The big picture

? Guiding question(s)

- What are the roles of stem cells in multicellular organisms?
- How are differentiated cells adapted to their specialised functions?

Keep the guiding questions in mind as you learn the science in this subtopic. You will be ready to answer them at the end of this subtopic. The guiding questions require you to pull together your knowledge and skills from different sections, to see the bigger picture and to build your conceptual understanding.

How much do you resemble a zebrafish (*Danio rerio*) (**Figure 1**)?

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Figure 1. Zebrafish (*Danio rerio*) are freshwater fish in the minnow family.

Credit: Dan Olsen, Getty Images

You certainly don't look like one, but both you and the zebrafish have genetic material that is made from long but differing sequences of the same four nitrogenous base building blocks. In fact, genetically speaking, you are 70% the same as a zebrafish (https://europepmc.org/article/PMC/3703927)! Watch **Video 1** to see a zebrafish in action.

Video 1. Close-up Animation of Zebrafish (Danio rerio) Swimming.

More information for video 1

A video features a close-up view of a school of zebrafish swimming in the water. The fish has a long, narrow body, rounded at the head and tapering at the tail. Its body is golden in color with distinct black horizontal stripes running from head to tail.

Student view

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The fish displays all major fins: dorsal, caudal, anal, pelvic, and pectoral. The pectoral fins are more transparent, while the others closely match the color of the body.

This video helps users to identify the physical features of a zebrafish.

So what is it that makes your cells different from zebrafish cells? Genes – sequences of DNA – can be turned on or off, a bit like light switches to generate different proteins that will cause the cell to become a different type. Interestingly, the complex human cell has fewer genes than a zebrafish. There are about 20 000 human genes compared with about 26 000 genes in the zebrafish genome.

The genome in a human generates approximately 200 different types of cell all with their own specific function. So how does this happen? At what stage do these cells get formed, and can anything be done to turn one cell into a totally different type of cell? In 2007, a team of scientists (https://phys.org/news/2008-02-scientists-reprogram-human-skin-cells.html) in California worked out how to take some human skin cells and reprogramme them so that they turn back into cells that have the same ability as embryonic stem cells (**Figure 2**). These cells are called induced pluripotent stem cells, iPS cells.

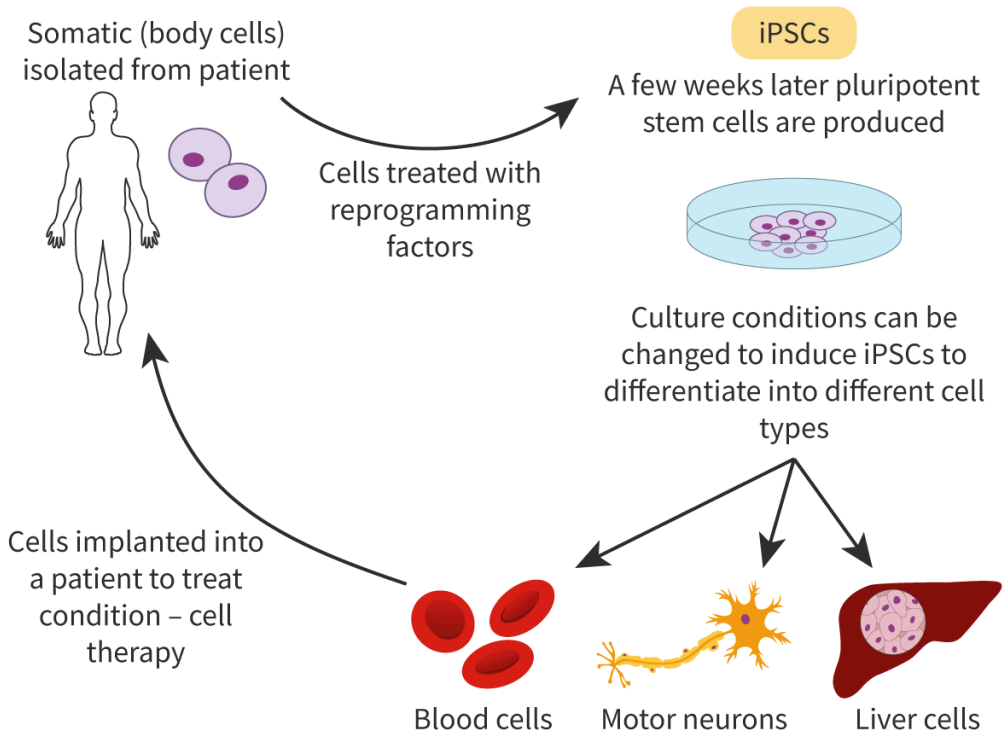

Figure 2. iPS cells (iPSCs) can generate many different types of cell.

More information for figure 2

Student view

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This diagram illustrates the process from isolating somatic, or body, cells from a patient to producing iPSCs and differentiating them into specific cell types for therapeutic use. The process starts with somatic cells isolated from the patient, shown on the left, which are then treated with reprogramming factors. This leads to the production of pluripotent stem cells, depicted in a dish under the label 'iPSCs.' These iPSCs, over a few weeks, are shown above as capable of differentiation under various culture conditions into different cell types such as blood cells, motor neurons, and liver cells, represented at the bottom of the diagram. The flow of cell treatment and differentiation is shown with arrows, indicating the direction of each step. The diagram includes explanatory text for each stage of the process, showing how initial somatic cells progress through to blood, neuron, and liver cell formation, ending with potential re-implantation into the patient for cell therapy.

[Generated by AI]

These iPS cells can then be used for therapeutic purposes. Scientists can take these cells, bathe them in growth media containing specific differentiation factors, and generate cells of a desired type. The cells will then grow and develop into the particular tissue ready for implanting in a patient. The first clinical trial was in 2014, where retinal cells were generated to treat age-related macular degeneration. Stargardt's disease is another disease of the eye that has benefitted from stem cell therapies. This disease is caused by a change in a gene called *ABCA4* which affects the way the body uses vitamin A. Stargardt's disease is the most common cause of blindness in children and normally presents itself before the age of 20.

Prior learning

Before you study this subtopic make sure that you understand the following:

- The basic structure of a cell (see subtopic A2.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43253/)).
- How eukaryotic cells are organised with internal organelles (see section A2.2.4—6 (/study/app/bio/sid-422-cid-755105/book/prokaryotic-and-eukaryotic-cells-id-43583/)).
- That cells within one organism have identical DNA (see section A1.2.1—4 (/study/app/bio/sid-422-cid-755105/book/nucleic-acids-and-their-structure-id-43580/)).

Student view

Stem cells

Learning outcomes

By the end of this section you should be able to:

- Explain how unspecialised cells form following fertilisation and how gradients impact gene expression for further development of the embryo.
- Outline the properties of stem cells and their different capabilities to become different cell types.
- Explain the function of stem cell niches and be able to describe bone marrow and hair follicles as examples of these.

Formation of stem cells

Have you ever wondered how we can start from a single cell, and yet the whole organism has eyes, nose and fingers all in the correct places? An exquisite mechanism exists that enables this to occur. At fertilisation the diploid single cell called a zygote begins dividing. Once it becomes a solid ball of about 16 to 32 cells, it has the appearance of a mulberry fruit (*Morus nigra*) and so is called a morula (**Figure 1**). See subtopic D2.1 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43548/) for more on cell and nuclear division.

Credit: Adela Stefan / 500px, Getty Images

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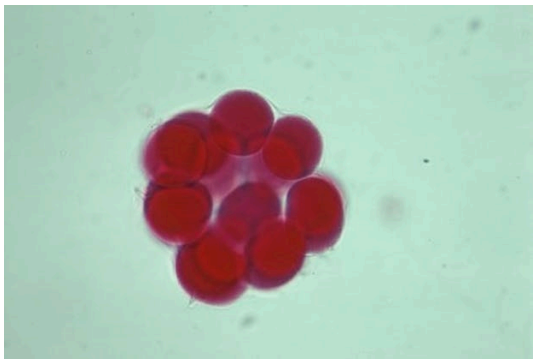

Credit: luismmolina, Getty Images

Figure 1. The mulberry fruit (*Morus nigra*) (left) is a cluster of tiny fruits, each with its own seed and resembles a morula (right).

These cells continue to divide and after 5–6 days the morula will start to differentiate into a hollow ball of cells called a blastocyst (**Figure 2**). This structure contains the outer layer of cells called the trophoblast, and the inner cell mass (ICM). The trophoblast will eventually develop into the placenta, whereas the ICM will become the embryo. The stages of embryo development are covered in more detail in section D3.1.15–17 (/study/app/bio/sid-422-cid-755105/book/post-fertilisation-events-and-embryonic-development-hl-id-46230/).

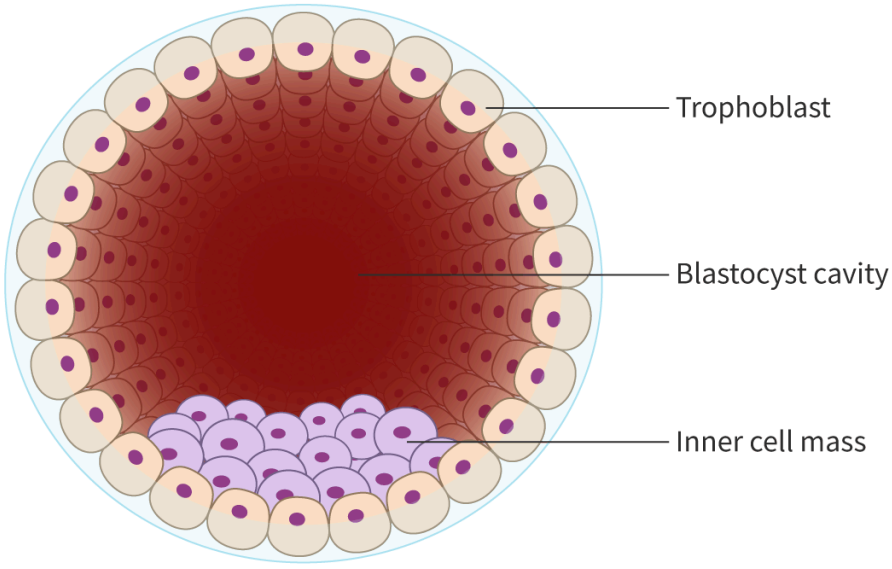

Figure 2. Detail of the blastocyst at 5—6 days after fertilisation.

More information for figure 2

Student view

This is a diagram of a blastocyst, a structure formed 5-6 days after fertilization. The image shows a hollow, spherical configuration with three labeled components. The outer layer consists of the trophoblast, a layer of cells encircling the structure. Interior to this layer is a cavity known as the blastocyst cavity, depicted as an open space. Lastly, the

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inner cell mass (ICM) is a cluster of cells situated towards one side of the blastocyst interior. The trophoblast is responsible for developing into the placenta, while the ICM will become the embryo. Each component is distinctly labeled on the diagram with arrows pointing to their respective positions.

[Generated by AI]

Morphogen gradients

In multicellular organisms, different cells are needed for very different functions. A liver cell is very distinct from a neuron and has specific proteins that need to be expressed in order to perform its function properly. It is important to remember that all the cells within one organism contain identical sequences of DNA, with the same forms of its genes (alleles – see subtopic D3.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43244/)). However, not all cells of an individual will express the same genes at the same time. This difference in gene expression is what determines the type of cell that is formed. Differentiation is the term that is given to cells as they develop from unspecialised to specialised cells.

In an embryo, the ICM cells are all identical to one another, and yet the body pattern of how that organism develops is genetically programmed down to the smallest detail. In the early embryo, certain cells secrete 'form-giving' molecules called morphogens. As these morphogens diffuse outwards from their source, a gradient is established in the local area (**Figure 3**).

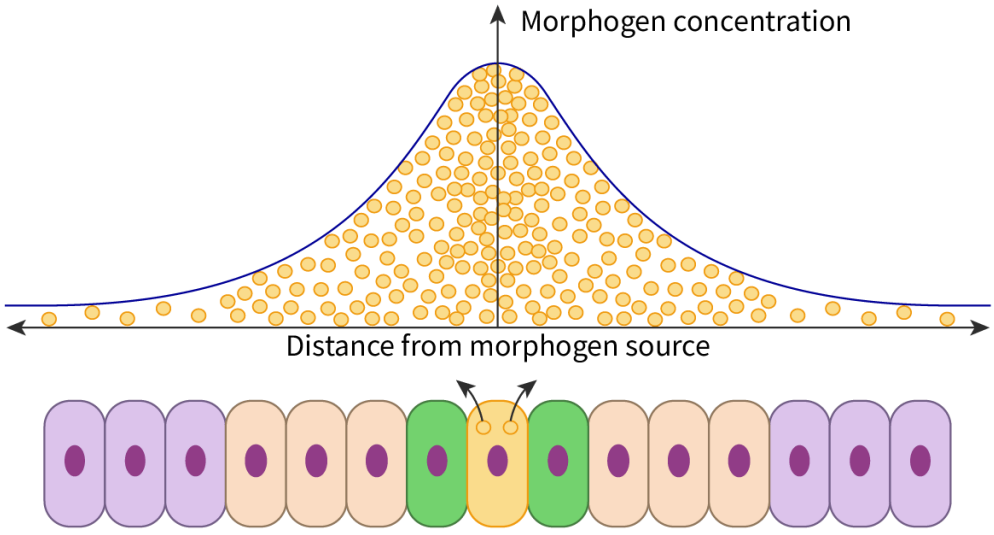

Figure 3. How cells respond to different concentrations of the morphogen.

More information for figure 3

Student view

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The diagram illustrates a morphogen concentration gradient and how cells at different distances from the source respond. At the top, the graph shows a bell-shaped curve labeled "Morphogen concentration" with the curve peaking in the center. Orange circles represent morphogen molecules, densely packed at the peak and dispersing towards the edges.

Below the graph, there is a row of cells represented as ovals. The concentration of morphogens at each cell location varies, demonstrated by the density of orange circles above them. The cells in the center, where morphogen concentration is highest, are colored green, while the surrounding cells are purple. The central green cells highlight specific responses at this concentration level.

Labeled axes emphasize "Distance from morphogen source" horizontally, and there are arrows pointing to the labeled cells from the peak and lower concentration positions of the graph, symbolizing how these cells sense and respond to the gradient.

[Generated by AI]

The distance of cells from the morphogen-secreting cell helps to organise and determine the fate of those cells. The cell ‘reads’ its distance in the concentration gradient through receptors on its surface and develops accordingly. This is remarkably efficient and means that relatively few genes are needed to determine the varied body patterns of the organism.

Stem cell potency

As we discuss embryonic stem cells, it is important to note that not all stem cells have the same ability to differentiate into new types of cell. There are several types of stem cell (**Table 1**).

Table 1. Summary of the types of cells that can be produced from the different types of stem cells.

Type of stem cell	Differentiated cells produced
Totipotent stem cells, e.g. the eight cells of the morula (the first cells formed following fertilisation of an egg cell)	Can differentiate into any type of cell including placental cells. Can give rise to a complete organism.

Student view

Overview (/study/ap 422-cid-755105/o

Type of stem cell	Differentiated cells produced
Pluripotent stem cells (e.g. embryonic stem cells of the blastocyst)	Can differentiate into all body cells, but cannot give rise to a whole organism.
Multipotent stem cells (e.g. umbilical cord stem cells)	Can differentiate into a few closely related types of body cell.
Unipotent stem cells	Can only differentiate into their associated cell type. For example, liver stem cells can only make liver cells.

The cells at the morula stage are totipotent stem cells as they not only can differentiate into any cell of the organism, but they can also give rise to the embryo, the placenta and the embryonic sac tissues. As the morula develops into a blastocyst, the cells become less adaptable. The inner cell mass cells discussed earlier are pluripotent stem cells as they cannot generate an entire organism, but are able to differentiate into any of three 'germ' layers. These layers are the endoderm (inner layer), the mesoderm (middle layer) and ectoderm (outer layer).

Other cells, called multipotent stem cells, can form into only a few closely related cell types. One example of these are the cells from the umbilical cord. Some parents choose to harvest (https://www.nhsbt.nhs.uk/cord-blood-bank/what-is-cord-blood/) these cells and store them for potential medical use for their child. Another example are the stem cells in bone marrow. These can give rise to all types of blood cells. This ability has allowed them to be used for transplants to correct conditions affecting blood cells such as cancers of the blood like leukaemia and or lymphoma. There are other stem cells that can only generate the associated type of cell. For example, liver stem cells can only make new liver cells. These are called unipotent stem cells.

Stem cell niche

The stem cell niche can be thought of as the microenvironment within the organism in which the stem cells live and receive their instructions (**Figure 4**). This environment influences the stem cells and how they differentiate. There are numerous interactions that can determine what happens to the stem cells in the niche. There are cell-to-cell interactions and the cell can also interact with the fluid outside of the cells (extracellular matrix). Signalling molecules can activate, or prevent genes from transcribing (see subtopic B2.2

Student view

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(/study/app/bio/sid-422-cid-755105/book/big-picture-id-43532/)). This leads to some cells being instructed to remain dormant (inactive) while others are directed to make more of the same kind of stem cell. Still others become differentiated into another kind of cell.

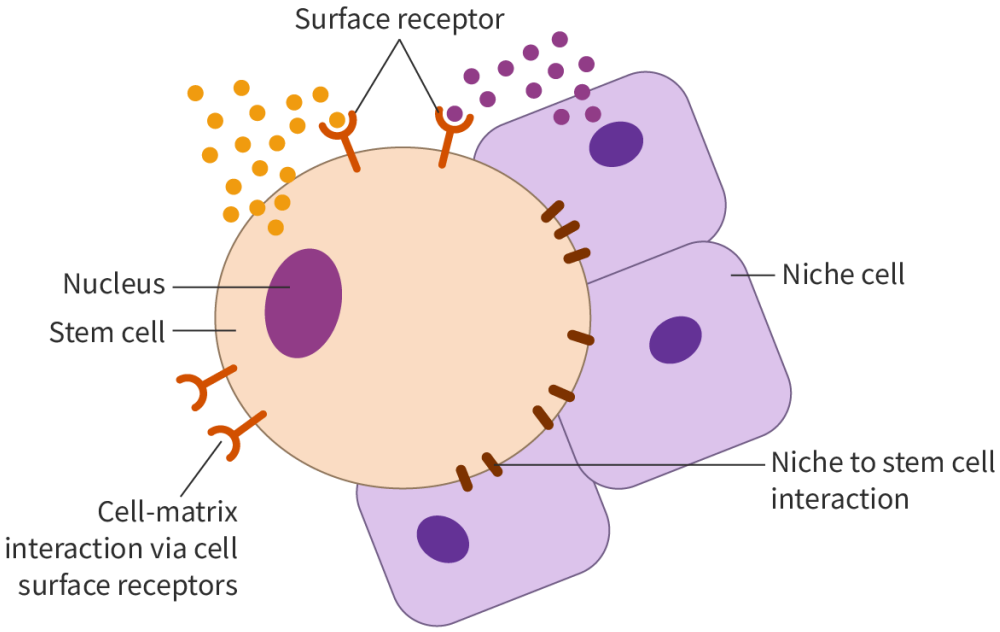

Figure 4. The stem cell niche involves the stem cells interacting with other cells and with the extracellular matrix.

More information for figure 4

The diagram illustrates the interactions between a stem cell and niche cells within the stem cell niche. A large, central stem cell is depicted with a visible nucleus, shown as a smaller purple circle within the larger beige circle representing the cell. Multiple surface receptors are highlighted on the stem cell's membrane, illustrated by outward-facing orange shapes. These receptors interact with small orange and purple dots, representing molecules in the extracellular matrix, indicating the cell-matrix interaction via surface receptors.

Surrounding the stem cell are several niche cells, labeled as such, depicted in a lighter purple color with their own nuclei. Arrows labeled "Niche to stem cell interaction" suggest interactions between these niche cells and the central stem cell.

The general positioning and interactions suggest a complex environment where the stem cell's behavior is influenced by signals from both the niche cells and extracellular molecules, reflecting the dynamic relationships in the stem cell niche.

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The stem cell niches in humans that have been studied most are those that make blood, skin, intestine, brain and muscle cells. Blood stem cells are found in the bone marrow throughout adulthood. The bone marrow is the soft, spongy centre of most bones and has many blood vessels associated with it. The bone marrow niche itself is made up of a combination of cells that make blood cells (haematopoietic) as well as those that are supportive cells (**Figure 5**). The supportive cells regulate the function of the ones that generate the blood cells. The maintenance of the blood cell niche is essential for the constant supply of functional blood cells throughout the human's life.

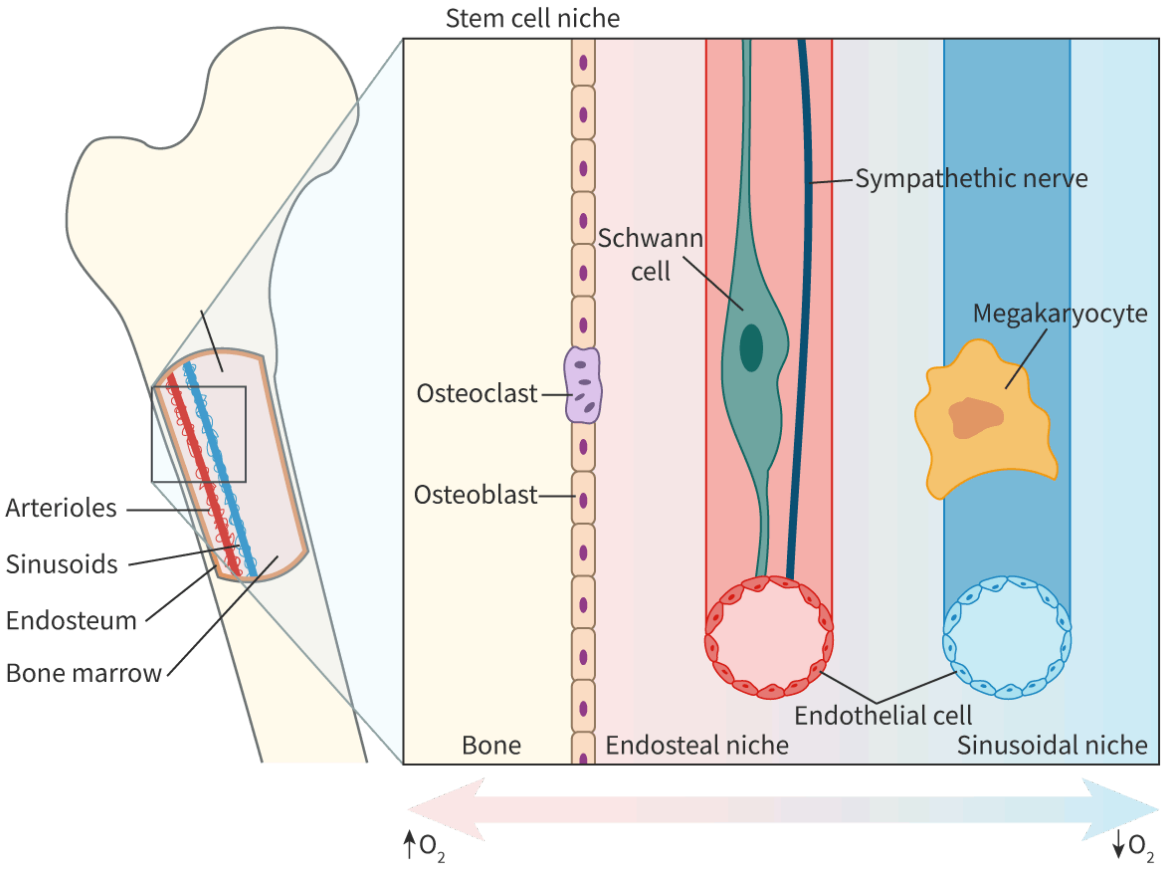

Figure 5. Location of the bone marrow stem cell niche.

More information for figure 5

The diagram illustrates the various components of the bone marrow stem cell niche within a cross-section of bone. It shows an outer structure labeled as "bone," followed by layers labeled "osteoclast" and "osteoblast," which represent cells involved in bone remodeling. Inside the bone, within the endosteal niche, there are Schwann cells and sympathetic nerves depicted. Adjacent to this, within the sinusoidal niche, there is a megakaryocyte and endothelial cells shown. The diagram highlights the interactions between these different cell types. Arterial and sinusoidal blood

Student view

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vessels are also illustrated, emphasizing the vascular nature of the bone marrow environment. A large arrow at the bottom indicates a gradient of oxygen concentration from high to low across the niche. This complex arrangement underscores the intricacy and functionality of the bone marrow niche in hosting hematopoietic stem cells.

[Generated by AI]

The skin is the largest organ in your body and it will be constantly replaced during your lifetime. Think about how many new skin cells you have already made since birth! Hair follicles are a very well-defined and well-studied mammalian cell niche. Hair follicles have cycles of degeneration, growth and rest so that your body is always covered with mature hair shafts. The hair follicle stem cells that are responsible for proliferation (something increasing rapidly in number or amount) of the hair are found in an area called the 'bulge' (**Figure 6**). Other cells in the follicle are responsible for the breakdown of old hairs and maintaining the rest stage. They work together in an elegant and choreographed way to achieve a full body of hair at all times.

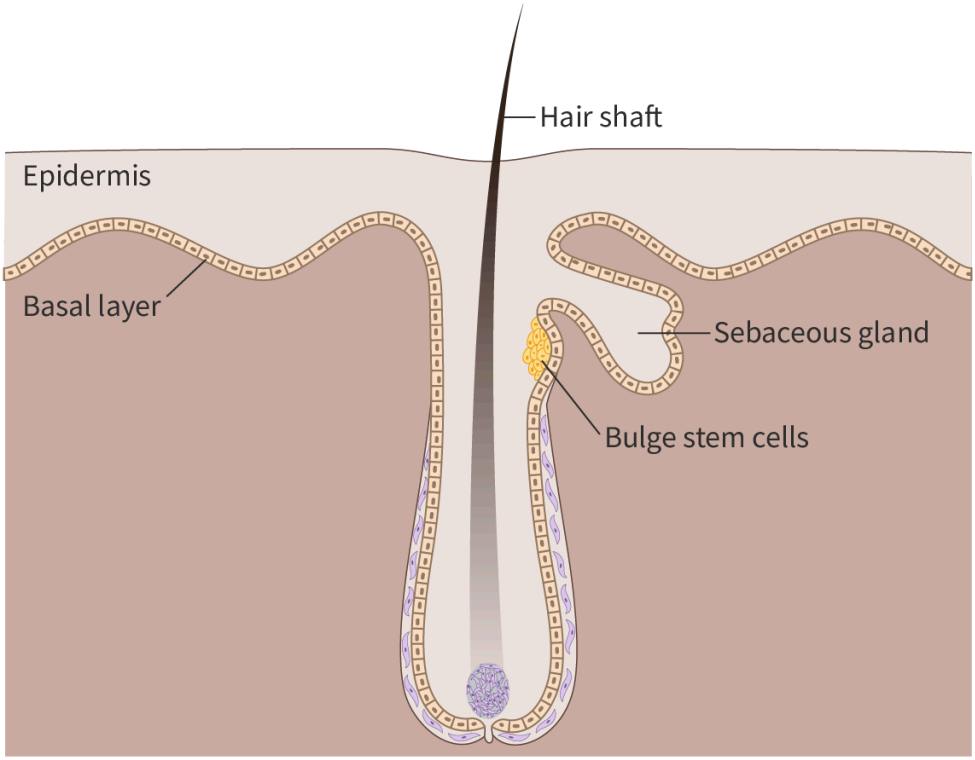

Figure 6. A hair follicle showing the stem cell niche at the bulge.

More information for figure 6

Student view

Overview (/study/ap 422-cid-755105/o

The image is a detailed diagram of a hair follicle, which is embedded in the skin. At the top, it shows the epidermis layer, with the basal layer beneath it. The hair shaft is visible projecting from the epidermis surface downward into the follicle. Below the epidermis, the folate branches and loops showing different cellular structures. To the right of the hair shaft, the sebaceous gland is labeled, which is known for secreting oils that moisturize the skin and hair. Further down, bulge stem cells are identified, which are responsible for hair regeneration. The primary focus of the diagram is on showing the position and interrelation of these components within the follicle structure to help understand hair growth and maintenance.

[Generated by AI]

Theory of Knowledge

Stem cell research requires the destruction of an embryo in order to extract the pluripotent stem cells. These cells can be used to advance medical treatments for many diseases. Different groups would argue that life begins at varying stages of embryonic development. Evaluate the ethical use of embryonic stem cells considering both sides of the argument. Use the information from EuroStemCell (https://www.eurostemcell.org/theme/ethics-and-society) to help build your arguments.

Try **Interactive 1** in this activity to understand the different stages of development of an embryo.

Activity

- **IB learner profile attribute:** Knowledgeable
- **Approaches to learning:** Thinking skills — Being curious about the natural world
- **Time required to complete activity:** 10 minutes
- **Activity type:** Individual activity

Student view

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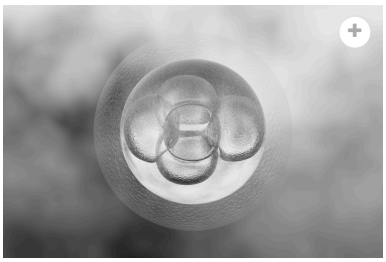

Name the stage of development

- Egg just fertilised
- Embryo
- Blastocyst
- Zygote
- Morula

Check

Rights of use

Interactive 1. Generate different cell types.

More information for interactive 1

This interactive consists of a series of six questions that test the user's understanding of the different stages of embryonic development. The interface includes a navigation bar at the bottom, allowing users to move between questions, with a glowing indicator that shows their current progress. A full-screen button is available on the top right of each visual for an enhanced viewing experience. Each question presents an image of a developing cell and prompts the user to select the correct stage of development. Users are provided with multiple-choice options and can check their answer after selecting a response. If the answer is incorrect, the user is given immediate feedback and can try again. At the end of the sequence, users receive a score summary and the option to retry the entire quiz or view correct solutions.

In the first question, the image shows a tightly packed ball of cells forming a smooth, spherical mass. This structure has no visible hollow space and resembles the morula stage, which occurs after multiple cell divisions. Based on this image, users are asked to name the stage of development, with the options: Blastocyst, Zygote, Embryo, Morula, and Egg just fertilised.
The second question presents an image of a fluid-filled cavity enclosed by a distinct outer cell layer with a concentrated inner cell mass. This visual matches the typical appearance of a blastocyst just prior to implantation. The same prompt is used, and the user must choose from the following options: Egg just fertilised, Morula, Embryo, Blastocyst, and Zygote.
The third question shows a clearly differentiated structure with defined body segments and tissue

Student view

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folds, indicating significant development. This complex form closely resembles the embryo stage. Once again, the prompt asks users to identify the stage of development, offering the choices: Zygote, Morula, Egg just fertilised, Blastocyst, and Embryo.

In the fourth question, the image focuses on a single, round cell with a well-defined nucleus and outer membrane, representing a fertilised egg at the single-cell phase. This form aligns with the characteristics of a zygote. The same five options are presented for selection: Egg just fertilised, Morula, Zygote, Blastocyst, and Embryo.

The fifth question shows a dramatic close-up of a sperm just making contact with the outer surface of the egg. This imagery visually captures the immediate post-fertilisation moment, suggesting the stage “Egg just fertilised.” Users are asked to pick the right term from these five options: Blastocyst, Morula, Embryo, Egg just fertilised, and Zygote.

The sixth and final task is an interactive drag-and-drop activity that reinforces conceptual sequencing. Users see five green tiles labelled “Egg just fertilised,” “Zygote,” “Morula,” “Blastocyst,” and “Embryo.” Below the tiles is a bold arrow labelled “Increasing complexity,” guiding users to arrange the cards from the earliest to the most developed stage. This engaging format supports deeper understanding through hands-on ordering of developmental stages.

In the final section which appears after clicking on the provided button “Finish”, users are presented with a report card displaying their score, including the number of correct answers. This section also provides a "Show solution" option, allowing users to review the correct answers for each question. Additionally, there is a "Retry" button, giving users the option to attempt the quiz again after learning the correct answers.

Solutions:

Q1: Blastocyst

Q2: Blastocyst

Q3: Embryo

Q4: Zygote

Q5: Egg just fertilised

Q6: Correct order: Egg just fertilised → Zygote → Morula → Blastocyst → Embryo

5 section questions

Student view

What determines cell size?

Learning outcomes

By the end of this section you should be able to:

- Describe the size differences in various human cells.
- Discuss the relationship between cell size and surface area in terms of the movement of material across a cell.

Size variations of human cells

A human body contains an astonishing number of cells – somewhere between 50 to 100 trillion cells. These cells range from the smallest being about 7.5 µm to significantly larger ones like the human egg cell or ovum (150 µm).

The volume inside a human egg cell is about 10 million times larger than the volume of a sperm cell (**Figure 1**)! In fact, the egg cell is one of the largest in the human body, while the sperm cell is one of the smallest! What might be the reason for the egg cell being so much larger than the sperm cell? You can read more about this size differential here (https://news.northwestern.edu/stories/2021/04/gametes-egg-and-sperm-cell-size-evolved-from-competition/).

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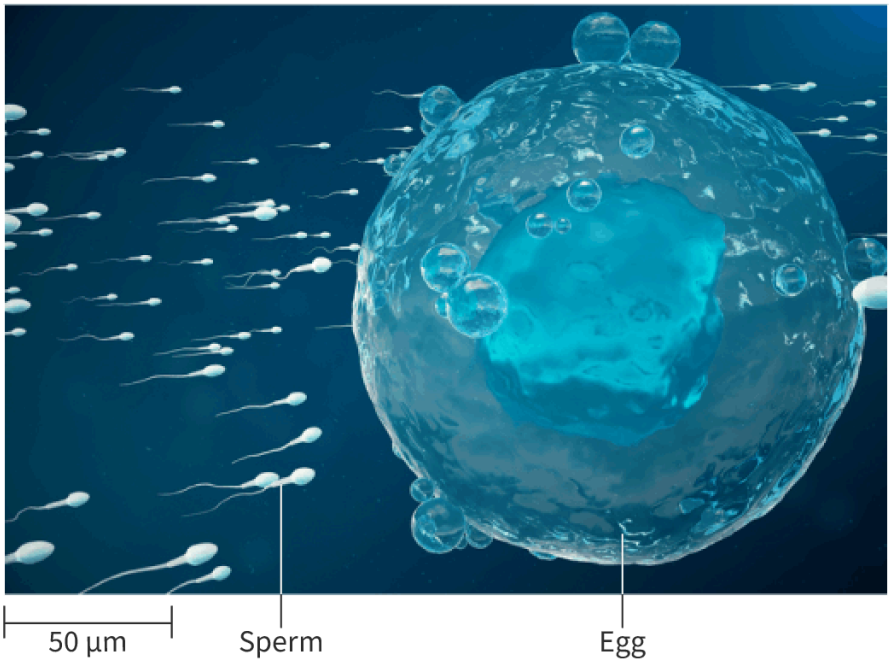

Figure 1. A human egg and sperm.

Study skills

A micrometre (µm) is equivalent to:

0.001 mm

0.0001 cm

0.000001 m

The structure of these cells is linked directly to their function. The spherical human egg cell has evolved to be large and highly specialised so that it contains all the nutrient materials needed for the early development of the embryo. The sperm on the other hand does not need such nutritional content and so remains small. See subtopic A2.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43253/) for more about cell structure.

Many human cells are approximately spherical in shape, but not all. Some specialised nerve cells are incredibly long. Neurons (see subtopic B3.3 (/study/app/bio/sid-422-cid-755105/book/big-picture-hl-id-43535/)) in the sciatic nerve (**Figure 2**) are the longest in the human body; their axons can exceed 1 m. The nerve starts at the base of the spine and ends in the foot. These elongated cells have evolved as part of the mechanism for communication between the spinal cord and other more distant parts of the body.

Student view

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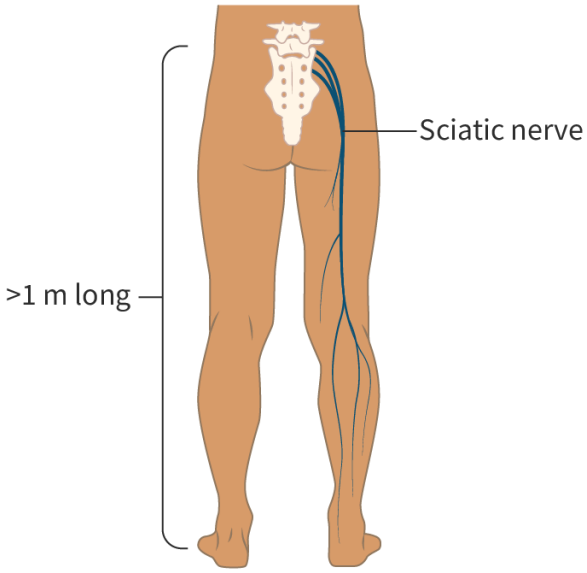

Figure 2. Location of the sciatic nerve.

More information for figure 2

The image shows a diagram of a human figure from the back, highlighting the location of the sciatic nerve. It starts at the base of the spine and extends down the leg, ending in the foot. The text in the image indicates that the nerve is more than 1 meter long. A label with an arrow points to the path of the sciatic nerve, which is depicted as a long, slender line running along the outline of the leg.

[Generated by AI]

Some of the smallest cells in the human body are the red blood cells (see subtopic A2.2 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43253/)) that measure approximately 7.5 µm in diameter and are only 2 µm in thickness (**Figure 3**). These small cells, also called erythrocytes, have no nucleus, which leaves space for packing in more haemoglobin for binding oxygen to transport around the body. These biconcave cells have a highly flexible membrane (see subtopic B2.1 (/study/app/bio/sid-422-cid-755105/book/the-big-picture-id-43205/)) that allows them to be repeatedly deformed and spring back in shape, which is important as they move through the circulatory system.

Student view

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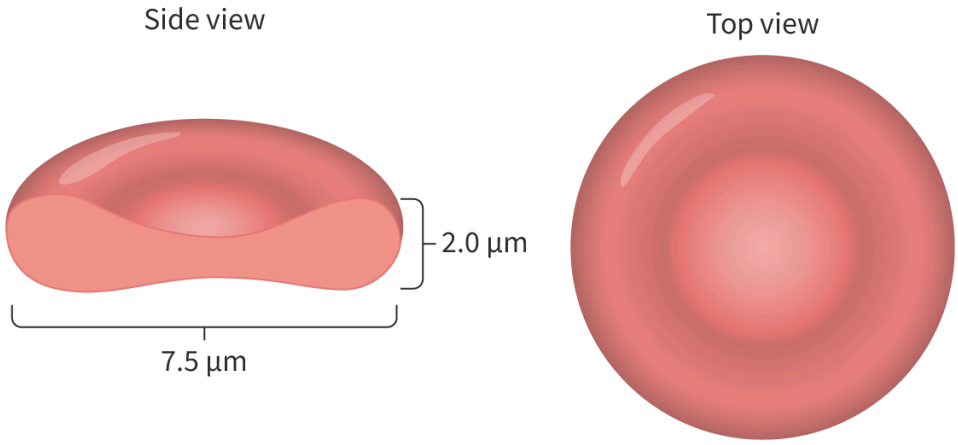

Figure 3. Morphology of the red blood cell.

More information for figure 3

The image is a diagram illustrating the morphology of a red blood cell from both side and top views. On the left, the side view shows the red blood cell as a biconcave disc, similar to a donut without a complete hole. It is labeled with measurements indicating it is 7.5 micrometers in diameter and 2.0 micrometers in thickness. The shape is slightly indented in the middle, typical of red blood cells, allowing for flexibility as it moves through blood vessels. On the right, the top view shows the circular shape of the red blood cell, which is necessary for its function in the bloodstream. Both views are depicted as shaded red, mimicking the natural color of blood cells.

[Generated by AI]

Nature of Science

Aspect: Evidence

Scientists have been able to use new techniques to observe previously unseen detail

Scientists have used super-resolution fluorescence microscopy (https://www.sciencedirect.com/topics/agricultural-and-biological-sciences/fluorescence-microscopy) to determine the internal structure of red blood cells. They have discovered the reason that red blood cells are so sturdy but remain so flexible. A two-dimensional mesh made of a protein called spectrin lies like a dome-shaped scaffold just underneath the membrane.

Student view

Overview (/study/ap 422-cid-755105/o

The less common white blood cells are larger than red blood cells and range from about 10 to 20 µm. Unlike the red blood cells, they have nuclei of various shapes which can aid in their identification (**Figure 4**). They are able to move in an amoeboid way (like an *Amoeba*) towards sites of infection and can squeeze out of blood vessels into surrounding tissues.

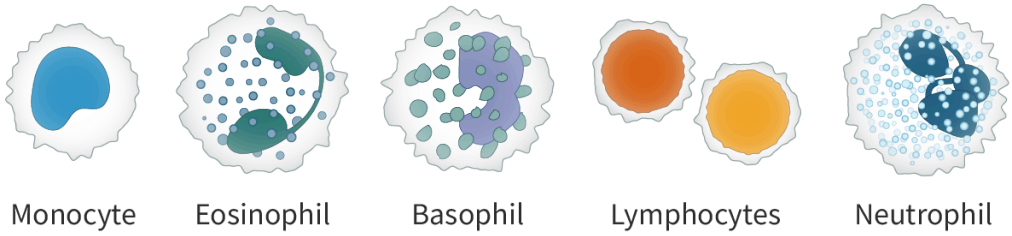

Figure 4. There are many different types of white blood cells that vary in size, structure and function.

We have just studied that cells are generally small. Striated muscle fibres however are an exception and are large, multinucleated cells. These cells can be extremely long!

Higher level (HL)

More details about these cells can be found in the next section B2.3.7–10 (/study/app/bio/sid-422-cid-755105/book/cell-adaptations-hl-id-44445/).

Keeping cells alive

Cells need to grow before they divide. However, they do not keep growing indefinitely. Cells have control mechanisms involving cell surface receptors and growth factors in the surrounding environment to ensure that the maximum size of any given cell type is consistent within an organism. As cells increase in size, there is more room for the organelles within them, and more space for the metabolic reactions to occur in the cytoplasm. You might therefore assume that a larger cell is better and more beneficial for the organism. When contemplating cell size, we need to consider the ratio of the volume of the cell with respect to its surface area which is made up by the cell membrane. You can think of a cell being similar to a balloon being pumped up. As the volume increases, the surface area does not increase at the same rate. We need to look at the ratio between the surface area and the volume (SA:V). The larger the cell becomes, the more the SA:V ratio reduces.

Student view

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Nature of Science

Aspect: Models

Scientists use models of cells to explain complex systems

Surface-area-to-volume relationships can be modelled using cubes of different side lengths, as described in **Video 1**. Although the cubes have a simpler shape than real organisms, scale factors operate in the same way.

Video 1. Surface area to volume.

When there is a larger SA:V, it is easier for nutrients to pass into the cell and for excretory products to exit the cell. So, why can't all cells become extremely small to maximise the movement across the membranes? The size that a cell achieves is a fine balance in being large enough to contain all the necessary organelles for the cell's particular function without compromising the ability for efficient gas exchange and nutrients across its membrane. Cells that are too small would not be able to contain the cellular components. Cells that are too large can contain more organelles, but the SA:V may be too small and the movement of nutrients into and out of the cell would be too slow to keep the cell alive.

Study skills

Student view

As a cell grows, its volume increases by the power of 3 (cubed), whereas the surface area increases by the power of 2 (squared). Therefore, its surface area-to-

Overview (/study/ap 422-cid-755105/o

volume ratio decreases.

Try this activity to help you understand the relationship between surface area and volume, using a cube as a model cell.

Activity

- **IB learner profile attribute:** Thinker
- **Approaches to learning:** Thinking skills — Providing a reasoned argument to support conclusions
- **Time required to complete activity:** 10—15 minutes
- **Activity type:** Individual activity

In **Interactive 1**, click on the dot and drag the corner of the cube to generate different sizes. As you change the cube size, the surface area, volume and SA:V will be calculated and shown on the diagram.

Student view

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Interactive 1. Surface area, volume and SA:V of different sized cubes.

More information for interactive 1

This drag-and-drop interactive helps users explore the relationship between **surface area and volume**, using a cube as a model for a cell.

This interactive displays a blue cube on a grid, with a ruler situated below it, allowing for the measurement of the cube's side length. A table at the bottom of the image dynamically updates as the cursor is dragged left or right, changing the cube's size. This table presents the length of the cube's side in centimeters, its surface area in square centimeters, its volume in cubic centimeters, and the ratio of surface area to volume.

Cells need to exchange materials with their environment. This exchange happens across the cell's surface. A higher Surface Area (SA):Volume (V) ratio means more surface area relative to the cell's volume, making exchange more efficient.

As you drag the cursor and make the cube bigger, notice the SA:V ratio gets smaller. This shows that larger cells have less surface area relative to their volume.

For example, in the cube surface area versus volume table, if we drag the side length to 3, we have the SA:V ratio as 2, and when the side length is doubled, that is 6, the SA:V ratio becomes 1.

This image demonstrates that the SA:V ratio is a limiting factor in cell size. Cells must maintain a high enough SA:V ratio to function efficiently.

Student view

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Surface area = (side length^2) × 6. The units are cm^2. For example:

$$2^2 = 4 \text{ cm}^2$$

$$4 \times 6 = 24 \text{ cm}^2$$

Volume = side length^3. The units are cm^3. For example:

$$2^3 = 8 \text{ cm}^3$$

SA:V is calculated by dividing the surface area by the volume. For example:

$$\frac{4}{8} = 0.5$$

Create a table similar to **Table 1** to record your results. Complete the details for a cube with a side length of 1 cm, writing down surface area, volume and SA:V. Now move to the cube with a side length of 2 cm, and do the same. Complete for all the cubes. Observe how the SA:V changes with the increasing size of the cube.

Table 1. Sample results table.

Length of side (cm)	Surface area (SA) cm^2	Volume (V) cm^3
1		
2		
3		
4		
10		

Write a statement giving your reasoning for why a fully functioning cell is dependent on the relationship between surface area and volume.

5 section questions

B2. Form and function: Cells / B2.3 Cell specialisation

Cell adaptations (HL)

Student view

B2.3.7: Adaptations to increase cell surface area-to-volume ratios (HL)

B2.3.8: Adaptations of type I and type II pneumocytes in alveoli (HL)

Higher level (HL)

Learning outcomes

By the end of this section you should be able to:

- Identify and describe cell types that increase surface area-to-volume ratios.
- Describe specific adaptations that cells in the lung, heart, muscle and gonads have undergone to perform their functions.

The need for cells to constantly achieve efficient transport of gases and nutrients across the membrane has resulted in some types evolving specialised methods to increase the surface area-to-volume ratios. For example, prokaryotic cells are smaller, allowing them to maintain a large SA:V. More complex organisms have eukaryotic cells that are compartmentalised to overcome difficulties with accessing nutrients and expelling waste.

Another method to increase surface area is for the cell to become flattened. Squamous epithelial cells are thin, flat, horizontal or elliptical shaped cells. Such cells are found lining the alveoli of the lungs, kidney tubules and capillaries among others. These cells are important in allowing diffusion of molecules such as gas exchange or nutrients.

Still another method is to have invaginations of membranes. Mitochondria (see section B2.2.4–6 (/study/app/bio/sid-422-cid-755105/book/structure-and-function-of-double-membranes-hl-id-44251/)) are double-membraned organelles that generate adenosine triphosphate (ATP) in cellular respiration. They contain numerous invaginations of the inner membrane called cristae enabling increased metabolic reactions to take place (**Figure 1**).

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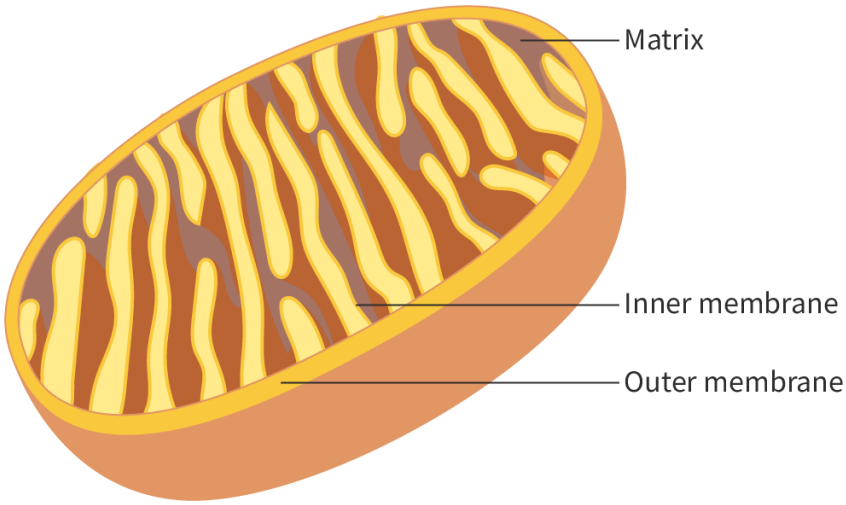

Figure 1. The internal structure of the mitochondrion shows multiple invaginations of the inner membrane to increase the number of membrane-bound reactions.

More information for figure 1

The image is a diagram illustrating the internal structure of a mitochondrion. It shows the mitochondrion in a cross-sectional view. The outer membrane is a smooth line that forms the outer boundary. Inside, the inner membrane forms multiple infoldings called cristae, which appear as wavy lines that increase the surface area for metabolic reactions. The cristae extend into the matrix, the innermost space of the mitochondrion. The diagram labels the 'Outer membrane' on the external border, the 'Inner membrane' on the boundary between the matrix and cristae, and the 'Matrix' in the innermost area of the organelle.

[Generated by AI]

Nature of Science

Aspect: Evidence

Observations of muscle biopsies from endurance-trained athletes showed evidence of higher mitochondrial cristae density than non-athletes

A 2017 study (https://physoc.onlinelibrary.wiley.com/doi/epdf/10.1113/JP273040) revealed that muscle biopsies taken from a part of the quadricep in the thigh had 23% higher mitochondrial cristae density in endurance-trained athletes compared with non-athletes. This was the first time that it was shown that the very structure of the mitochondria is important for increased cellular respiration, not only the number of mitochondria present in a tissue.

Student view

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The structures of the plant photosynthetic thylakoid membranes within the chloroplast organelle are well understood. You can read more about these structures in subtopic C1.3 (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43539/). These organelles have also evolved to have multiple membranes enabling more reactions to occur than would be possible if there were less surface area (**Figure 2**).

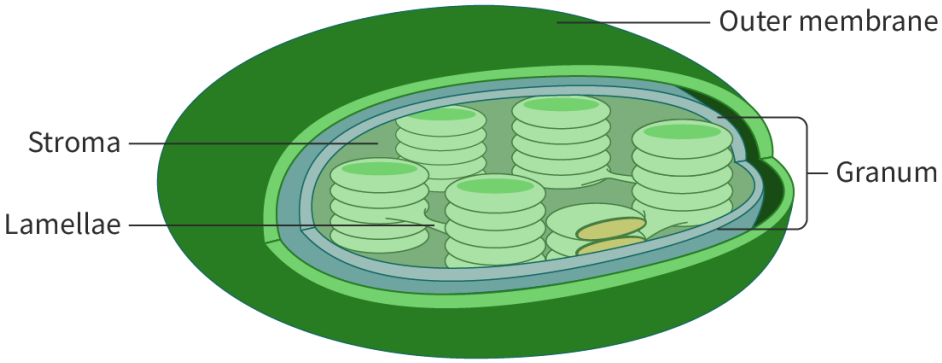

Figure 2. Structure of a chloroplast showing the lamellae.

More information for figure 2

The image is a diagram illustrating the structure of a chloroplast, an organelle found in plant cells. It's a cross-section showing several components: the outer membrane, the stroma, the lamellae, and the granum. The outer membrane is depicted as the external layer encompassing the chloroplast. Inside the membrane, the stroma is the fluid-filled space. The granum consists of stacks of disc-shaped thylakoids, shown as multiple green discs stacked together. The lamellae are depicted as connecting structures between the grana. Each part is labeled to identify these components clearly.

[Generated by AI]

In the mammalian digestive system, the small intestine has very large numbers (10 to 40 per mm^2) of slim finger-like projections called villi (singular: villus). The columnar cells or enterocyte cells that are found at the surface of these villi are the ones that are responsible for the absorption of nutrients into the bloodstream. The villi already increase the surface area of the small intestine but to further increase the surface area, each columnar cell itself has about 600 smaller projections called microvilli (**Figure 3**). These form the brush border of the small intestine and facilitate the maximum absorption possible in the intestine.

Student view

Overview (/study/ap 422- cid- 755105/o

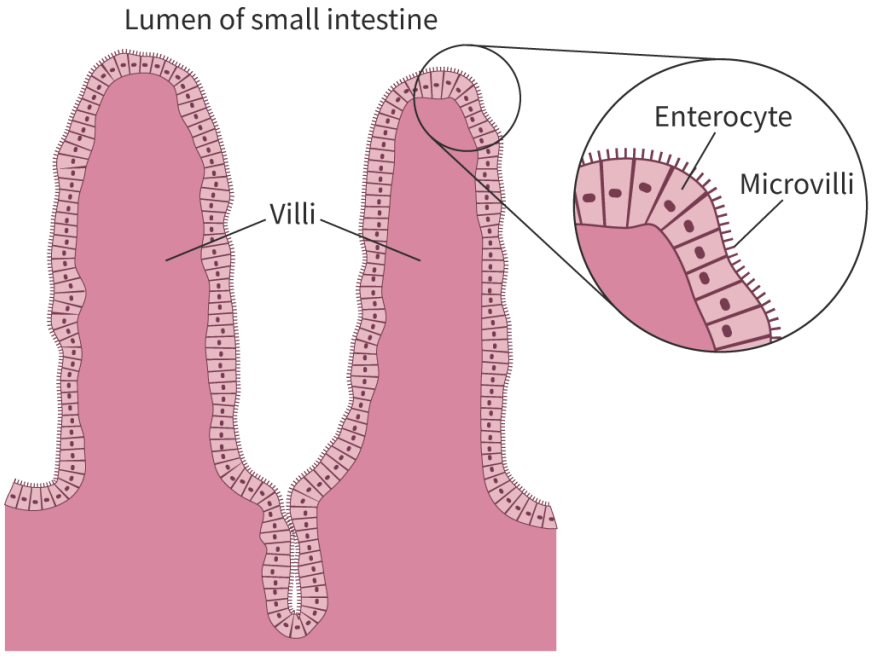

Figure 3. The villi are composed of enterocytes each of which have about 600 microvilli on their surface.

More information for figure 3

The diagram illustrates the structure of the villi within the small intestine. It depicts two elongated, finger-like projections that extend into the lumen of the small intestine. Each villus is lined with columnar cells known as enterocytes. A magnified section is shown to the right, highlighting an individual enterocyte with its surface bristling with tiny microvilli. The microvilli are densely packed, appearing like a brush border, maximizing the surface area for nutrient absorption. Various labels point to different sections: the lumen of the small intestine, villi, enterocyte, and microvilli.

[Generated by AI]

International Mindedness

Rotavirus (https://www.nature.com/articles/nrdp201783) is a leading cause of death of children under the age of 5, mostly in low-income countries.

Rotavirus infects enterocyte cells of the small intestine. These are the cells that compose the villi. On their uppermost surface enterocytes have smaller projections called microvilli. By destroying these cells, the ability of the small intestine to absorb nutrients is severely reduced. This results in severe diarrhoea and dehydration causing the death of more than 200 000 people annually. Effective vaccines are available for rotavirus but for a number of reasons, low-income countries may struggle to have full coverage for their population. This could be due to conflict and

Student view

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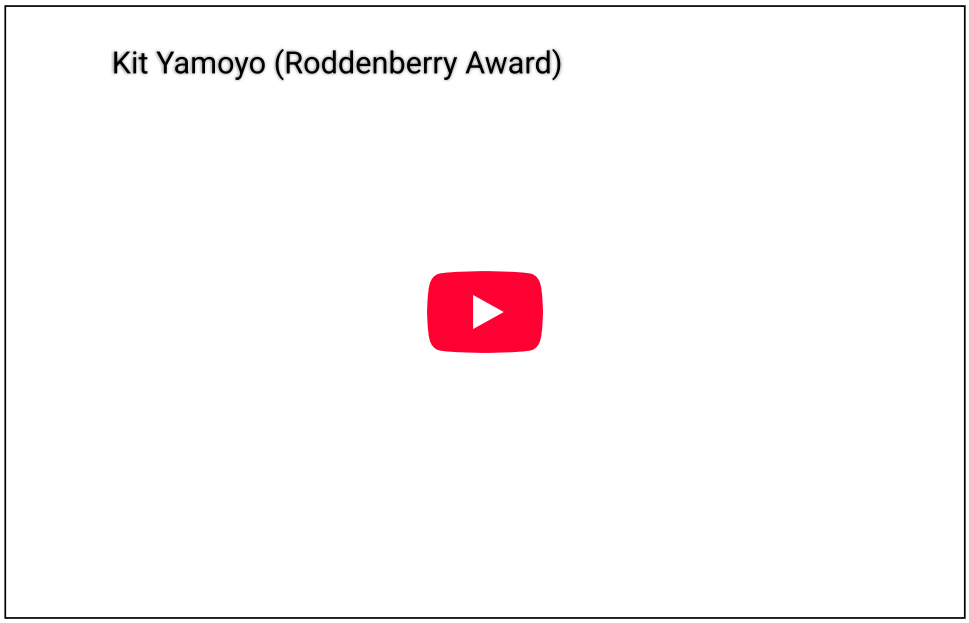
insecurity in the region, poor transport infrastructure for distributing medicines around the country, a lack of electricity needed to store the vaccines as well as overloaded and poorly funded healthcare. Oral rehydration salts (ORS) made up with water are frequently used to help rehydrate infants. Often the correct measuring tools are not available. Watch **Video 1** for an innovative way of providing the ORS in a container that can be used for measuring the water accurately.



Video 1. An innovative method used to provide oral rehydration salts.

The same technique as used in the small intestine is also employed in the kidney (see section D3.3.8 (/study/app/bio/sid-422-cid-755105/book/osmoregulation-hl-id-44810/)). The proximal convoluted tubule is a very important region for absorption of water, salts and glucose, and amino acids back into the bloodstream (**Figure 4**). The lining of the proximal convoluted tubule has cuboidal-shaped cells with microvilli to increase the absorption of these substances.

Student view

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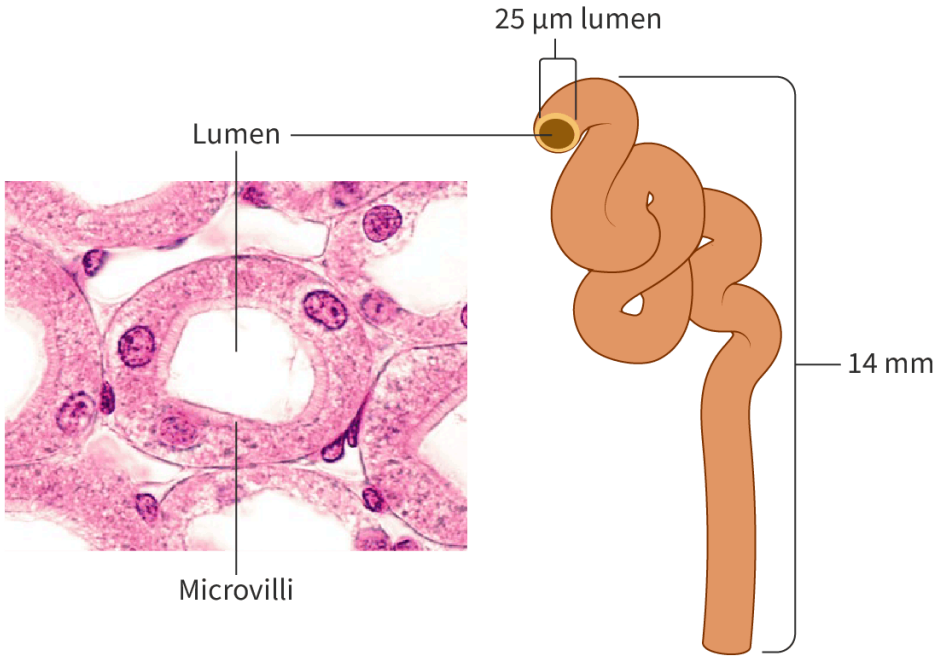

Figure 4. A transverse section through the kidney proximal convoluted tubule showing microvilli facing the lumen.

More information for figure 4

The image is a detailed diagram of the kidney's proximal convoluted tubule. It consists of two main parts: a histological section showing pink-stained tissue with labeled microvilli inside tubule cells, and an illustration of the tubule's shape and structure. The histological section highlights the microvilli, which increase surface area for absorption, surrounded by labels indicating the "Lumen" (the central passageway). The accompanying diagram shows a convoluted orange tubular structure (the proximal tubule) with a lumen labeled as 25 µm and the overall tubular structure labeled as 14 mm in length. The tubule is shown in a coiled configuration, representing its natural form within the kidney.

[Generated by AI]

Cell adaptations in lung tissue

In order to function properly, some tissues need more than one cell type to be present. The lung has two different cell adaptations that fulfil very different roles. The need to have gases diffuse easily from the inside of the alveoli into the surrounding capillaries and vice versa requires a shortened distance. The reduction in diffusion distances is met by squamous type I pneumocytes which are very thin (0.1–0.2 µm thick) and flattened out. These cells have few organelles and have a diameter of 50 µm. These make up about 95% of the alveolar surface. Between neighbouring cells, there are tight junctions. In contrast, the type II pneumocytes make up only 5% of the alveolar surface but outnumber the type I cells. They are cuboidal in shape, with the tip of the cell protruding into the alveolar space (**Figure 5**). They contain many organelles and have distinct secretory vesicles (

Student view

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lamellar bodies) that are responsible for secreting surfactant (see section B3.1.1–4 (/study/app/bio/sid-422-cid-755105/book/gas-exchange-as-a-vital-function-id-44438/)) into the alveolar space. The surfactant is made of phospholipids and proteins and is essential to prevent the alveoli from collapsing.

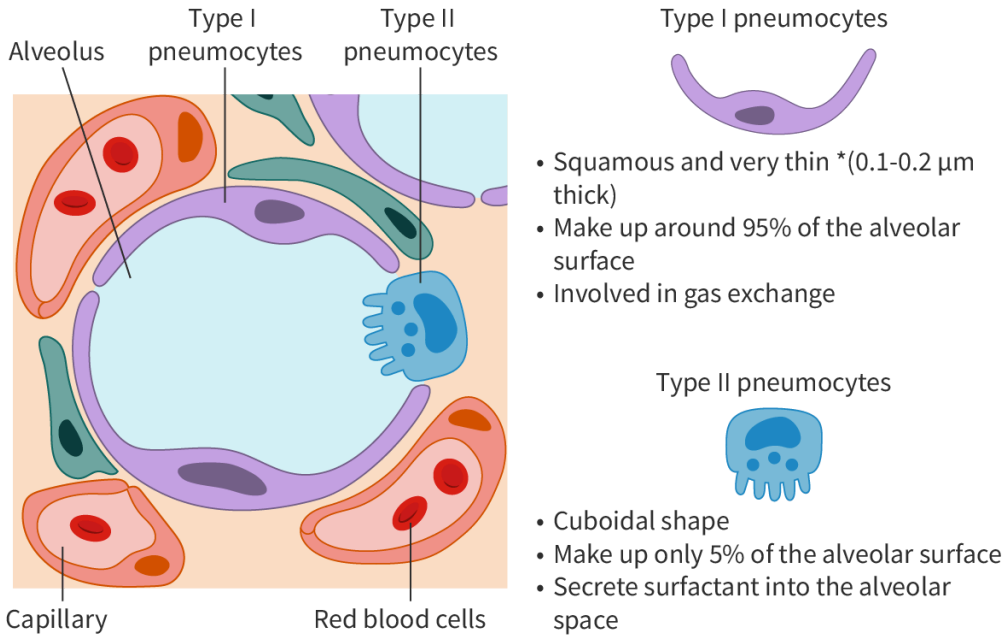

Figure 5. Two types of cells with different adaptations are required in the lung to enable full functionality of the organ.

More information for figure 5

The image is a diagram illustrating the lung's alveolus structure and types of pneumocytes involved in lung function. It shows an alveolus surrounded by capillary structures. The diagram highlights two types of cells:

1. **Type I pneumocytes** are shown as thin, elongated structures forming the majority of the alveolar surface (95%). They are labelled as "Squamous and very thin (0.1—0.2 µm thick)", "Make up around 95% of the alveolar surface", and "Involved in gas exchange".
2. **Type II pneumocytes** are depicted as larger, cuboidal cells covering only 5% of the alveolar surface but outnumber Type I pneumocytes. They are responsible for secreting surfactant into the alveolar space. The text associated with them reads: "Cuboidal shape", "Make up only 5% of the alveolar surface", and "Secrete surfactant into the alveolar space".

The alveolus is bordered by a segment labeled "Capillary" containing red blood cells, highlighting its role in facilitating gas exchange between alveoli and blood.

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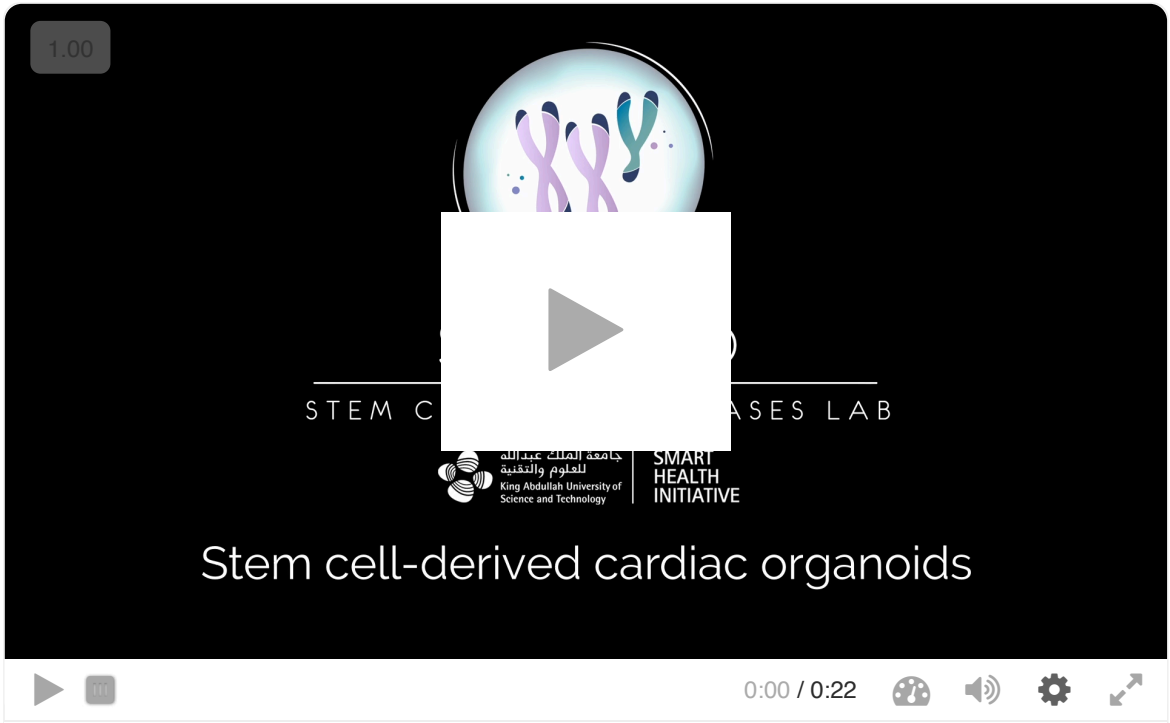
Cell adaptations in muscles

Within the human system, muscles can take three distinct forms (**Figure 6**). Cardiac muscle is found in the heart, skeletal muscle is attached to the skeleton, and smooth muscle is found in many places such as blood vessels and the intestinal tract. Both cardiac (see section B3.2.14–16 (/study/app/bio/sid-422-cid-755105/book/adaptations-of-the-heart-hl-id-44448/)) and skeletal (see section B3.3.2–4 (/study/app/bio/sid-422-cid-755105/book/muscle-contraction-hl-id-44815/)) muscles are made up of repeating units called sarcomeres that allow the tissue to contract. This gives the muscle a striated appearance. The skeletal muscles require stimulation from the nervous system in order for them to contract. However, the cardiac muscle is under involuntary control (myogenic).

Cardiac cells are called cardiomyocytes and form the contractile walls in the heart. Adult cardiomyocytes are large (150 μm). They have a single nucleus, contain many mitochondria and have branched fibres. These branches connect them to neighbouring cardiomyocytes in three-dimensions via gap junctions at intercalated discs. This branched pattern allows the electrical impulses to pass in an efficient way throughout the heart so that all the cells can contract together in a synchronised manner. The single nucleus of cardiomyocytes is regarded to be another important factor in facilitating rapid signal transmission so the cells contract in unison.

Cardiac organoids, generated from human iPS cells are three-dimensional, complex multicellular structures that replicate the whole organ's morphological features. **Video 2** shows some cardiac organoids beating.



Student view

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Video 2. Three-dimensional Cardiac Organoids Generated from Human iPS Cells.

More information for video 2

The interactive consists of a video with accompanying visuals and text. Users can play or pause the video using the playback controls, and the timeline at the bottom allows them to navigate through the video. Additionally, at the bottom right corner, there is an option to expand the video to full-screen mode, enhancing the visual experience and allowing users to view the content in a larger format.
The video begins with an image of a logo for the STEMD (Stem Cells and Diseases Lab) initiative, with the title "Stem cell-derived cardiac organoids" displayed. The logo and title are set against a simple black background with minimal text and design elements. Following this, the video transitions to a close-up view of cells in a microscope, where cardiac organoids, derived from human iPS cells, are shown as three-dimensional, complex structures. The organoids are seen moving and twitching, mimicking the behavior of a beating heart. Finally, the video ends with the KAUST (King Abdullah University of Science and Technology) logo, along with a call to action promoting the website and hashtag #DestinationKAUST. This interactive introduces the concept of stem cell-derived cardiac organoids, providing an overview of their three-dimensional structure and functionality. The video showcases the behavior of these organoids, demonstrating their beating motion, which simulates heart activity.

In contrast, skeletal muscle is attached to bones, and is responsible for moving the skeleton as the muscle contracts and relaxes. Skeletal muscles are arranged in bundles surrounded by connective tissue. As mentioned in section B2.3.5–6 (/study/app/bio/sid-422-cid-755105/book/what-determines-cell-size-id-45384/), these muscle cells can be up to 12 cm in an adult human, and because of their length, they are often known as muscle fibres. Unlike cardiac muscle, these fibres are unbranched. The lack of branching enables very precise control of voluntary muscle contractions in only one direction which is important for controlled movement of the body. The branch points can be areas of structural weakness in skeletal muscle and therefore are often only found in regenerating muscle of this type. Skeletal muscle fibres contain many myofibrils, which in turn are made up of numerous filaments of actin (thin filaments) and myosin (thick filaments). Each muscle fibre (cell) is called a syncytium because they contain many nuclei within the same cytoplasm. This is due to many mononucleated precursor cells having fused together. We generally think of cells having one nucleus and so muscle fibres are an anomaly. Having many nuclei (multinucleated) enables the tissue to conduct more protein synthesis and repair.

Student view

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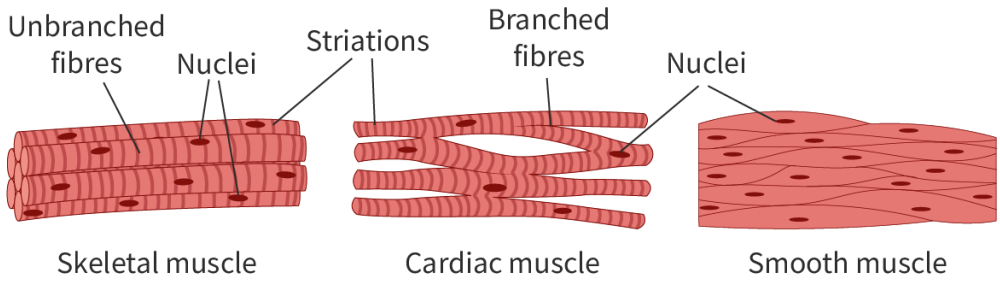

Figure 6. Three main types of muscle cells — cardiac, smooth and skeletal muscle.

More information for figure 6

The image is an illustration showing three types of muscle cells: skeletal muscle, cardiac muscle, and smooth muscle. On the left, the skeletal muscle is depicted with cylindrical unbranched fibers, and labels indicating 'Nuclei' and 'Unbranched fibres.' These fibers resemble long tubes aligned next to each other. In the center, the cardiac muscle is shown with branched fibers and striations, labeled as 'Striations' and 'Branched fibres.' This type has interwoven, branching fibers that are shorter than skeletal muscle fibers. On the right, the smooth muscle is illustrated with spindle-shaped cells and densely packed fibers, labeled 'Nuclei.' These fibers are unstriated, unlike the other two types. Each muscle type's structural characteristics are annotated with lines pointing to relevant parts of the illustration.

[Generated by AI]

Cell adaptations in sperm and egg cells

The reproductive cells are called gametes and contain just half of the genetic material of other body cells. As mentioned in section B2.3.1–4 (/study/app/bio/sid-422-cid-755105/book/stem-cells-id-45383/), the human egg cell is one of the largest of human cells. The cytoplasm of the egg is rich in lipids, proteins and polysaccharides. The egg has several specialised layers of cells covering the outside which assist in preventing more than one sperm fertilising the egg. Section D3.1.5 (/study/app/bio/sid-422-cid-755105/book/menstrual-cycle-and-fertilisation-id-45415/) covers this in more detail.

While very few egg cells are produced, the male produces a vast number of sperm. Production of these is costly in terms of energy, and so, as a compromise, sperm cells are far smaller. Sperm have evolved to be motile (able to move) and so contain many mitochondria in order to provide the energy needed to drive a ‘whip-like’ flagellum to propel the sperm forward. The sperm cannot travel backwards with this mechanism. There is little cytoplasm in the head of the sperm, with the majority of the space being taken up with the haploid nucleus. Covering the entire head of the sperm is an acrosome cap which contains digestive enzymes that will be used to penetrate the egg cells’ zona pellucida (see section D3.1.5 (/study/app/bio/sid-422-cid-755105/book/menstrual-cycle-and-fertilisation-id-

Student view

Overview (/study/ap 422-cid-755105/o

45415/)). There is no storage of nutrients for the supply of energy within the sperm, so this has to be provided by the male in the seminal fluid in which the sperm swims.

Try this activity to help with your understanding of cell adaptations.

Activity

- **IB learner profile attribute:** Communicator
- **Approaches to learning:** Communication skills — Clearly communicating complex ideas in response to open-ended questions
- **Time required to complete activity:** 20—30 minutes
- **Activity type:** Pair and then group activity

Instructions

In pairs, you are going to make a concept diagram for the cell types and adaptations that you have learned about in this section.

Download the scaffold that is provided in the button below.

Cell adaptation diagram (https://d3vrb2m3yrmyfi.cloudfront.net/media/edusys_2/content_uploads/Biolo B2.3.7-10 ACTIVITY.3d509b86d5305e2c5814.pdf)

On the diagram, write out the cell and organelle adaptations that you have learned about which cells employ to reduce the surface area-to-volume ratio problem. For each adaptation, give all the cell types (listed below) that use this form. Try to draw and annotate these diagrams with as much detail as you can.

Cells and organelles to include: enterocytes, pneumocyte type I, microvilli, mitochondria, chloroplasts.

For example: *microvilli → enterocytes in the small intestine → increased surface area to allow for greater absorption of nutrients into the bloodstream.*

See how many other adaptations you can add.

Once you have completed three different cell or organelle examples, switch with another pair. Silently, read what they have added to their diagram, and silently, write additional information on their poster that they may have forgotten.

Student view

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Finally, come back to your own poster and reflect on what you have learned about cellular adaptations.

5 section questions

Summary and key terms

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/summary-and-key-terms-id-44449/print/) Assign

- Unspecialised cells form immediately following fertilisation.
- Gradients of morphogens within the early fertilised cell impact gene expression for further development of the embryo.
- There are several stem cell types that have various capabilities to differentiate into new cells.
- The stem cell niche is the microenvironment in which stem cells live and receive their instructions.
- Humans possess cells with a range of different cell sizes, that carry out a variety of functions.
- The relationship between cell size and its surface area determines the rate of movement of material across a cell membrane.

Higher level (HL)

- There are many different strategies employed by cells to increase surface area-to-volume ratios.
- Specific adaptations of cells in the lung, heart, skeletal muscle and gonads enable them to effectively carry out their function.

Student view

Overview (/study/ap 422-cid-755105/o

Key terms

Review these key terms. Do you know them all? Fill in as many gaps as you can using the terms in this list.

1. All organisms start from a single cell. The cells of the can give rise to the entire organism and so are called . At the the stem cells receive instructions about what they will differentiate into.
2. Cells grow but are limited in their size by the rate at which materials move across their surface. The surface area-to-volume ratio must be to allow materials to be moved across efficiently. Some cells have different adaptations to increase .
3. Some cells, like , have become flattened to increase surface area-to-volume ratio.
4. [HL] Cells of the proximal convoluted tubule have to increase absorption of substances back into the bloodstream.
5. [HL] Some cells that need to perform a high level of protein synthesis and degradation are and are formed by fusion of many cells.
6. [HL] Some cells have specialised features to aid in . The sperm has a whip-like .

surface area | erythrocytes | stem cell niche | totipotent | microvilli | large | morula | motility | flagellum | multinucleate

Check

Interactive 1. Cell Specialisation

B2. Form and function: Cells / B2.3 Cell specialisation

Checklist

Student view

Section | Student... (0/0) | Feedback | Print (/study/app/bio/sid-422-cid-755105/book/checklist-id-44811/print/) | Assign

Overview (/study/ap 422- cid- 755105/o

What you should know

After studying this subtopic you should be able to:

- Explain how unspecialised cells form following fertilisation and how gradients impact gene expression for further development of the embryo.
- Outline the properties of stem cells and their different capabilities to become different cell types.
- Explain the function of stem cell niches and be able to describe bone marrow and hair follicles as examples of these.
- Describe the size differences in various human cells.
- Discuss the relationship between cell size and surface area in terms of the movement of material across a cell.

Higher level (HL)

- Identify and describe cell types that increase surface area-to-volume ratios
- Describe specific adaptations that cells in the lung, heart, muscle and gonads have undergone to perform their functions.

Investigation

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/investigation-id-45386/print/) Assign

- **IB learner profile attribute:** Risk-taker
- **Approaches to learning:** Communication skills – Using digital media for communicating information
- **Time required to complete activity:** 30–45 mins
- **Activity type:** Whole-class activity

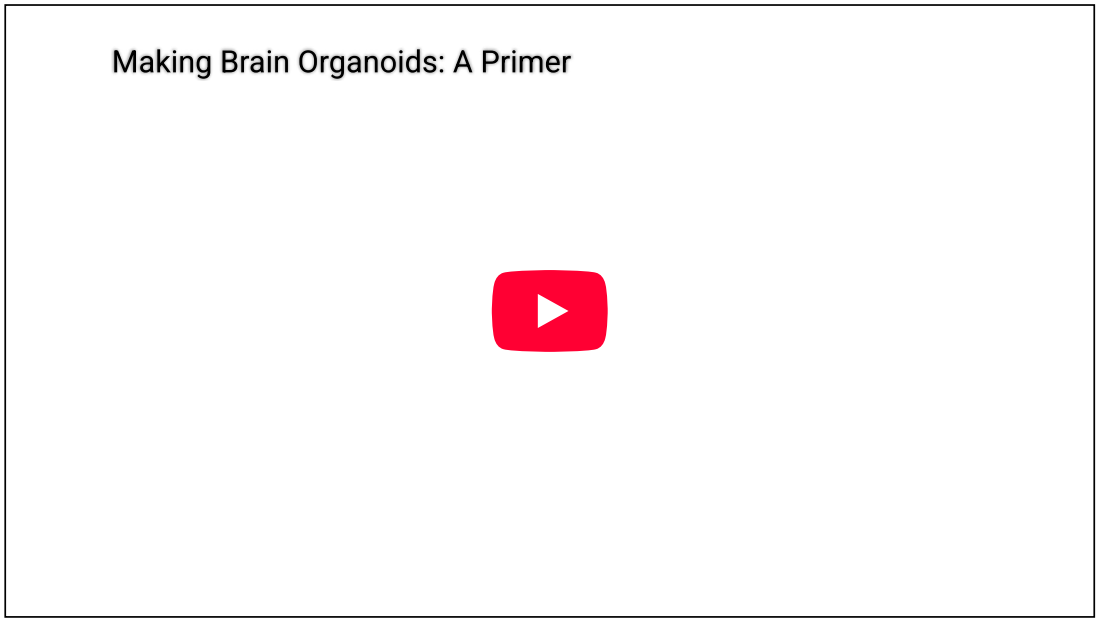
Student view

Overview (/study/ap 422-cid-755105/o

Your task

When testing human medicines, drug companies wish to test on systems as close to the human model as possible. Thanks to the ability to produce iPS cells, there is less need to use controversial embryonic stem cells for research which is fraught with ethical issues. More recently, it has been possible to coax iPS cells to generate three-dimensional self-structures called organoids. These have been shown to be powerful tools that mimic animal models. They can be infected with diseases and observed for the progression of the disease to be able to compare normal and abnormal development in a way that has not been possible before.

Using this (https://hsci.harvard.edu/organoids) article and information from **Video 1**, generate a class Padlet presentation to share this information. Your teacher will set-up Padlet to present your findings in this investigation.



Video 1. Making brain organoids.

In groups of two or three, select two questions from below to answer on the Padlet. Ensure that each group focuses on different questions. Spend 10–20 minutes formulating your answers for these questions and summarising them on the Padlet. Spend the remainder of the lesson sharing your answers with the class until you all have a thorough understanding of how these structures, which are differentiated from stem cells into specialised cells, are a pioneering area of research.

1. How are organoids generated?
2. What diseases can be studied with organoids?
3. What is the advantage of studying disease using organoids as opposed to single cells?

Student view

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4. How do organoids compare to animal models in terms of their ability to recapitulate human disease?
5. Why is it important to model drugs on human tissue and not rodents (for example)?
6. What are the advantages and disadvantages of using organoids in research?
7. How can organoids be used to develop new therapies for human diseases?
8. What are the ethical considerations of using organoids in research?
9. How can the use of organoids encourage personalised medicine?

Reflection

Section Student... (0/0) Feedback Print (/study/app/bio/sid-422-cid-755105/book/reflection-id-46875/print/) Assign

Teacher instructions

The goal of this section is to encourage students to reflect on their learning and conceptual understanding of the subject at the end of this subtopic. It asks them to go back to the guiding questions posed at the start of the subtopic and assess how confident they now are in answering them. What have they learned, and what outstanding questions do they have? Are they able to see the bigger picture and the connections between the different topics?

Students can submit their reflections to you by clicking on 'Submit'. You will then see their answers in the 'Insights' part of the Kognity platform.

Reflection

Now that you've completed this subtopic, let's come back to the guiding question introduced in The big picture (/study/app/bio/sid-422-cid-755105/book/big-picture-id-43533/).

- What are the roles of stem cells in multicellular organisms?
- How are differentiated cells adapted to their specialised functions?

With these questions in mind, take a moment to reflect on your learning so far and type your reflections into the space provided.

You can use the following questions to guide you:

Student view

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- What main points have you learned from this subtopic?
- Is anything unclear? What questions do you still have?
- How confident do you feel in answering the guiding questions?
- What connections do you see between this subtopic and other parts of the course?

⚠ Once you submit your response, you won't be able to edit it.

0/2000

Submit

Rate subtopic B2.3 Cell specialisation

Help us improve the content and user experience.

☆ ☆ ☆ ☆ ☆

Student view