloid cells (e.g., neutrophils), stop maturing, and just continue proliferating. In a real sense, these blood cells refuse to “grow up” – and that’s the problem. In leukemia, the immature cells fill up the bone marrow and prevent other blood cells from maturing. As a result, the patient usually dies from anemia (due to a scarcity of red blood cells) or from infections (due to a deficit of immune system cells). In lymphoma, large clusters of immature cells form in lymph nodes and other secondary lymphoid organs – clusters that in some ways resemble solid tumors. Lymphoma patients usually succumb to infections or organ malfunction.

There is another way to classify human cancers: **spontaneous** and **virus-associated.** **Most human tumors are “spontaneous.” They arise when a single cell happens to accumulate a collection of mutations that causes it to acquire the properties of a cancer cell.** These mutations can result from errors made when cellular DNA is copied to be passed down to daughter cells, or from the effects of mutagenic compounds (**carcinogens**). Such mutagens can be byproducts of normal cellular metabolism, or can be present in the air we breathe and the food we eat. Mutations can also be caused by radiation (including UV light) or by errors made in assembling the segments of DNA that make up the B and T cell receptors. As we go through life, these mutations occur “spontaneously.” However, there are certain factors that can accelerate the rate of mutation and increase the chances that a cell will become cancerous: cigarette smoking, a fatty diet, an increased radiation exposure from living at

high altitude, working in a plutonium processing plant, and so on.

Some viruses produce proteins that can interfere with the proper functioning of growth-promoting and safeguard systems. Infection with these special tumor viruses decreases the total number of cellular genes which must be mutated to turn a normal cell into a cancer cell. Consequently, a tumor virus infection can be an accelerating factor for cancer. For example, essentially all human cervical cancers involve an infection by the human papillomavirus. This sexually transmitted virus infects cells that line the uterine cervix and expresses viral proteins in these cells that can disable two safeguard systems, including the safeguards provided by p53. Likewise, hepatitis B virus can establish a chronic infection of liver cells, can inactivate p53, and can act as an accelerating factor for liver cancer.

The hallmark of virus-associated cancer is that only a small fraction of infected individuals actually get cancer, yet for those who do, virus or viral genes can usually be recovered from their tumors. For example, less than 1% of women infected with genital human papillomavirus will ever get cancer of the cervix, yet HPV genes have been found in over 90% of all cervical carcinomas examined. The reason for this, of course, is that **the virus can't cause cancer by itself – it can only accelerate the process that involves the accumulation of cancer-causing mutations.** About one fifth of all human cancers have a viral infection as an accelerating factor.

IMMUNE SURVEILLANCE AGAINST CANCER

From this introduction, it should be clear that **powerful defenses exist within the cell (e.g., tumor suppressor proteins) to deal harshly with most wannabe cancer cells. But does the immune system of a healthy human provide significant protection against cancerous cells which might go on to form a tumor?** To try to answer this question, let's examine the roles which various immune system cells might play in cancer surveillance – keeping in mind that their ability to provide meaningful surveillance may depend critically on the type of cancer.

CTLs and spontaneous tumors

The majority of human cancers are spontaneous tumors that are not of blood cell origin. It has been proposed that killer T cells might provide surveillance against these solid tumors, preventing their formation. Let's try to evaluate this possibility.

The activation problem

Imagine that a heavy smoker finally accumulates enough mutations in the cells of his lungs to turn one of them into a cancer cell. Remember, **it only takes one bad cell to make a cancer.** And let's suppose that because of these mutations, this cell expresses antigens that could be recognized as foreign by CTLs. Now let me ask you a question: Where are this man's naive T cells while the tumor is starting to grow in his lung? That's right. They are circulating through the blood, lymph, and secondary lymphoid organs. Do they leave this circulation pattern to enter the tissues of the lung? No, not until after they have been activated.

So right away, in terms of immune surveillance, we have a "traffic problem." To make self tolerance work, naive T cells are not allowed out into the tissues. Consequently, it's unlikely that virgin T cells ever would "see" tumor antigens expressed in the lung – because they just don't go there. **What we have here is a serious conflict between the need to preserve tolerance of self (and avoid autoimmune disease) and the need to provide surveillance against tumors that arise, as most tumors do, out in the tissues. And self tolerance usually wins.**

Now, sometimes virgin T cells do disobey the traffic laws and wander out into the tissues. So you might imagine that this kind of adventure could give some T cells a chance to look at the tumor that's growing in this guy's lung, and be activated. But wait! What is required for T cell activation? First of all, killer T cells must recognize antigens which are produced within a cell and presented by class I MHC molecules on the surface of that cell – and a cancer cell could do that. However, CTLs also require co-stimulation from the cell that presents the antigen. Is this lung tumor cell going to provide that co-stimulation? I don't think so! This isn't an antigen presenting cell, after all. It's a plain old lung cell, and lung cells don't usually express co-stimulatory molecules like B7. So if a virgin CTL goes rogue and breaks the traffic laws, enters the lung, and recognizes a tumor antigen displayed by class I MHC molecules on a cancer cell, that CTL most likely will be anergized or killed – because the cancer cell will not provide the co-stimulation the CTL needs for survival.

Again we see a conflict between tolerance of self and tumor surveillance. **The two-key system of specific recognition plus co-stimulation was set up so that T cells which recognize self antigens out in the tissues, but which do not receive proper co-stimulation, will be anergized or killed to prevent autoimmunity. Unfortunately, this same two-key system makes it very difficult for CTLs to be activated by tumor cells that arise in the tissues.** So the bottom line is that **a CTL would have to per-**

form “unnatural acts” to be activated by a tumor that is beginning to grow out in the tissues: The CTL would have to break the traffic laws and somehow avoid being anergized or killed. This could happen, of course, but it would be very inefficient compared to the activation of CTLs in response to, for example, a viral infection.

You might ask, “Why, during evolution, was such a premium placed on avoiding autoimmune disease that the immune system’s ability to defend against cancer was compromised?” What we need to remember is that our immune system evolved to protect humans until we are past our “breeding age.” Autoimmune disease can be devastating to a young person, but cancer is usually a disease that affects people later in life. Consequently, **evolutionary pressure to protect humans of child-bearing age resulted in an immune system that sacrifices a robust defense against cancer in favor of protection against autoimmune disease.**

The mutation problem

A possible solution to the traffic problem is that cancer cells from the primary tumor might metastasize to a lymph node, where T cells might be activated. However, by the time this happens, the original tumor will have probably become quite large. Even a tumor that weighs only about half an ounce will contain more than ten billion cancer cells – more cells than there are people on our planet! This poses a major problem for immune surveillance, because cancer cells usually mutate like crazy, and with so many cells mutating, it is likely that some of these mutations will prevent recognition or presentation of tumor antigens. For example, the gene encoding the tumor antigen itself might mutate so that the tumor antigen can no longer be recognized by activated CTLs, or will no longer fit properly into the groove of an MHC molecule for presentation. Also, genes that encode the TAP transporters can mutate in a tumor cell, with the result that tumor antigens will not be efficiently transported for loading onto class I MHC molecules. And tumor cells can mutate so that they stop producing the particular MHC molecules that CTLs are restricted to recognize. This happens quite frequently: About 15% of the tumors that have been examined have lost expression of at least one of their MHC molecules. Indeed, **a tumor cell’s high mutation rate is its greatest advantage over the immune system, and usually keeps these cells one step ahead of surveillance by CTLs.**

Cancer cells fight back

There is another difficulty which tumor-specific CTLs must face in providing surveillance against solid tumors:

Cancer cells fight back. Once a solid tumor has been established, the cancer cells can modify the environment in the neighborhood of the tumor to make it more difficult for immune system cells to operate. In Lecture 8, I mentioned an inhibitory receptor, PD-1, which is found on the surface of activated T cells. The natural function of this checkpoint protein is to restrain CTLs so that the immune response does not become over-exuberant. However, many types of cancer cells express ligands for these immunosuppressive proteins, and ligation of PD-1 on T cells can impair their function. This can help protect the growing tumor from killing by tumor-specific CTLs.

Many tumors also express high levels of indoleamine 2,3-dioxygenase. This enzyme catalyzes the metabolism of the essential amino acid tryptophan, resulting in the rapid consumption of tryptophan from the tumor environment. And when killer T cells are starved of tryptophan, they stop proliferating and become anergic. Some tumors produce prostaglandin E₂, which decreases NK cell function, making it less likely that NK cells will destroy cells in the tumor which have lost class I MHC expression or are displaying surface molecules indicating that they are stressed. In addition, tumor cells can influence helper T cells in their neighborhood to become regulatory T cells. Exactly how this is accomplished is not well understood, but the resulting iTregs secrete TGFβ and IL-10, creating an immunosuppressive environment in which immune system cells function poorly.

My conclusion is that **killer T cells provide limited protection against solid tumors when these cells first become cancerous – because it is very difficult to activate CTLs early in the course of the disease. Later, when the tumor becomes larger, killer T cells may be activated. However, at this late stage, CTLs are relatively ineffective at eradicating the tumor. The high mutation rate of cancer cells helps them escape immunosurveillance, and the tumor can create an immunosuppressive environment that reduces the effectiveness of tumor-specific killer T cells. Consequently, even when it occurs, CTL surveillance against solid tumors is usually a case of “too little, too late.”**

CTLs and cancerous blood cells

Okay, so CTLs probably don’t provide serious surveillance against non-blood-cell, spontaneous tumors, especially when they first arise. That’s a real bummer, because these make up the majority of human tumors. But what about blood cell cancers like leukemia and lymphoma? Maybe CTLs are useful against them. After all, immunosuppressed humans do have higher frequencies of

leukemia and lymphoma than humans with healthy immune systems. This suggests that there might be fundamental differences between immune surveillance against tumors in tissues and organs versus surveillance against cancerous blood cells. Let's take a look at what these differences might be.

One of the problems that CTLs have in providing surveillance against tumors that arise in tissues is that these tumors are simply not on the normal traffic pattern of virgin T cells – and it's hard to imagine how a CTL could be activated by a cancer it doesn't see. In contrast, most blood cell cancers are found in the blood, lymph, and secondary lymphoid organs, and this is ideal for viewing by virgin CTLs, which pass through these areas all the time. Thus, **in the case of blood cell cancers, the traffic patterns of cancer cells and virgin T cells actually intersect. Moreover, in contrast to tumors in tissues, which are usually unable to supply the co-stimulation required for activation of virgin T cells, some cancerous blood cells actually express high levels of B7, and therefore can provide the necessary co-stimulation.**

Solid tumors create an immunosuppressive environment around them which makes it very difficult for tumor-specific CTLs to function. Blood cell cancers do not create such a barrier, so they likely are easier targets for destruction by CTLs. Also, on average, cancerous blood cells have fewer mutations than most solid tumors. For this reason, the immune system might have an easier time dealing with blood cell cancers because the likelihood of “escape mutations” might be less than with highly mutated solid tumors.

These properties of blood cell cancers suggest that CTLs may provide surveillance against some of them. Unfortunately, this surveillance must be incomplete, because people with otherwise healthy immune systems still get leukemias and lymphomas.

CTLs and virus-associated cancers

Certain viral infections can predispose a person to particular types of cancer. Because killer T cells are good at defending against viral infections, it is easy to imagine that CTLs might provide surveillance against virus-associated tumors. Unfortunately, this surveillance is probably quite limited. Here's why.

Most viruses cause “acute” infections in which all the virus-infected cells are rather quickly destroyed by the immune system. Consequently, **viruses which only cause acute infections do not play a role in cancer** – because a dead cell isn't going to make a tumor. This explains why most viral infections are not associated with human cancer.

There are some viruses, however, which can evade the immune system and cause long-term (sometimes life-long) infections (e.g., hepatitis B virus and the human papillomavirus). Indeed, **all viruses which have been shown to play a role in causing cancer are able to establish chronic infections during which they “hide” from the immune system.** CTLs cannot destroy virus-infected cells while they are hiding, and because these hidden cells are the very ones which eventually become cancerous, it can be argued that CTLs do not provide effective surveillance against virus-associated cancer.

Of course, you might propose that without killer T cells, more cells would be infected during a virus attack, thereby increasing the number of cells in which the virus might be able to establish a long-term, hidden infection. And this probably is true. In fact, this may help explain why humans with deficient immune systems have higher than normal rates of virus-associated tumors. However, the bottom line is that **CTLs cannot provide significant surveillance against virus-infected cells that have become cancerous, because these cancers only result from long-term viral infections – infections which CTLs cannot detect or cannot deal with effectively.**

IMMUNE SURVEILLANCE BY MACROPHAGES AND NK CELLS

Macrophages and natural killer cells may provide surveillance against some cancers. Hyperactivated macrophages secrete TNF and express it on their surface. Either form of TNF can kill certain types of tumor cells in the test tube. This brings up an important point: **What happens in the test tube is not always the same as what happens in an animal.** For example, there are mouse sarcoma cells that are very resistant to killing by TNF in the test tube. In contrast, when live mice that have these same sarcomas are treated with TNF, their tumors are rapidly destroyed. Studies of this phenomenon showed that the reason TNF is able to kill the tumor when it is in the animal is that this cytokine actually attacks the blood vessels that feed the tumor, cutting off the blood supply and causing the tumor cells to starve to death. This type of death is called necrosis, and it was this observation that led scientists to name this cytokine “tumor necrosis factor.”

In humans, there are examples of cancer therapies in which activated macrophages are likely to play a major role in tumor rejection. One such therapy involves injecting the tumor with **bacille Calmette–Guérin (BCG)**, a cousin of the bacterium that causes tuberculosis. BCG hyperactivates macrophages, and when it is injected

directly into a tumor (e.g., a melanoma), the tumor fills up with highly activated macrophages that can destroy the cancer. In fact, one way of treating bladder cancer is to inject it with BCG – a treatment which is quite effective in eliminating superficial tumors, probably through the action of hyperactivated macrophages.

But how do macrophages tell the difference between normal cells and cancer cells? The answer to this question is not known for certain, but evidence suggests that macrophages recognize tumor cells that have unusual cell surface molecules. One of the duties of macrophages in the spleen is to test red blood cells to see if they have been damaged or are old. Macrophages use their sense of “feel” to determine which red cells are past their prime. And when they find an old one, they eat it. What macrophages feel for is a fat molecule called phosphatidylserine. This particular fat is usually found on the inside of young red blood cells, but flips to the outside when the cells get old. Like old red blood cells, tumor cells also tend to have unusual surface molecules, and in fact, some express phosphatidylserine on their surface. It is believed that **the abnormal expression of surface molecules on tumor cells may allow activated macrophages to differentiate between cancer cells and normal cells.**

Natural killer cells target cells that express low levels of class I MHC molecules and which display unusual surface molecules (e.g., proteins which indicate that the target cells are “stressed”). In the test tube, natural killer cells can destroy some tumor cells, and there is also evidence that NK cells can kill cancer cells in the body. Certainly, there would be a number of advantages to having macrophages and NK cells provide surveillance against wannabe cancer cells. First, **unlike CTLs, which take a week or more to get cranked up, macrophages and NK cells are quick-acting.** This is an important consideration, because the longer abnormal cells have to proliferate, the greater is the likelihood they will mutate to take on the characteristics of metastatic cancer cells. In addition, once a tumor becomes large, it is much more difficult for the immune system to deal with. So you would like the weapons that protect against cancer cells to be ready to go just as soon as the cells start to get a little weird.

You would also want anti-tumor weapons to be focused on diverse targets, because a single target (e.g., the MHC-peptide combination seen by a killer T cell) can be mutated, rendering the target unrecognizable. **Both NK cells and macrophages recognize diverse target structures, so the chance of them being fooled by a single mutation is small.** In addition, **macrophages are located out in the tissues where most tumors arise, so they could intercept cancer cells at an early stage.** And with immune surveillance, as with real estate, location is everything.

There are problems, however, with macrophages and NK cells providing surveillance against cancer. **Macrophages need to be hyperactivated before they can kill cancer cells.** That's what the BCG treatments do: They hyperactivate macrophages by causing inflammation. So if a wannabe cancer cell arises at a site where an inflammatory reaction is taking place, macrophages in the area can be hyperactivated. But if there's no inflammatory reaction going on, macrophages will probably remain in a resting state and simply ignore the cancer cells. Unlike macrophages, which are found in large numbers in our tissues, most NK cells are found in the blood. Like neutrophils, NK cells are “on call.” And the cells which do the calling are activated macrophages and dendritic cells that are responding to an invasion. So **unless there is an inflammatory reaction going on in the tissues, most NK cells will just continue to circulate in the blood.**

As a tumor grows, it eventually becomes so large that the neighboring blood vessels cannot provide the nutrients and oxygen required for continued growth, and some of the cancer cells begin to die. Cancer cells also die when they accumulate mutations that are lethal. Consequently, at a later stage in the growth of a tumor, dying cancer cells may provide the signals required to activate macrophages – which can then recruit natural killer cells from the blood. So at this point, macrophages and NK cells may play a role in destroying at least some of the tumor cells. In addition, because NK cells do not need to be activated to kill, natural killer cells that are circulating in the blood may be able to destroy either blood cell cancers or cancer cells that are metastasizing through the blood from a primary tumor.

REVIEW

Although it is certain that human cells have built-in safeguards to help protect them from becoming cancerous, it is not nearly so clear what role the immune system

plays in protecting us against this terrible disease. Natural killer cells and macrophages can recognize and kill some tumor cells – those which have unusual molecules on their

surface, and NK cells can target cancer cells which have downregulated expression of class I MHC molecules. NK cells may also reduce the frequency of metastases or help slow the metastatic process once a primary tumor has formed. Consequently, macrophages and NK cells may be useful against certain types of cancer.

Unfortunately, it is unlikely that killer T cells provide significant surveillance against most solid tumors in humans. There are several reasons for this. First there is the activation problem. Many safeguards are in place to protect humans against autoimmunity, and these safeguards make it very difficult for cancer-specific CTLs to be activated – especially during the early stages of tumor development. Virgin T cells circulate through the blood/lymphatic system and are activated in the secondary lymphoid organs. Consequently, the normal traffic pattern of naive T cells keeps them from coming in contact with cancer cells in the tissues. In addition, most cancer cells cannot supply the co-stimulation required to activate killer T cells, so even a “chance encounter” between a naive T cell and a tumor cell out in the tissues isn’t likely to result in activation.

Another obstacle to cancer surveillance by killer T cells is that, because of their high mutation rate, cancer cells

represent a “moving target.” Even if a CTL can be activated so that it can attack some cells in a tumor, it is very likely that there will be other cancer cells within the tumor which have mutated so that they are invisible to that killer T cell. Finally, solid tumors can create an immunosuppressive environment around them which can make CTLs ineffective against these tumors.

It is more likely that CTLs provide some surveillance against blood cell cancers than against solid tumors. The circulation patterns of naive T cells can bring them into contact with blood cell cancers, some cancerous blood cells express co-stimulatory molecules like B7, cancerous blood cells generally have lower mutation rates than do cells in solid tumors, and blood cell cancers do not cloak themselves in an immunosuppressive environment.

It is also unlikely that killer T cells provide significant surveillance against virus-associated cancers. These cancers arise in cells in which the virus has already established a “stealth” infection that cannot be detected by killer T cells. Consequently, the fact that a cancer cell was virus-infected would not make it a target for destruction by virus-specific CTLs.

KNOWN UNKNOWNS

1. Tumor-specific CTLs can be detected in some cancer patients. How were these CTLs activated?
2. Does the immune system provide meaningful surveillance against cancer cells that have metastasized from

a primary tumor and taken up residence in other parts of the body?

3. How does the microenvironment around solid tumors influence T cells to become iTregs?

THOUGHT QUESTIONS

1. There is a conflict between immune surveillance against cancer and the preservation of tolerance of self antigens. Explain.
2. Discuss why the adaptive immune system may provide some surveillance against blood cell cancers, but is usually ineffective against solid tumors.
3. Why can macrophages and NK cells only be expected to destroy cancer cells under special circumstances?
4. Vaccines against tumor viruses can help prevent virus-associated cancer. What obstacles do you foresee which might make it difficult for immunologists to make vaccines that would prevent other forms of cancer?

HEADS UP

Antibodies manufactured in the lab are being used to treat disease. Some therapeutic antibodies bind to cytokines or growth factors and prevent these proteins from signaling. Others tag cells for destruction. Therapeutic antibodies can also be used to block the action of checkpoint proteins to give T cells a better chance to fight cancer. And T cells removed from a patient can be modified and infused back into that patient as a cancer therapy.

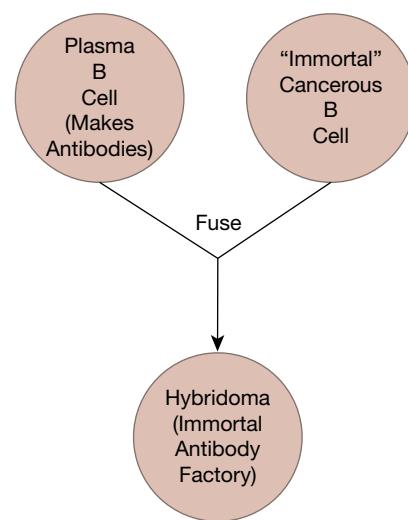
INTRODUCTION

Currently, there is great interest in using immunotherapies to treat human diseases such as autoimmunity and cancer. In this lecture, I will discuss some examples of the approaches that are being tried, sometimes with great success. What you will notice is that all of these immunotherapies are based on an understanding of how the immune system normally functions to protect us from disease.

IMMUNOTHERAPY USING MONOCLONAL ANTIBODIES

Antibodies have properties that make them extremely useful to the immune system. For example, they can bind tightly to a specific target, and can direct the immune system to destroy that target. These same properties could also make antibodies useful in treating disease. But there is a problem: Although plasma B cells produce a ton of antibodies, plasma B cells have a very short

lifetime – usually only a few days. So for antibodies to have practical value as “drugs,” a procedure would need to be devised that would extend the life of plasma cells. Two scientists named George Köhler and Cesar Milstein recognized that many cancerous blood cells are “immortal”: they can be grown in the lab almost indefinitely. They hypothesized that if they could somehow fuse a cancerous B cell that didn’t make any antibodies with a B cell that was making the antibody they wished to mass produce, they might be able to create a hybrid cell – a **hybridoma**. Ideally, this hybrid would combine the best qualities of both of its “parents”: **A hybridoma could make large quantities of the desired antibody and, because it could be grown indefinitely in the lab, it could be used as an antibody factory.** Although this sounds a bit like science fiction, their idea worked! Indeed, this discovery is so important that Köhler and Milstein were awarded the Nobel Prize. Because the hybridoma technology results in a clone of immortal cells that produces only one kind of antibody, the antibodies that are made are called **monoclonal antibodies**.



Currently, about half of all drugs in clinical trials are monoclonal antibodies, and a number of monoclonal antibodies have already been approved for immunotherapy by the Food and Drug Administration (FDA) in the United States. The common term (e.g., in a TV ad) for a therapeutic monoclonal antibody is a “biologic.”

Using monoclonal antibodies to treat autoimmune disease

Some therapeutic monoclonal antibodies are designed to bind to specific proteins and keep them from functioning. The inflammation associated with rheumatoid arthritis is caused mainly by tumor necrosis factor (TNF), a cytokine produced by macrophages which infiltrate the joints under the direction of self-reactive helper T cells. Monoclonal antibodies (e.g., Humira (adalimumab)) can block the action of TNF, either by binding to TNF or to its receptor. TNF blockers can be very effective in decreasing the severity of arthritis symptoms, and these monoclonal antibodies are now the world’s most popular class of drugs, with annual sales that exceed US\$25 billion. These antibodies are administered by injection under the skin, usually every two weeks. Although TNF blockers work well, it is important to keep in mind that TNF is a cytokine which is an important part of the immune defense. Consequently, inhibiting its action leaves patients susceptible to infections. I’m sure you have heard the long list of disclaimers when these drugs are advertised on TV!

Plaque psoriasis is another autoimmune disease that is being treated with monoclonal antibodies. The bad actor in this disease is the cytokine IL-17, which can cause skin cells (keratinocytes) to proliferate when they should not. This errant proliferation results in the patches (plaques) of thickened and scaling skin that characterize the disease. Monoclonal antibodies (e.g., Cosentyx (secukinumab)) that block the interaction between IL-17 and its receptor on keratinocytes are quite effective in treating moderate-to-severe plaque psoriasis. However, one of the normal functions of IL-17 is to help defend against fungal infections (e.g., *Candida albicans*). Consequently, patients who are treated with IL-17 blockers have an increased susceptibility to yeast infections.

Monoclonal antibodies are also being used to eliminate immune system cells that are responsible for causing disease. Campath-1H (alemtuzumab) is a monoclonal antibody that binds to CD52, an antigen that is abundant on the surface of B cells, T cells and monocytes – but not on the surface of other cell types. When Campath-1H binds to CD52, it can trigger destruction of its target cell either by fixing complement (and overwhelming the cell’s anti-complement defenses) or by antibody-dependent

cellular cytotoxicity (ADCC), in which the monoclonal antibody identifies the target and a phagocyte does the killing. Importantly, although this monoclonal antibody can deplete B and T cells, it does not destroy the blood stem cells that produce these lymphocytes. As a result, after the immunotherapy has been discontinued, new B and T cells can be made to replace the ones that have been destroyed. Campath-1H is currently used to treat multiple sclerosis, an autoimmune disease mediated by self-reactive T cells.

The monoclonal antibodies pioneered by Köhler and Milstein were made by fusing two mouse cells – so they were mouse antibodies. Consequently, these antibodies could be seen as foreign by the human immune system and destroyed, limiting the time that they would survive in the body of a patient. To circumvent this potential problem, genetic engineering can be used to replace most or all of the foreign DNA sequence that encodes the antibody molecules with the corresponding human sequence. As a result, the patient’s immune system will be tolerant of these “humanized” monoclonal antibodies. Campath-1H was the first humanized antibody to be approved by the FDA.

Using monoclonal antibodies to treat cancer

Monoclonal antibodies are being used to treat several types of cancer. Rituximab is a monoclonal antibody that binds to a protein called CD20 on the surface of B cells, and marks these cells for destruction by antibody-dependent cellular cytotoxicity. This was the first monoclonal antibody approved by the FDA for the treatment of cancer, and it has been used very successfully to treat non-Hodgkin lymphoma – a blood cell cancer which arises when B cells suffer mutations that block their maturation process. CD20 is expressed on the surface of immature B cells (e.g., non-Hodgkin lymphoma cells), but it is not found on the surface of blood stem cells which function to restock the blood system. Moreover, CD20 is not expressed on B cells that have matured to the antibody-producing stage. The idea here is that rituximab will bind to the CD20-expressing lymphoma cells and tag them for destruction, but will spare blood stem cells and long-lived plasma B cells which, as a consequence of an earlier infection or vaccination, are producing protective antibodies.

Roughly 25% of patients with metastatic breast cancer have tumors which produce unusually large amounts of a growth factor receptor called Her2. When this surface receptor is ligated by growth factor proteins, it causes these cancer cells to proliferate. The monoclonal antibody Herceptin (trastuzumab) can bind to the Her2 receptor,

"covering" it, and preventing it from receiving signals which would trigger proliferation. As a result, for the subset of patients whose breast cancers overproduce Her2, this immunotherapy can increase survival time by slowing the growth of metastases.

In Lecture 8, we discussed how two "checkpoint proteins," CTLA-4 and PD-1, appear on the surface of activated T cells to keep them from becoming overly exuberant. T cells which undergo repeated rounds of activation and proliferation express increasing amounts of CTLA-4 on their surface. This checkpoint protein competes with the activation receptor CD28 for binding to B7 (expressed on activated dendritic cells), and makes it harder for T cells to be reactivated in secondary lymphoid organs. This can limit the ability of tumor-specific T cells to build up their numbers to the point where they might be numerous enough to destroy a tumor.

Ligation of the checkpoint protein PD-1 does not interfere with activation. Rather, ligation of PD-1 suppresses the effector function of T cells (e.g., the ability to kill their target cells) and their ability to proliferate. Indeed, the normal purpose for PD-1 expression appears to be to dampen the immune response and minimize the collateral damage to tissues which might result if T cells continued to function after an infection has been cleared. Tumor cells frequently express PD-L1, the ligand for PD-1, and other cells in the tumor environment can be induced to express PD-L1 in response to cytokines such as IFN- γ , which result from the inflammation associated with a tumor. By expressing or inducing the expression of PD-L1, solid tumors can "protect themselves" by creating a local environment which is hostile to the T cells that otherwise might destroy them.

Immunologists reasoned that if cancer patients do have T cells which can target their tumors, these cells might be held in check by either or both of these checkpoint proteins. If so, it might be possible to "reinvigorate" the anti-tumor immune response by treating patients with monoclonal antibodies that would block the interaction between the checkpoint proteins on T cells and their ligands. One of the first checkpoint inhibitors to reach the market was a monoclonal antibody called ipilimumab that can bind to CTLA-4 on the surface of T cells and prevent this checkpoint protein from soaking up the limited number of B7 proteins on APCs. This type of checkpoint blockade has been most effective in treating metastatic melanoma, and has extended the life of some patients. However, one of CTLA-4's normal functions is to provide protection against autoimmunity by making it harder to reactivate self-reactive T cells that are chronically stimulated by plentiful self antigens. Consequently, monoclonal

antibody blockade of CTLA-4 can result in serious side effects such as colitis and liver inflammation – conditions that are commonly associated with autoimmune disorders.

More recently, monoclonal antibodies have been created that can bind either to PD-1 on T cells or to PD-L1 and block the interaction of these two proteins. PD-1 blockade seems to cause less serious autoimmune-type side effects than does CTLA-4 blockade, and PD-1 blockers have been used to treat about a dozen different cancers with response rates ranging from 15% to 90%. Hodgkin lymphoma, advanced melanoma, and lung cancer are among the cancer types which have been successfully treated. Even for bladder cancer, where the response rate is only about 15%, and where untreated patients typically survive for less than one year, treatment with monoclonal antibodies that block the PD-1/PD-L1 interaction has extended the life of some patients for more than three years. Probably the most famous patient to have received PD-1 blockade therapy was Jimmy Carter. In 2015, President Carter was diagnosed with a malignant melanoma that had metastasized to his brain and liver. The prediction was that he would live only a matter of months. He was treated with a combination of radiation, chemotherapy, and a PD-1 blocker – and is still alive more than six years later.

It is important to note that **checkpoint blockade only works as a cancer treatment if a patient's immune system is already making anti-tumor T cells – cells whose effectiveness is limited either because there are too few of them, or because they do not function well**. Although checkpoint blockade has been useful in treating some cancers, tumor-specific T cells are not found in the majority of human tumors, indicating that most cancer cells do not activate the adaptive immune system. In patients who do have tumor-specific T cells, it has been found that most of these T cells have receptors that bind to **neoantigens** – "new" antigens which cancer cells make as a result of mutations in the DNA that encodes normal cellular proteins. As a consequence of such mutations, neoantigens are essentially foreign antigens – antigens to which CTLs are not tolerant.

In general, immunotherapy with antibodies that block the PD-1/PD-L1 interaction work best if the patient's tumor cells express high levels of PD-L1. Hodgkin lymphoma cells, for example, have a genetic mutation that causes them to overexpress PD-L1, and the response rate for treatment of this cancer with PD-1 blockade approaches 90%. Unfortunately, Hodgkin lymphoma is the exception. Checkpoint blockade can generally extend the life of only about 20% of people with certain other cancers. Moreover,

there is currently no good way to predict who the “lucky” 20% might be.

Well-established tumors that contain cells with many genetic mutations have a greater likelihood of producing neoantigens that can be recognized by T cells. However, such tumors also have a higher probability of including “escape” variants – cancer cells in which the neoantigen can no longer be presented or recognized. Consequently, although the positive responses to checkpoint immunotherapy can last for years, most patients’ tumors do not disappear completely, and many tumors that regress or are stable as a result of checkpoint blockade begin to grow again after a relatively short time. Finally, checkpoint inhibitors are administered by infusion once every two or three weeks in a hospital, and these treatments are expensive: This monoclonal antibody treatment currently costs about US\$100,000 per year per patient.

The functions of CTLA-4 and PD-1 are nonredundant. CTLA-4 acts mainly in the secondary lymphoid organs to prevent T cell activation. In contrast, PD-1 usually functions at the site of the cancer as a negative regulator of the anti-cancer response. Clinical trials suggest that blocking both of the these checkpoints is more effective than blocking just one or the other. However, this combination treatment also is more toxic than treatment with a single blocker.

IMMUNOTHERAPY USING T CELLS

T cells can also be used to treat disease. In some cases, this involves assisting “natural” T cells that just need help getting the job done. In other cases, T cells are modified by genetic engineering to make them “better, faster, stronger.”

Cancer immunotherapy using adoptive cell transfer

When surgeons removed tumors from patients with cancer (e.g., melanomas), they often found that the cancerous tissue had been “infiltrated” by T cells – cells which they named **“tumor infiltrating lymphocytes”** or **TILs**. When these cells were examined, it was discovered that some of them had receptors which could recognize antigens expressed by the cancer cells. This finding suggested that the immune system was trying to deal with the cancer, but there might just be too few tumor-specific T cells to do the job.

To test this idea, immunologists devised the following procedure: They made many individual cultures from single cells recovered from a patient’s tumor, and grew these cells in the presence of IL-2 to cause tumor

infiltrating lymphocytes to proliferate. Next, each culture was tested to identify the one which contained T cells that had the highest activity against the cells of the tumor. This “winning” culture was forced to proliferate further to produce about 100 billion tumor-specific T cells. Finally, these “living drugs” were infused back into the patient to treat his cancer.

This procedure, called **adoptive cell transfer (ACT)**, has resulted in the cessation of tumor growth and even tumor eradication in some melanoma patients. In one trial, the tumors of 20 of 93 patients regressed completely, and 19 of these individuals experienced no recurrences when tested five to ten years after they had been treated – indicating that they were probably cured. So far, only melanomas have yielded TILs that are useful in ACT.

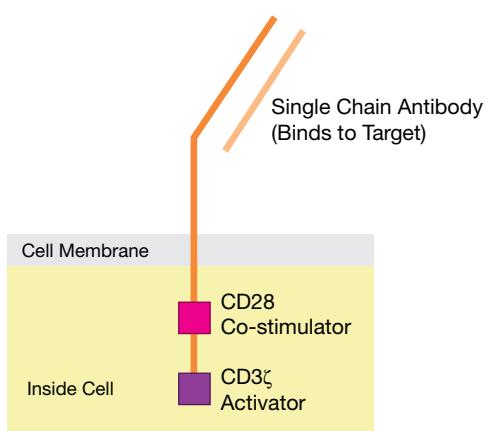
Adoptive cell transfer has several advantages. This immunotherapy relies on the expansion of naturally occurring tumor-specific T cells, and it is not necessary to know which antigen(s) is recognized by the TILs that are isolated. Also, most TILs target neoantigens. As a result, even when a very large number of TILs is administered, these treatments generally don’t cause autoimmunity. On the other hand, because TILs usually recognize mutated proteins that are unique to each patient, ACT is extremely expensive.

Cancer immunotherapy using engineered T cells

The goal of adoptive cell transfer is to greatly increase the number of natural tumor-specific lymphocytes, so that they are numerous enough to win a battle the patient’s immune system is already fighting. However, this type of immunotherapy fails if tumor-specific T cells do not exist or cannot be isolated. In addition, TILs can only destroy cancer cells whose MHC molecules are able to present the tumor antigen which the TILs recognize – and cancer cells are notorious for mutating to prevent antigen presentation. Moreover, tumors are genetically heterogeneous, so some tumor cells may express the TILs’ target antigen, whereas other cells in the tumor may not. To circumvent these potential problems, immunologists are exploring ways to use genetic engineering to “upgrade” a patient’s T cells, and to use these manipulated T cells to treat that patient’s cancer.

Although a number of different approaches are being used to engineer T cells to fight cancer, the therapy that has given the best results so far is called chimeric antigen receptor (CAR) T cell therapy. The name comes from a Greek mythological creature which had the head of a lion, the body of a goat, and the tail of a dragon. The concept behind **CAR T cell therapy** is to use genetic engineering to

modify a patient's T cells so that they produce an "artificial" T cell receptor. Like the mythological creature, this synthetic TCR usually has three parts: First there is a recognition domain which is displayed on the surface of the engineered T cell, and which can bind to the desired surface antigen on the target cancer cell. This recognition domain is usually a single heavy/light chain binding region "borrowed" from an antibody molecule that recognizes the target antigen. This extracellular recognition domain is connected to a second protein inside the cell that contains the T cell's CD3 ζ protein, which can signal that the target receptor has been engaged. And to provide the necessary co-stimulatory signal, the CD3 ζ protein is joined to the signaling domain of a co-stimulatory molecule like CD28. The idea here is that the recognition domain of the CAR T cell will identify the target cell, the CD3 ζ protein will send the TCR engaged signal, and the CD28 domain will provide the required co-stimulation to activate the T cell so it can destroy its target. Pretty amazing!



So CAR T cells are "designer" T cells with enhanced capabilities. The genes that encode the chimeric protein are usually inserted into the genome of a lentivirus (e.g., a version of HIV-1, modified so that it is non-pathogenic), and this virus is then used to infect T cells that have been harvested from the patient's blood. This "carrier" lentivirus can incorporate its genetic information, including the engineered CAR construct, into the genome of the infected T cell, so that when the cell proliferates, all of its progeny will express the chimeric receptor protein. The virus-infected T cells are then forced to proliferate in the lab to build up their numbers, and are infused back into the patient. As you can imagine, this type of genetic engineering isn't easy. CAR T cell immunotherapy, in which T cells are "repurposed" or "redirected" to destroy cancer cells, is the result of many thousands of hours of research over a period of more than twenty years.

Although CAR T cells are being developed with recognition domains that can bind to various antigens on the surface of cancer cells, the target which has been most successful in the clinic is the protein CD19. This protein is part of the B cell's co-receptor, which binds to opsonized antigens, and makes it easier for antigens that are decorated with complement proteins to activate B cells. Importantly, CD19 is expressed on the surface of most leukemias and lymphomas, and CD19 CAR T cell therapy has been used successfully to treat two types of B cell malignancies: acute lymphoblastic leukemia and non-Hodgkin lymphoma. The goal of CD19 CAR T cell therapy is to destroy all the B cells in a patient's body which express CD19. This protein appears on the surface of B cells early in their development and continues to be expressed until B cells are about to become plasma cells. So the result of depleting B cells that express CD19 is that B cells which have already become plasma cells are spared, but B cells that have not matured to the plasma cell stage (including the cancerous B cells) are destroyed. Of course, not having B cells which can protect against new invaders is not a good thing, because it can put the patient at risk for life-threatening infections. Consequently, patients typically are given gamma globulin to help them fight infections. One trial used CD19 CAR T cell immunotherapy to treat forty-five children and young adults with acute lymphoblastic leukemia. About 90% of them went into remission as a result of the treatment, but about half of these relapsed within a year.

CAR T cells are engineered to recognize antigens expressed on the surface of their target cells (e.g., CD19). Consequently **there is no requirement that the receptors of CAR T cells recognize antigens presented by MHC molecules**. This avoids the problem of cancer cells "hiding" by mutating to disrupt the antigen presentation machinery. Nevertheless, many of the patients who relapse after CD19 CAR T cell therapy do so because mutations in the gene for CD19 make the cancer cells "invisible" to the engineered receptor. So escape mutations are still a problem with CAR T cell immunotherapy. Moreover, part of the "magic" of antigen presentation is that CTLs are able to look at peptides that are normally found inside the target cell. The receptors of CAR T cells can only look at surface proteins (e.g., CD19), so the number of potential targets for CAR T cell therapy is limited.

One must also be very careful to choose the best target for CAR T cell therapy. T cells with natural TCRs have undergone rigorous testing for tolerance of self antigens, but CAR targeting domains have not received this training. Consequently, cells chosen for CAR T cell elimination must be cells that are not essential for human health. And CAR T cell therapy is not without side effects.

Most patients experience some level of cytokine release syndrome, which involves a systemic inflammatory response that can result in high fever, elevated blood pressure, and organ dysfunction. Also, roughly one-third of patients suffer from neurological problems, including hallucinations, delirium, and seizures. Fortunately, in most cases, these side effects can be treated to decrease their severity.

So far, most of the successes with CAR T cell therapy have been with blood cell cancers such as leukemias and lymphomas. Success with solid tumors has been limited. One reason is that blood cell cancers are easier to target than solid tumors because we can live without certain types of blood cells – at least temporarily. In contrast, most of the “easy” targets on the surface of solid tumors are also found on cells that are essential for life, and targeting these shared antigens could cause life-threatening autoimmunity. Moreover, the effectiveness of CAR T cell therapy against solid tumors is dampened by the immunosuppressive tumor microenvironment. And, as time goes on, the expression level of the artificial T cell receptor wanes, and these engineered cells become

exhausted from the effort of trying to destroy the tumor. The limited success of CAR T cell immunotherapy against solid tumors is unfortunate because solid tumors are responsible for about 90% of all cancer fatalities. At present, CAR T cell immunotherapy is very complicated and unpleasant for patients, and is usually used as a “last resort” for people with an otherwise desperate prognosis. Novartis’ CAR T cell treatment for children with end-stage leukemia was the first therapy using engineered T cells to reach the market. This immunotherapy can result in long-lasting remissions and even cures. However, because CAR T cells must be engineered for each individual patient, this highly personalized therapy is costly: about US\$500,000 per patient.

Other approaches which employ the weapons of the immune system to treat cancer are in various stages of testing. We can all hope that these experiments will be successful, because, as it stands now, about one out of every three of us will get cancer. But please remember one thing: **It is estimated that 20–40% of all cancers can be prevented by living a healthy lifestyle.**

REVIEW

Hybridomas are made in the laboratory by fusing a B cell that produces a desired antibody and a cancerous B cell that can live forever. The monoclonal antibodies produced by these antibody factories have been used to treat autoimmune disease and cancer. Some monoclonal antibodies block the interaction between cytokines or growth factors and their receptors. Other monoclonal antibodies recognize antigens on the surface of cells (e.g., cancerous B cells) and mark these cells for destruction. Monoclonal antibodies that block the binding of the checkpoint proteins CTLA-4 and PD-1 to their ligands can “reinvigorate” T cells that are tumor-specific.

T cells can also be manipulated and used to treat cancer. Adoptive cell transfer uses naturally occurring tumor-specific T cells (TILs) that have been isolated from individual patients, and grown in culture to increase their numbers. CAR T cells are “designer” T cells with enhanced capabilities. They are made by using genetic engineering to equip T cells with artificial T cell receptors that can recognize cancer cells without the requirement for antigen presentation by MHC molecules.

KNOWN UNKNOWNS

1. Why do some cancer patients respond well to checkpoint blockade therapy whereas others do not?

THOUGHT QUESTIONS

- 1.** One of the barriers to effective CAR T cell therapy for solid tumors is the inhospitable environment which solid tumors create to protect themselves from T cells. What “combination therapy” might help overcome this problem?
- 2.** Checkpoint inhibitors usually work best for patients whose tumors have accumulated many mutations. Why do you think this is?
- 3.** Discuss the advantages and disadvantages of the following cancer immunotherapies: monoclonal antibodies that prevent growth factors from binding to their receptors, tumor infiltrating lymphocytes, checkpoint blockade, and CAR T cell therapy.

LECTURE 17

COVID-19 and the Immune System

HEADS UP!

The respiratory tract is one of the easiest routes by which a virus can attack a human. The epithelial cells which line the airways can function as innate immune system cells, and specialized tertiary lymphoid organs can be “built on demand” to deal with respiratory infections. The mRNA COVID-19 vaccine is an example of a new vaccine strategy, and there are major differences between the immune system’s response to a SARS-CoV-2 infection and an mRNA COVID-19 vaccination. Central memory B cells and memory T cells can provide protection against viral variants. The purpose of a vaccination is not to prevent infection. It is to prevent or minimize disease.

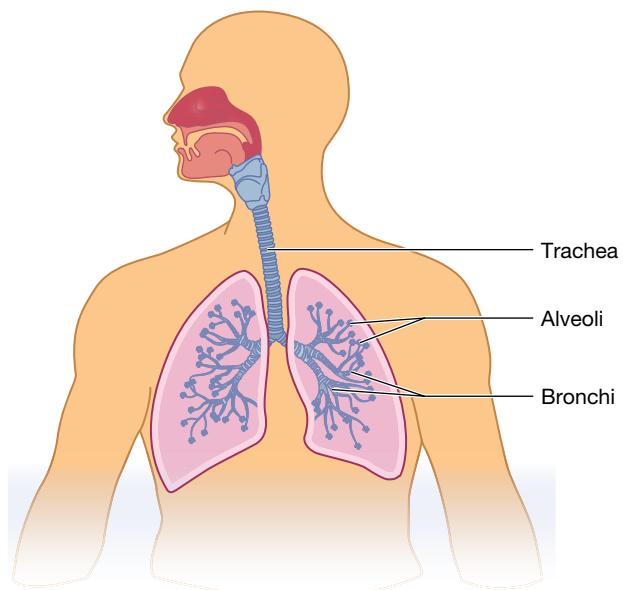
INTRODUCTION

SARS-CoV-2 is a coronavirus which has caused the infectious disease COVID-19 in millions of people worldwide. One of the consequences of this pandemic is that it has given immunologists a “laboratory” in which to make new discoveries about the immune response to viral infections, and about immunological memory. Moreover, the COVID-19 vaccine program has resulted in major advances in vaccine design, and the urgent need for a vaccine has fast-tracked studies which otherwise would have taken years to complete. The COVID-19 pandemic also gives us an interesting, real-world example of the immune system in action against a respiratory virus, both during a natural infection and as the result of vaccination.

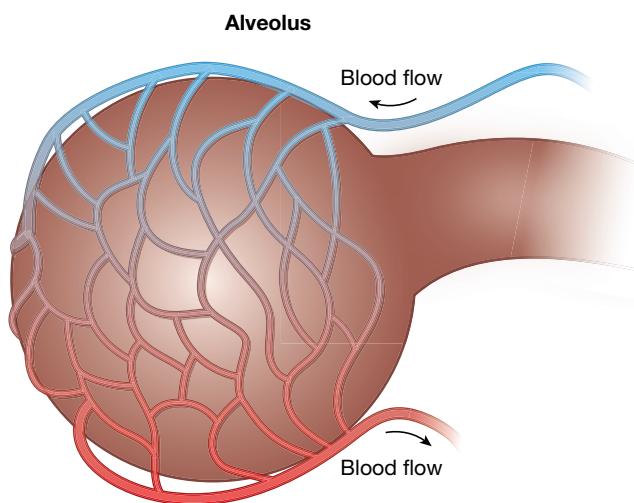
THE RESPIRATORY SYSTEM

SARS-CoV-2 is predominantly a respiratory virus which is spread when droplets containing the virus are inhaled and taken into the airways. A hearty sneeze from a person infected with a respiratory virus can produce more than 10,000 virus-containing droplets, and one infected cell can produce thousands of new viruses. These are two of the features which make respiratory viruses so successful. In addition, the internal surface of the respiratory tract is the largest surface in the body that is in direct contact with the external environment. So it is an inviting target for viruses and other airborne pathogens.

Here is a drawing which depicts the human respiratory system.



Our respiratory system is a bit like an upside-down tree. The “trunk” begins at our nose, extends down through the trachea, and then branches into the bronchi and bronchioles. This part of the “tree” is essentially a gas delivery system, which functions to transport air from our nose or mouth to the **alveoli** – the “leaves of the tree” – which are little air sacs wrapped in a network of capillaries. It is in the alveoli that oxygen from the air is exchanged for carbon dioxide in the blood. There are a lot of these little sacs, and the total surface area of the alveoli is about 100 square meters.



The respiratory tree is lined with epithelial cells which are our first line of defense against respiratory viruses. In the airways, these cells are interspersed with “goblet” cells which produce mucus. The blanket of mucus which covers the epithelium functions to entrap inhaled particles and microbes – including viruses. In addition, over half of the airway epithelial cells have cilia – little “paddles” that “wave” in a coordinated fashion to propel the mucus and trapped invaders upward so that they can be swallowed or coughed up. An adult human has more than a trillion cilia. To aid their access to epithelial cells of the airways, most viruses try to disable the ciliary elevator either by infecting and destroying ciliated epithelial cells or by “shaving” off their cilia – and SARS-CoV-2 is no exception. The loss of this protective barrier leaves the airways vulnerable to bacterial infections, and bacterial pneumonia is a common result of a severe respiratory virus infection. Interestingly, the epithelial cells of the alveoli do not have cilia, and there are no mucus-producing goblet cells in the alveolar epithelium. As a result, the epithelial cells of the alveoli are not bathed in a thick coat of mucus. This makes sense because the primary

function of the alveoli is gas exchange, which would be hindered by a thick layer of mucus.

SARS-CoV-2

In order to understand the challenges which SARS-CoV-2 presents to the immune system, and the responses of the immune system to these challenges, we need to talk a bit about the life cycle of this virus. SARS-CoV-2 is a member of the coronavirus family of viruses, and consists essentially of the viral messenger RNA wrapped in a lipid coat that is studded with spikes made of protein. SARS-CoV-2 is one of the largest RNA viruses, with a single-stranded genome of about 30,000 bases. Importantly, **this large genome encodes proofreading machinery which helps the virus correct mistakes made during replication. Because of this feature, the mutation rate of SARS-CoV-2 is roughly 100-fold lower than that of HIV-1, which cannot proofread.**

SARS-CoV-2 infects its target cells when the spike proteins that decorate its lipid coat bind to a protein called ACE2 on the surface of the target. This ACE2 receptor is found on tissues and organs in many parts of the body (e.g., heart and kidney), but most notably on epithelial cells that line the respiratory tract. It is also expressed on the surface of monocytes, macrophages, and dendritic cells. Once bound to the cellular receptor, the spike protein, aided by a host protease, facilitates fusion between the virus coat and the cell’s plasma membrane. The viral mRNA is then taken into the cell and is translated by the cell’s machinery to produce the viral proteins. Not all the steps in the assembly of new viruses and their exit from a SARS-CoV-2-infected cell have been fully characterized. However, the net result is that more viral mRNA is produced and enclosed in lipid coats, and the newly minted viruses are released from the cell – usually resulting in the death of the cell. These viruses can then go on to infect and replicate in other cells of the respiratory system. Replication of SARS-CoV-2 in the upper respiratory tract (especially the nasal epithelium) is important for viral spread, whereas infection of the lower respiratory tract can lead to severe disease.

THE IMMUNE RESPONSE TO RESPIRATORY VIRUSES

The epithelial cells that line the airways are part of the innate immune system. These cells are equipped with pattern-recognition receptors, including TLR3, TLR7,

and TLR8, which can detect infection by respiratory viruses. Upon detection, the infected pulmonary epithelial cells secrete battle cytokines which can recruit innate immune system cells. There is a rapid influx of neutrophils from the blood to the site of the infection, and macrophages are recruited from the tissues surrounding the airways and from the blood. Like epithelial cells, macrophages have receptors that recognize pathogen-associated molecular patterns (PAMPs) such as SARS-CoV-2 RNA as well as receptors that detect damage-associated molecular patterns (DAMPs) – molecules released by dying epithelial cells. In addition, infected epithelial cells, as well as plasmacytoid dendritic cells in the tissues of the airways, produce type 1 interferons (IFN- α and IFN- β), which can interfere with viral replication, and can alert nearby cells to the viral attack. This interferon response happens very fast and is extremely important in the early defense against viruses.

There actually are two different types of macrophages which protect our airways. “Interstitial” macrophages are your classic macrophages which inhabit the tissues surrounding your lungs. These macrophages are on-call. In contrast, the “alveolar” macrophages are permanent residents of the alveoli. Most alveolar macrophages took their places in the lungs while we were still embryos, and they proliferate there as needed to maintain their numbers during our lifetime. It may seem strange, but these alveolar macrophages actually spend their lives crawling around on the inside (the lumen) of the alveolar sacs! There they are perfectly positioned to intercept pathogens such as viruses, as well as particles which you may breathe in. **Usually, alveolar macrophages are “non-inflammatory,” and their main job is phagocytosis.** They are basically airways scavengers which phagocytose dust particles, allergens, and pollutants to keep the alveoli clean. However, **if an infection reaches the end of the respiratory tree, alveolar macrophages can be activated. When their pattern-recognition receptors are ligated or they receive danger signals from infected epithelial cells, they can engulf and destroy virus-laden alveolar cells, and can recruit interstitial macrophages from the surrounding tissues to join the battle.**

Once the innate immune system gets fired up, the adaptive immune system can be aroused. The tissues which surround the respiratory tract are home to dendritic cells, and some of these DCs “reach out” into the airways to check for pathogens. Once activated, dendritic cells can travel to lymph nodes that drain the tissues surrounding the respiratory tract and activate helper T cells and CTLs. Interestingly, in addition to lymph nodes, **the tissues that surround the respiratory tract also contain specialized**

lymphoid organs called the nasal-associated lymphoid tissue (the NALT) and the bronchus-associated lymphoid tissue (the BALT). These tertiary lymphoid organs resemble the Peyer’s patches found in the tissues around the intestines. They contain dendritic cells, follicular dendritic cells, germinal centers, high endothelial venules, and specialized areas for B and T cells – all the components required for an adaptive immune response. Some of these tertiary lymphoid organs even include M cells that can sample the environment in the lumen of the respiratory tract. What is remarkable in adult humans is that, unlike lymph nodes, **most of these tertiary lymphoid organs are not permanent. They are “organized” in response to infections, and can disappear once the infection has been resolved.** They are rather like lymph nodes which are “built on demand” – and in just the right spots.

Plasma B cells, activated in lymph nodes which drain the airways or in the NALT and BALT, produce both IgA and IgG antibodies. This makes perfect sense. **In the upper airways, the main antibody protection is provided by virus-specific IgA antibodies.** Epithelial cells which line the upper airways are equipped with receptors that bind dimeric IgA and transport these antibodies through the epithelial cells into the lumen of the airways. **The epithelial cells of the alveoli do not have this transport system, but IgG antibodies can diffuse across the thin alveolar epithelium.** Helper T cells which are activated in lymph nodes or in the NALT and BALT can help B cells affinity mature and class switch, and can help activate CTLs, which can kill infected epithelial cells.

THE PATHOLOGY OF A SARS-CoV-2 INFECTION

One of the challenges that faces the immune system in protecting the lungs is to eliminate viruses and destroy virus-infected cells without causing so much damage that the gas exchange function of the lungs is compromised. Early in a SARS-CoV-2 infection, the virus replicates rapidly in the epithelial cells that line the upper airways, and the innate system senses danger and is activated. Then the adaptive immune system is mobilized, and about a week after the onset of symptoms, virus-specific B and T cells can usually be detected in the blood of an infected individual. In most cases, the innate and adaptive immune responses destroy the attacking virus, and the immune system goes back into “surveillance mode.” This type of immune response is generally associated with flu-like symptoms such as

fever, muscle aches, and coughing. This is exactly the kind of defense the immune system is designed to mount against an attack by a respiratory virus.

In some SARS-CoV-2 infections, the battle does not go this well. Although the epithelial cells of the upper airways are the first targets of infection, if the initial immune response is not strong or fast enough, virus produced there can be “breathed into” the lungs and infect the cells of the lower respiratory tract. When alveolar epithelial cells are killed by the virus or by the immune response to the virus, the barrier that separates the air sacs from the surrounding tissues is breached, and fluid and immune system cells can enter the alveoli, causing pneumonia and a decrease in the efficiency with which gas is exchanged. This can lead to shortness of breath and low blood oxygen levels. Interestingly, damage caused by activated macrophages is a major mechanism of lung injury during a serious SARS-CoV-2 infection. Thankfully, even when this happens, the immune system can still gain the upper hand and defeat the virus.

In a minority of cases of COVID-19, however, the outcome is not so favorable, and the result is acute respiratory distress syndrome (ARDS) in which, because of the large number of alveoli that are rendered nonfunctional, oxygen levels in the blood decline to life-threatening levels. Respiratory failure is the most frequent cause of death from COVID-19. In addition, if the infection cannot be controlled, the immune system may become overly exuberant, and the secretion of cytokines that are normally used to strengthen the defense can get out of control. This is sometimes referred to as a “cytokine storm.” For example, IL-6, a cytokine produced by battling macrophages, influences Th cells to produce large amounts of IL-17, which functions to recruit neutrophils from the blood. And neutrophils leave a trail of destruction wherever they go. This cytokine storm can damage organs such as the heart, liver, and kidneys.

THE mRNA VACCINE PLATFORM

In response to the COVID-19 pandemic, more than 100 companies have designed vaccines which are in various stages of testing and production. In addition to the strategies (platforms) for vaccine production that we discussed in Lecture 14, some companies are employing platforms which have not been used before – at least not in humans.

From an immunological point of view, one of the most interesting new platforms is a nucleic acid vaccine, which is essentially SARS-CoV-2 mRNA wrapped in a lipid coat.

Although this mRNA vaccine platform is new, the original findings which led to the invention of this type of vaccine were published back in 1989. Those experiments demonstrated that mRNA, mixed with a special lipid preparation, could be taken up by human cells, and that these cells could then produce the protein encoded by the mRNA. This process of introducing viral mRNA into a cell is called **transfection**. The reason it took about 30 years to perfect this type of vaccine and to bring it to market is that many innovations were required to turn the original idea into a usable vaccine. Indeed, the mRNA vaccine is a real triumph of biological engineering for which a Nobel Prize is certain to be awarded. The only question is which of the hundreds of scientists who contributed to this effort will be recognized!

With the mRNA COVID-19 vaccine, lipid nanoparticles containing viral mRNA are injected into the arm of the recipient. There, cells take up these nanoparticles by endocytosis, the mRNA is released from its lipid coat into the cytoplasm, and the mRNA is translated to produce viral proteins. When the viral mRNA is first taken into the transfected cell, the cell’s pattern-recognition receptors immediately recognize the single-stranded viral RNA as foreign. If the transfected cell is a dendritic cell or a macrophage, this danger signal will cause that cell to be activated and to begin to produce cytokines (e.g., TNF and IFN- γ) which will fire up the innate immune system. Recognition of the viral mRNA as foreign also will activate the interferon system. What this all means is that **the mRNA in the vaccine acts as its own adjuvant to help activate the immune system** – and that’s a good thing. However, there is a potential problem. The type 1 interferons (IFN- α and IFN- β) produced will decrease production of the mRNA-encoded protein in the transfected cells. In fact, the interferon system can shut down the process so quickly that very little viral protein will be produced, rendering the vaccine ineffective. This problem was solved when vaccine designers discovered that one of the four mRNA bases, uridine, was responsible for much of the interferon system activation. To fix this, a “fake” nucleotide, pseudouridine, is substituted for uridine when the vaccine mRNA is synthesized in the lab. The result is that the immune system will still be activated when pattern-recognition receptors recognize the viral mRNA, but the strength of the interferon response is diminished enough to allow robust production of the mRNA-encoded protein.

In a SARS-CoV-2 infection, the primary focus of B cells and the antibodies they produce is the viral spike protein. This protein has two parts, S1 and S2. S1 contains the receptor-binding domain, which plugs into the ACE2

receptor on target cells. S2 facilitates fusion of the viral envelope with the target cell's plasma membrane, allowing the virus to enter the cell. **Neutralizing antibodies can bind to S1 and prevent the virus from attaching to its receptor, or they can bind to S2 and prevent fusion and viral entry.** Antibodies which bind to the receptor-binding domain of the virus seem to be the dominant form of neutralizing antibodies. Interestingly, three copies of the spike protein join together to make a trimer. However, this trimer is metastable, and can arrange itself into one of two forms: prefusion or postfusion. The postfusion conformation is the shape that the spike protein assumes after it has fused with the target cell's membrane. In the prefusion conformation, the spike protein has the right shape to plug into the ACE2 receptor. Consequently, it is the prefusion form to which neutralizing antibodies can bind to prevent viral entry into a target cell. So to maximize the number of spike proteins which are in the proper conformation to elicit neutralizing antibodies, scientists introduced mutations into the vaccine mRNA which "lock" the spike trimer in the prefusion conformation. As you can see, the mRNA vaccine platform is the result of some very clever thinking!

mRNA VACCINATION VERSUS NATURAL INFECTION

Like other vaccines, the COVID-19 mRNA vaccine is intended to mimic a natural infection as closely as possible in order to produce antibodies and memory cells which can prepare the immune system to defend against a real SARS-CoV-2 infection. However, **no vaccine can perfectly mimic a natural infection.**

Cells transfected with the COVID-19 mRNA vaccine secrete spike proteins which can be taken up by dendritic cells and presented by class II MHC molecules to activate Th cells. Likewise, when dendritic cells in the arm of a vaccine recipient are transfected with the COVID-19 mRNA vaccine, the spike proteins produced by the transfected DCs can be presented by class I MHC molecules to activate virus-specific CTLs. So **the way in which Th cells and killer T cells are activated by the vaccine is quite similar to the activation of these cells in response to a natural infection.** How about B cell activation? SARS-CoV-2 virus particles have a surface which is studded with spike proteins. Consequently, BCRs which bind to these spikes can be crosslinked, leading to B cell activation and spike-specific antibody production. But what about the vaccine? The lipid envelopes which enclose the vaccine mRNA don't have spikes on their surface. Moreover, cells transfected by the vaccine don't make

virus particles. They just make spike proteins. So **it is not clear how vaccination results in the crosslinking of B cell receptors.**

In a natural respiratory infection, the initial activation of the adaptive immune system takes place in the lymph nodes that drain the tissues surrounding the airways, or in the lymph-node-like structures of the NALT and BALT. There, helper T cells, B cells, and CTLs are activated. In contrast, when a person is vaccinated by an intramuscular injection in the arm, the initial immune reaction takes place at that site. That's why your arm gets sore. So **the initial sites of immune activation in a natural SARS-CoV-2 infection and a COVID-19 mRNA vaccination are very different.**

When SARS-CoV-2 is inhaled, it infects epithelial cells of the upper respiratory tract, takes over the cell's protein-making machinery, and produces new viruses, which can infect other cells in the respiratory tract. So **in a natural infection, the virus replicates in the cells it infects and there are multiple rounds of infection. Indeed, a natural infection can last a week or more. In contrast, with the COVID-19 mRNA vaccine, there is no viral replication. It's a "one-shot" deal. Only the cells which take up mRNA from the original injection produce the spike protein.**

During a respiratory tract infection, B cells activated in the neighborhood of the respiratory tract are encouraged to make predominantly IgA antibodies. These antibodies are very effective in reducing the quantity of virus which the sneeze of an infected person can spread to others. **In contrast, when the cells of your arm are transfected during vaccination, the local immune response can be expected to produce mainly IgG antibodies – which are perfect for defending your arm, but not your upper respiratory system.** Although a mixture of SARS-CoV-2-specific IgG and IgA antibodies can be detected in the blood of vaccinated individuals, analysis of antibody isotypes in the tissues surrounding the airways is very difficult. Consequently, **it is not known how robust the airways' IgA response is in a vaccinated individual relative to the IgA response in a person who has been infected.**

Once a SARS-CoV-2 attack has been repulsed, an infected person will be left with antibodies, memory B cells, and memory T cells. Some of these memory T cells, the tissue-resident memory T cells, will be positioned "on site" in the tissues around the respiratory tract. These T cells are strategically positioned to defend against a subsequent SARS-CoV-2 infection. After a person has been vaccinated, virus-specific memory T cells can be detected in the blood. However, **it is not known how**

many tissue-resident memory T cells are on guard in the lung tissue of a vaccine recipient.

Fortunately, although there are important differences between a SARS-CoV-2 infection and an mRNA vaccination, it is clear that mRNA vaccines can prepare the immune system to deal with a SARS-CoV-2 infection and can, in most cases, prevent life-threatening disease. Although our focus here is on the mRNA COVID-19 vaccine, some of these differences between a natural infection and a vaccination apply to other vaccines we routinely receive (e.g., the seasonal influenza vaccine).

CORRELATES OF PROTECTION

For most vaccines, the level of pathogen-specific antibodies in the blood is a reliable indicator of how well the vaccine will protect from disease. **For COVID-19, however, immunologists have not been able to define measurable correlates of protection that can accurately predict the strength of protection against disease conferred either by a vaccine or by a natural infection.** Several weeks after a second dose of the mRNA vaccine or after a natural infection, the antibody response peaks. After this, antibody levels decline, reaching a much lower maintenance level a few months later. This decline is the typical response to an infection – and it makes sense. The immune system must be ready to defend against other assaults, and all of its “energy” cannot be invested in defending against a single pathogen. This maintenance level of neutralizing antibodies is maintained by a population of long-lived plasma B cells, which can continue to make antibodies for months or even years.

Although the level of neutralizing antibodies in the blood does appear to be well correlated with protection, there are cases in which neutralizing antibodies could not be detected, yet the patient recovered from COVID-19. So neutralizing antibodies are probably not the whole story. For example, **non-neutralizing antibodies may also be important for protection.** These antibodies can work by binding to the virus and opsonizing it for phagocytic digestion, by forming bridges between infected cells and phagocytes or NK cells (antibody-dependent cellular cytotoxicity), and by activating the complement system. The memory response also includes effector memory T cells which circulate through the blood and lymph, as well as tissue-resident memory T cells. During a subsequent attack, memory Th cells are ready to provide help to B cells and CTLs, and memory CTLs are poised to limit viral replication by killing virus-infected cells. So **it is likely that virus-specific memory T cell levels are also**

important correlates of protection. Indeed, we would expect that the immune system would mobilize multiple weapon systems in response to a COVID-19 vaccination or a SARS-CoV-2 infection, and that these systems would work together to provide disease protection. Certainly, that's the way the system is supposed to work!

REINFECTION

Many are surprised that people who have been infected with SARS-CoV-2 or have received the vaccine can be reinfected. However, it is important to understand that **the purpose of a vaccination is not to prevent infection. The purpose is to prevent or minimize disease.** If you have been infected with SARS-CoV-2 or have been vaccinated, your antibody levels will wane with time. If you inhale droplets containing SARS-CoV-2 it is almost certain that epithelial cells in your nasal passages will be infected, and that new viruses will be produced. Indeed, the chance is very small that antibodies in your nasal passages will “intercept” every one of the viruses in those droplets before they can infect an epithelial cell. So **the question is not whether you can be reinfected if you have been vaccinated. You can be! The question is how rapidly will your immune system react to limit the replication and proliferation of the virus in your respiratory tract – if you are reinfected.**

SARS-CoV-2 is certainly not unique in terms of reinfection. Studies have shown that people who have been infected with influenza virus can be reinfected by the same strain of virus, and people who have been vaccinated against seasonal influenza can be reinfected during the same flu season when their immunity wanes. That's why many doctors suggest that we get our flu vaccines sometime in November – so that our immune system will be “maximally primed” during the peak of the flu season. Waning immunity is also one reason we are encouraged to get a flu shot every year, even if the flu strains in circulation have not changed.

VIRAL VARIANTS

Although SARS-CoV-2 is equipped with a proofreading apparatus, it is still error-prone. This can result in “escape” mutations in which a B cell’s epitope is mutated so that the B cell’s receptors will no longer bind tightly to the viral protein. These viral “variants” can even be caused by a single mutation in the viral mRNA, which slightly changes the shape of the S protein. Fortunately, the

adaptive immune system has evolved ways to decrease the impact of viral variants.

When a pathogen attacks for the first time, a collection of B cells is activated which recognizes many different epitopes of the invader (for example, different parts of the invader's coat). As these B cells proliferate, they form clones which are specific for different epitopes. This type of response is said to be polyclonal.

Then, as B cells undergo repeated rounds of somatic hypermutation, this collection of B cells becomes less diverse, as the "winners" – those B cells whose receptors bind most tightly to their epitopes – are selected to proliferate further. **Eventually, the pool of hypermutating B cells becomes focused on a few, immunodominant epitopes – the tightest binders. Because long-lived plasma cells typically have undergone many rounds of somatic hypermutation, the receptors on these memory cells and the antibodies they produce recognize mainly immunodominant epitopes.** This is a good thing, of course, because you want the antibodies made by long-lived plasma cells to bind tightly to their target epitopes.

In contrast, **central memory B cells usually have not undergone repeated rounds of somatic hypermutation. As a result, central memory B cells are not so focused on immunodominant epitopes. The collection of central memory B cells is still highly polyclonal.** Isn't this a bad thing, you might ask? After all, don't we want to select those B cells which make antibodies that bind most tightly to their targets? Not always, and here's why.

The antibodies provided by long-lived plasma cells are great for tagging the current invader or that same invader

if it attacks again. But pathogens have a nasty habit of mutating – and then making a return visit. Suppose that a virus mutates so that the immunodominant epitope on which long-lived plasma cells are focused no longer exists. These memory cells and the antibodies they produce would be useless, and the immune system would have to start from scratch to make antibodies that focus on a different epitope. So wouldn't it be useful to have a large reservoir of B cells that was still highly polyclonal – a collection of B cell clones with receptors that could recognize many different viral epitopes? You bet it would! These B cells could then be used as "raw material" to be hypermutated in germinal centers, and selected to focus on current epitopes of the viral variant. And **that is one of the important functions of central memory B cells. They give the immune system the ability to adapt rapidly to pathogens which have mutated and returned.**

T cells also can provide protection against SARS-CoV-2 variants. Neutralizing antibodies recognize the overall shape of the S protein. This shape can be changed by many different viral mutations to produce variants which can defeat antibody neutralization. In contrast, a T cell's receptors recognize short peptides derived from many different viral proteins, not just the S protein. And even the peptides cut from the S protein need have nothing to do with neutralizing the virus. Indeed, any viral peptide which can be presented by MHC molecules and recognized by T cell receptors can activate T cells. Consequently, **the T cell response to a viral infection is generally much "broader" than that of B cells, making it harder for viral variants to escape T cell surveillance.**

REVIEW

Epithelial cells in the airways act as members of the innate immune system, can detect pathogens such as viruses, and can produce battle cytokines to recruit macrophages and neutrophils. The upper respiratory tract is protected by IgA antibodies which can bind to a respiratory virus and keep it from attaching to its receptor on airway epithelial cells. In addition, a dense blanket of mucus covers the upper airways. This mucus can trap pathogens, and with the help of ciliated cells, transport them upward to be swallowed or coughed up. The alveoli at the end of the respiratory tree are designed for gas exchange, so the surface of the alveoli has only a thin coat of mucus. The inner surface of the alveoli is patrolled by alveolar

macrophages. These macrophages pick up "trash" that has been breathed in, but they can also ingest invaders and summon more macrophages from the tissues outside the alveoli to battle invading pathogens.

During a respiratory infection, tertiary lymphoid organs (the BALT and the NALT), which resemble Peyer's patches, can be constructed in the tissues that surround the airways. These organs function similarly to lymph nodes in which B and T cells can be activated in response to an infection.

The COVID-19 mRNA vaccine uses lipid nanoparticles which contain mRNA that encodes the viral spike protein. These nanoparticles are taken into the cell by endocytosis

and the mRNA is released into the cytoplasm of the transfected cell. There the mRNA is translated into spike proteins by the cell's machinery. The spike proteins can elicit both antibody and T cell responses, and memory B and T cells can be produced to prepare for a future visit by the virus.

There are important differences between a natural SARS-CoV-2 infection and the COVID-19 mRNA vaccination. A natural infection can last for days, with new viruses being continually produced by multiple rounds of infection. With the vaccination, spike proteins are only produced by those cells that are initially transfected by the vaccine. The vaccine is injected into the muscle of the arm, whereas the virus first enters the body via the respiratory system. B cells in your arm are programmed to make mainly IgG antibodies, and it is not clear how or where the IgA antibodies needed to protect the upper airways are made. When a natural infection has been subdued, tissue-resident T cells remain in the tissues surrounding the airways, where they are strategically placed to defend against a subsequent infection. With the vaccination, it is

not clear how many tissue-resident T cells settle down in lung tissues, because the initial immune response takes place in the tissues of the arm.

It has been difficult to define measurable correlates of protection, which can predict the strength of protection against disease conferred either by a COVID-19 vaccine or by a natural infection. Antibodies, T cells, and the innate immune system likely all contribute to protection. The purpose of a vaccination is not to prevent infection. It is to prevent or minimize disease.

Although SARS-CoV-2 can proofread its RNA, the virus still has a high mutation rate, and this can lead to the production of viral variants. Fortunately, central memory B cells are polyclonal, so the collection of central memory B cells can recognize many different viral epitopes. Consequently, it is likely that some of these B cells will have receptors which can recognize a variant, be reactivated, and produce protective antibodies. T cells also are "variant-resistant" because they too are polyclonal, so the collection of memory T cells can recognize many different viral peptides.

KNOWN UNKNOWNS

- 1.** What is the relative importance of memory B cells versus memory T cells in protection against a SARS-CoV-2 infection?
- 2.** How are IgA antibodies made in response to an intramuscular vaccination in the arm?
- 3.** What measurable correlates of protection can predict the degree of protection against COVID-19 that is conferred by a vaccine or a natural infection?
- 4.** Does an intramuscular COVID-19 vaccination elicit the formation of tertiary lymphoid organs (BALT and NALT) in the tissues that surround the airways?

THOUGHT QUESTIONS

- 1.** Can you think of a way to vaccinate with an mRNA vaccine which might be more likely to provide IgA antibody protection for the airways?
- 2.** What properties of memory B cells make them useful in defending against infection?

Glossary

Activating receptors: Receptors on the surface of NK cells which detect infected cells.

Adjuvant: A vaccine component included to increase its potency.

Adoptive cell transfer: A type of immunotherapy in which T cells are removed from a patient's body, forced to proliferate in the lab, and infused back into the patient to fight disease.

Allergen: An antigen that causes allergies.

Anergy: A state of nonfunctionality.

Anergize: To render nonfunctional.

Antibody-dependent cellular cytotoxicity: Antibodies form a "bridge" between the target and the cytotoxic cell. Antibody-directed killing by cells of the innate system.

Antigen: A rather loosely used term for the target (e.g., a viral protein) of an antibody or a T cell. To be more precise, an antibody binds to a region of an antigen called the epitope, and the T cell receptor binds to a peptide that is a fragment of an antigen.

Antigen presenting cells: Cells that can present antigen efficiently to T cells via MHC molecules, and which can supply the co-stimulatory molecules required to activate T cells.

Anti-retroviral treatment: Chemotherapy that targets specific aspects of the HIV-1 replication cycle.

Apoptosis: The process during which a cell commits suicide in response to problems within the cell or to signals from outside the cell.

Atopic individual: Someone who has allergies.

Autophagy: A process by which starved cells recycle their components.

β 2-microglobulin: The nonpolymorphic chain of the class I MHC molecule.

Bronchus-associated lymphoid tissue (BALT):

Tertiary lymphoid organs that resemble the Peyer's patches found in the tissues around the intestines.

CAR T cell therapy: A type of immunotherapy in which T cells are removed from a patient's body, fitted with an engineered T cell receptor, and infused back into the patient to fight disease.

Central tolerance induction: The process by which T cells with receptors that recognize abundant self antigens in the thymus are anergized or deleted.

Checkpoint proteins: Proteins (e.g., CTLA-4 and PD-1) that are expressed on the surface of immune system cells and which help turn off the immune system once an invasion has been repulsed.

Chemokine: A special cytokine used to direct cells to their proper locations.

Clonal selection principle: When receptors on B or T cells recognize their cognate antigen, these cells are triggered (selected) to proliferate. As a result, a clone of B or T cells with identical antigen specificities is produced.

Cognate antigen: The antigen (e.g., a bacterial protein) which a B or T cell's receptors recognize and bind to.

Colon: A synonym for large intestine.

Commensal bacteria: Bacteria that have a beneficial, symbiotic relationship with their host.

Conduits: Tiny tubes which transport antigen within lymph nodes.

Co-receptor: The CD4 or CD8 molecules on T cells, or the complement receptor on B cells.

Cortical thymic epithelial cells: Cells in the cortex of the thymus which are the "examiners" during positive selection (MHC restriction) of T cells.

Co-stimulation: The second “key” that B and T cells need for activation.

Crosslink: Cluster together (e.g., an antigen may crosslink a B cell’s receptors).

Cross reacts: Recognizes several different epitopes. For example, a B cell’s receptors may bind to (cross react with) several different epitopes.

CTLA-4: A receptor on activated T cells which, when ligated (e.g., by B7), interferes with the reactivation of these cells. A “checkpoint” protein.

Cytokine profile: The mixture of different cytokines that a cell secretes.

Cytokines: Hormone-like messenger molecules that cells use to communicate.

Cytotoxic lymphocyte: A synonym for killer T cell.

Delayed-type hypersensitivity: An inflammatory reaction in which Th cells recognize a specific invader and secrete cytokines that activate and recruit innate system cells to do the killing.

Dendritic cell: A starfish-shaped cell which, when activated by battle signals, travels from the tissues to the secondary lymphoid organs to activate naive T cells.

Elite controller: A rare HIV-1-infected individual whose immune system is able to control the viral load so that it remains low for an extended period without anti-retroviral treatment.

Endogenous protein: A protein that is produced within the cell in question – the opposite of an exogenous protein.

Endoplasmic reticulum: A large sack-like structure inside a cell from which most proteins destined for transport to the cell surface begin their journey.

Endothelial cells: Cells shaped like shingles which line the inside of your blood vessels.

Epigenetic modifications: Modifications to DNA (e.g., DNA methylation) or chromatin (e.g., histone acetylation) which change gene expression without changing the DNA sequence.

Epithelial cells: Cells that form part of the barrier that separates your body from the outside world.

Epitope: The region of an antigen that is recognized by a B or T cell’s receptors.

Exogenous protein: A protein that is found outside the cell in question – the opposite of an endogenous protein.

Extracellular bacteria: Bacteria that can multiply outside of their host’s cells.

Fas: A protein on the surface of a target cell which, when ligated by a FasL protein on a killer cell, can instruct the target cell to commit suicide.

f-met peptide: A peptide which includes a special initiator amino acid that is characteristic of proteins made by bacteria.

Follicular dendritic cell: A starfish-shaped cell which retains opsonized antigens in germinal centers and displays these antigens to help activate B cells.

Follicular helper T cell: A helper T cell which has been “licensed” to provide help to B cells in germinal centers.

Germinal center: An area in a secondary lymphoid organ in which B cells proliferate, undergo somatic hypermutation, and switch classes.

Granzyme B: An enzyme which CTLs and NK cells use to destroy their targets.

Herd immunity: This occurs when so many people in a population have either been infected by or immunized against a pathogen that too few susceptible individuals remain for the pathogen to survive.

High endothelial venule: A region in a blood vessel where there are high endothelial cells which allow lymphocytes to exit the blood.

Hybridoma: A hybrid B cell that can produce monoclonal antibodies, and which can be grown indefinitely in the lab.

Immunodominant epitope: An epitope which the majority of B cells recognize.

Inducible regulatory T cells: CD4⁺ T cells which produce cytokines that suppress the immune response to invaders.

Inflammatory response: A term used to describe the physical manifestations caused by the immune system’s battle against invaders (e.g., swelling, redness, and pain).

Inhibitory receptors: Receptors on the surface of NK cells which detect the expression of class I MHC molecules on potential target cells and inhibit the killing of those cells.

Interferon alpha and beta: Warning cytokines secreted by virus-infected cells (the type I interferons).

Interferon gamma: A battle cytokine secreted mainly by Th1 helper T cells and NK cells.

Interleukin: A protein (cytokine) that is used for communication between leukocytes.

Intestinal microbiota: The sum of all the microbes in the intestines (bacteria, viruses, fungi, and parasites).

Invariant chain: A small protein which occupies the binding groove of a class II MHC molecule until it is replaced by an exogenous peptide.

Isotype: A synonym for class. The isotype of an antibody (e.g., IgA or IgG) is determined by the constant region of its heavy chain.

Lamina propria: The tissues that surround the small and large intestine.

Leukocytes: A generic term that includes all of the different kinds of white blood cells.

Ligand: A molecule that binds to a receptor (e.g., the Fas ligand binds to the Fas receptor protein on the surface of a cell).

Ligate: Bind to. When a receptor has bound its ligand, that receptor is said to be ligated.

Lipopolysaccharide: A component of the cell wall of many bacteria. It serves as a “danger signal” for the innate immune system.

Lymph: The liquid that “leaks” out of blood vessels into the tissues.

Lymphocyte: The generic term for a B cell or a T cell.

Lymphoid follicle: The region of a secondary lymphoid organ that contains follicular dendritic cells embedded in a sea of B cells.

M cell: A cell that crowns a Peyer’s patch, and which specializes in sampling antigen from the intestine.

Medullary thymic epithelial cell: A cell found in the medulla of the thymus which expresses tissue-specific self antigens, and which takes part in the examination of T cells for tolerance of self antigens (negative selection).

MHC proteins: Proteins encoded by the major histocompatibility complex (a chromosomal region that includes a “complex” of genes involved in antigen presentation).

MHC restriction: A synonym for positive selection. Survival in the thymus is restricted to T cells whose receptors recognize MHC–self antigen complexes.

Microbe: A generic term which includes bacteria, viruses, fungi, and parasites.

Mitogen: A molecule that can cause the polyclonal activation of B cells.

Monoclonal antibodies: Antibodies produced by the hybridoma technology of Köhler and Milstein.

Monocytes: White blood cells that are the precursors of macrophages or dendritic cells.

Mucosa: The tissues and associated mucus that protect exposed surfaces such as the gastrointestinal and respiratory tracts.

Mucosal-associated lymphoid tissues: Secondary lymphoid organs that are associated with mucosa (e.g., Peyer’s patches and tonsils).

Naive lymphocytes: B or T cells which have never been activated.

Nanoparticle: Tiny particles, usually composed of proteins or lipids, which can be used, for example, for vaccines.

Nasal-associated lymphoid tissue (NALT): Tertiary lymphoid organs that resemble the Peyer’s patches found in the tissues around the intestines.

Natural regulatory T cells: CD4⁺ T cells that are selected in the thymus and which negatively regulate the immune response by interfering with the activation of self-reactive T cells in the secondary lymphoid organs.

Necrosis: Cell death, typically caused by burns or other trauma. This type of cell death (as opposed to apoptotic cell death) usually results in the contents of the cell being dumped into the tissues.

Negative selection: Synonym for central tolerance induction. The selection of T cells whose receptors do not recognize MHC–self peptide complexes in the thymus.

Neoantigen: A “new” antigen that a cell makes as a result of a mutation in the DNA that encodes a normal cellular protein.

Neutralizing antibody: An antibody which can bind to a pathogen and prevent it from infecting or reproducing in the cells it would like to infect.

Neutrophil extracellular traps (NETs): Web-like structures composed of cellular DNA that is decorated with neutrophil granule proteins.

Non-neutralizing antibody: An antibody that does not block infection, but which can tag a pathogen for ingestion by phagocytes or a pathogen-infected cell for destruction by antibody-dependent cellular cytotoxicity.

Opsonize: To “decorate” with fragments of complement proteins or with antibodies.

Pathogen: A disease-causing agent (e.g., a bacterium or a virus).

PD-1: A receptor on activated T cells which, when ligated (e.g., by PD-L1), interferes with the function of the T cell.

Peptide: A small fragment of a protein, usually only tens of amino acids in length.

Perforin: A molecule used by CTLs and NK cells to help destroy their targets.

Peripheral tolerance induction: Mechanisms that induce self tolerance outside of the thymus.

Phagocytes: Cells such as macrophages and neutrophils that engulf (phagocytose) invaders.

Plasma B cells: B cells which produce a large burst of antibodies in response to an attack and then die.

Plasmacytoid dendritic cells: Important cells during a viral infection, because they can produce a ton of type I interferon.

Polyclonal activation: Activation of many B cells with different specificities.

Positive selection: A synonym for MHC restriction.

Primary lymphoid organs: The thymus and the bone marrow.

Proliferate: Increase in number. A cell proliferates by dividing into two daughter cells, which then can divide again to give four cells, and so on. Cellular reproduction.

Proteasome: A multi-protein complex in the cell that chops up proteins into small pieces.

Receptor editing: The process by which B cells in the bone marrow can “draw again from the deck” to try to make a BCR that is not self-reactive.

Secondary lymphoid organs: Organs such as lymph nodes, Peyer’s patches, and the spleen in which activation of naive B and T cells takes place.

Secret: Export out of the cell (e.g., cytokines are secreted by the T cells that produce them, and antibodies are secreted by B cells).

Subcapsular sinus: The cavity (sinus) that is just below the capsule which covers a lymph node.

Thymic dendritic cell: A cell found in the medulla of the thymus which tests T cells for tolerance of self antigens (negative selection).

Tolerance of self: Not viewing self as an attacker.

Toll-like receptors: Receptor molecules found on the surface of cells or inside cells. These receptors have evolved to recognize the signatures of common invaders, and to generate signals which alert the immune system to danger.

Trained immunity: The ability of some cells of the innate system to become better defenders after they have been activated by a previous encounter with a pathogen.

Transfection: A process by which DNA or RNA is introduced into cells.

Tumor infiltrating lymphocytes (TILs): T cells that are found in the neighborhood of tumors.

Tumor necrosis factor: A battle cytokine secreted mainly by macrophages and helper T cells.

Virgin lymphocyte: A B or T cell which has never been activated. A synonym for naive lymphocyte.

Acronyms and Abbreviations

ACT:	Adoptive cell transfer	LPS:	Lipopolysaccharide
ADCC:	Antibody-dependent cellular cytotoxicity	MAC:	Membrane attack complex
APC:	Antigen presenting cell	MALT:	Mucosal-associated lymphoid tissue
ART:	Anti-retroviral therapy	MBL:	Mannose-binding lectin
BALT:	Bronchus-associated lymphoid tissue	MHC:	Major histocompatibility complex
BCR:	B cell receptor	mTEC:	Medullary thymic epithelial cell
CAR:	Chimeric antigen receptor	NALT:	Nasal-associated lymphoid tissue
cTEC:	Cortical thymic epithelial cell	NETs:	Neutrophil extracellular traps
CTL:	Cytotoxic lymphocyte, killer T cell	NK:	Natural killer, as in NK cell
DAMP:	Damage-associated molecular pattern	nTreg:	Natural regulatory T cell
DC:	Dendritic cell	PALS:	Periarteriolar lymphocyte sheath
DTH:	Delayed-type hypersensitivity	PAMP:	Pathogen-associated molecular pattern
ER:	Endoplasmic reticulum	PD-1:	Programmed death 1
Fab:	Antigen-binding fragment of an antibody molecule	PD-L1:	The ligand for PD-1
FasL:	Fas ligand	pDC:	Plasmacytoid dendritic cell
Fc:	Constant fragment of an antibody molecule	PRR:	Pattern-recognition receptor
FDC:	Follicular dendritic cell	SCIDS:	Severe combined immunodeficiency syndrome
Hc:	Heavy chain protein of an antibody molecule	TCR:	T cell receptor
HEV:	High endothelial venule	TDC:	Thymic dendritic cell
IFN:	Interferon, as in IFN- α	Tfh cell:	Follicular helper T cell
IgG:	Immunoglobulin G	Th cell:	Helper T cell
IL:	Interleukin, as in IL-1	TIL:	Tumor infiltrating lymphocyte
iTreg:	Inducible regulatory T cell	TLR:	Toll-like receptor
Lc:	Light chain protein of an antibody molecule	TNF:	Tumor necrosis factor

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