Glycolysis

This lecture will cover glycolysis, the backbone of carbohydrate metabolism. This pathway is especially important because it is the intersection of several pathways of carbohydrate metabolism (gluconeogenesis, glycogenesis, glycogenolysis and the TCA cycle) as well as both the source and result of amino acid synthesis and degradation. An understanding of how glucose flows through glycolysis is also important for understanding how other monosaccharides such as fructose and galactose are metabolized. We will focus on the regulation of glycolysis by energy status, metabolites and hormonal factors. While most of the reactions are listed here, it is important that you focus on the key steps of control and how they are regulated.

Contents

Learning Objectives

- Define the role relative locations of of glycolysis, gluconeogenesis, the TCA cycle as nodes of carbohydrate metabolism metabolism.
- Assess the enzymatic differences and tissue distributions of glucokinase vs hexokinase and explain why this is important.
- Determine how much ATP is produced from glycolysis, and the efficiency of aerobic vs non-aerobic glycolysis
- Summarize the key points of regulation of glycolysis and what metabolites and hormones regulate these enzymes
- Evaluate the differences between how muscle and liver glycolysis are regulated. Assess why this is relevant for the functions of these tissues
- Define the potential fates of pyruvate, and what enzyme activities dictate the next steps in its metabolism
- Discriminate how non-glucose carbohydrates such as galactose and fructose enter glycolysis, and how their point of entry affects how they are regulated.
- Predict the effects of specific inborn errors in glucose, galactose and fructose metabolism based on the location of the affected mutated enzyme in the relevant pathways

Glycolysis converts glucose to pyruvate

Glycolysis is the process by which glucose is catabolized to pyruvate. It is the first step to full oxidation of glucose to carbon dioxide, or can end with pyruvate being released as lactate. This is the backbone of metabolism, and as most carboydrate, amino acid and lipid metabolic pathways involve glycolysis in one way or another. For a refresher on glycolysis, I recommend the textbooks on reserve at the Shapiro library [Berg et al., 2013, Ferrier, 2017][1].

[1] The relevant chapter of Berg is also available free here: `https://www.ncbi.nlm.nih.gov/books/NBK22395/`.

How does glucose enter cells?

Glucose, much like amino acids, lactate and glycerol is normally impermeable to the plasma membrane of cells. Therefore, in order to enter the cell, specific transporters are required. In the case of glucose, two transporters are the most relevant; GLUT2 and GLUT4. These are passive transporters that only allow glucose to follow its concentration gradient. In the liver, GLUT2 is typically expressed and present at the membrane of the hepatocyte. This allows glucose to enter the hepatocyte (for example after a meal) or to exit the cell (for example during glycogenolysis or gluconeogenesis[2]).

[2] The production of glucose from precursors such as alanine, lactate or glutamate

GLUT4 on the other hand is the main transporter in muscle and adipocyte cells. GLUT4 is normally present on intracellular vesicles within the cell and is therefore unable to conduct glucose into the cell. When insulin is present, these vesicles fuse with the plasma membrane of these cells, placing GLUT4 transporters on the plasma membrane, and allowing for glucose to enter down its concentration gradient. GLUT4 trafficking is the first regulated step for glucose oxidation and storage in muscle and fat cells. For more details on how GLUT4 trafficking is regulated see Leto et al. [2013].

GLYCOLYSIS OCCURS IN THE CYTOPLASM OF CELLS. All of glycolysis occurs in the cytoplasm of cells, unlike the TCA cycle or the electron transport chain, which require mitochondria. As we will discuss later in the semester, mitochondria are also required for the oxidation of fatty acids and some amino acids. This means that cells with little or few mitochondria (fast-twitch muscle fibers, or red blood cells for example) are highly dependent on glycolysis to generate ATP.

The conversion of glucose to glucose-6-phosphate

THERE ARE TWO ENZYMES THAT CATALYSE THE FIRST STEP AFTER GLUCOSE ENTERS THE CELL. This step phosphorylates glucose at the

6 position, generating glucose-6-phosphate (G6P):

$$Glucose + ATP \rightarrow Glucose - 6 - Phosphate \quad (1)$$

In liver cells[3] and pancreas cells, this is done by an enzyme called *glucokinase*. This is a co-operative enzyme[4] that has a very high maximal catalytic rate (V_{max}). This means that at low levels of glucose, very little glucose is phosphorylated but at high levels of glucose, G6P can be produced at high rates. Furthermore, glucokinase is negatively allosterically regulated by G6P.

[3] also known as hepatocytes.

[4] If you forget what this means, review the metabolic control systems handout.

HEXOKINASE IS A HIGH AFFINITY ENZYME that catalyzes the same reaction in most other cells, for example muscle and liver cells. This means that it is very efficient at low glucose concentrations, but does not have as high of a maximum rate[5]. In contrast to glucokinase, there is no allosteric regulation of hexokinase. Think about the differences in how glucose enters these cells, in contrast to liver cells and how the kinetics relate to the regulation of glucose uptake. The differences between glucokinase and hexokinase are summarized in Table 1.

[5] It is important that you understand the differences in glucose affinity and V_{max} between glucokinase and hexokinase and what this means.

Enzyme	Kinetics	Regulation	Tissues
Hexokinase	High Affinity		Muscle/Adipose
Glucokinase	Co-operative	G6P (-)	Pancreas/Liver

Table 1: Differences between glucokinase and hexokinase.

CONVERSION OF G6P TO GLUCOSE PRIMARILY OCCURS IN THE LIVER. This is because most cells do not express Glucose-6-phosphatase, the enzyme that converts G6P back to glucose. In the liver, this allows for dephosphorylated glucose to be released back into the blood, the last step in gluconeogenesis.[6] This is relevant because in non-hepatic cells, the phosphorylation of glucose is *irreversible* and traps glucose within the cell[7].

[6] Which will be discussed three lectures from now.

[7] Think about why the co-operative properties of hexokinase works in tandem with the ability to dephosphorylate glucose in liver cells.

What are the fates of glucose-6-phosphate?

Once phosphorylated, G6P can enter four separate pathways (3 in non-hepatic tissues), depending on the relative activities of the rate limiting steps in these pathways. If glycogen synthase activity is elevated glucose can become stored as glycogen. If G6P Dehydrogenase (G6PDH) activity is elevated, glucose will flow through the pentose phosphate shunt. Glycolysis will proceed if phosphofructokinase-1 (PFK1) is active. These routes are summarized in Figure 1.

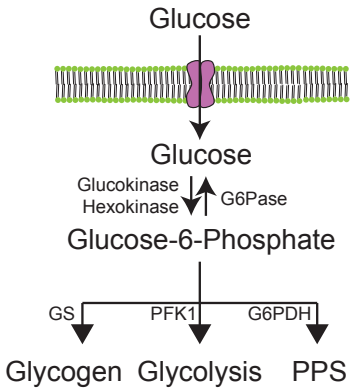

Figure 1: Fates of phosphorylated glucose.

The first committed step of glycolysis is catalysed by PFK1

The most important regulatory step that controls flow through glycolysis is catalyzed by PFK1[8]. This is the first committed step of glycolysis and catalyzes the third step in glycolysis[9]:

$$G6P \leftrightarrow F6P \tag{2}$$

$$F6P + ATP \rightarrow F16bP \tag{3}$$

Because this is such an important regulatory node, there are several facets to the reguation of PFK1. This is accomplished via four allosteric regulators, listed in Table 2. Citrate is a part of the TCA cycle which we will discuss next lecture. Elevations in citrate indicate that there are sufficient molecules in the TCA cycle, a condition known as *anaplerosis*[10]. Functionally, this means that when there are sufficient metabolites downstream of glycolysis, glycolysis is impaired at this step. This is known as negative feedback and is common in many of the pathways we will discuss this semester.

[8] For all these reactions G indicates Glucose, F indicates Fructose, GA indicates Glyceraldehyde and PG indicates Phosphoglycerate.

[9] Reaction 2, catalyzed by Phosphoglucose isomerase is a reversible, equillibrium reaction

Table 2: Regulators of PFK1 activity

Molecule	Direction
F2,6bP	Positive
AMP	Positive
ATP	Negative
Citrate	Negative

[10] As we will learn later in the semester, Citrate is a substrate for *de novo* lipogenesis as a substrate for the enzyme ATP-Citrate Lyase. Furthermore Citrate is an activator of another key lipogenic enzyme, named Acetyl Co-A Carboxylase. Therefore citrate plays a key role in controlling both glucose breakdown and lipid synthesis.

ATP and AMP levels indivate the cellular energy status. In terms of PFK1 regulation, this means that when energy is low (low ATP/high AMP), PFK1 is activated and glycolysis (which is energy generating) proceeds. This is one way in which energy can control glycolytic flux.

Fructose-2,6-bisphosphate is the most potent regulator of PFK1 activity. This molecule is generated from the same Fructose-6-phosphate (F6P) precursor that PFK1 acts on, but instead phosphorylates fructose on the 2-position by an enzyme known as PFK2. This is known as feed-forward regulation, and means that when F6P builds up, it can be converted to F26bP to relieve the buildup of F6P in the cytoplasm[11].

[11] An analogy for this might be if you are stuck in traffic and honk (to signal the traffic ahead to move faster).

PFK2 is regulated by reversible phosphorylation in the liver. In addition to the above allosteric regulators, PFK2 activity is also *blocked* by PKA-dependent phosphorylation. PKA in the liver is activated by hormones such as glucagon and epinephrine. One biological goal of these hormones in the liver is to *promote gluconeogensis*, and therefore it would be counterproductive to have glycolysis occuring at the same time. As such, by reducing PFK2 activity (and reducing F26bP levels), PFK1 activity and glycolytic flux is all reduced.[12]

[12] I appreciate that this is a lot of regulation, so I recommend sketching out PFK1/PFK2 and the various positive and negative regulators. Take a step back and think about what would cause these regulators to change, and how this would affect glycolytic flux. Think about whether this would make "sense" based on what glycolysis is doing.

The next several steps of glycolysis are neither regulated

OR RATE LIMITING. In general, the F16bP molecule is broken in two by aldolase, then each part rapidly is converted into phosphoenolpyruvate via the following reactions:

$$F16bP \leftrightarrow DHAP + GA3P \tag{4}$$

$$GA3P + NAD+ \leftrightarrow 1,3bPG + NADH \tag{5}$$

$$1,3bPG + ADP \leftrightarrow 3PG + ATP \tag{6}$$

$$3PG \leftrightarrow 2PG \tag{7}$$

$$2PG \leftrightarrow Phosphoenolpyruvate \tag{8}$$

While these steps are not regulated, or associated with known nutrient deficiencies or inborn errors of metabolism, there are two key points about steps 5 and 6, the generation of NADH and ATP respectively[13]. ATP is the primary fuel source in cells, and one molecule NADH is converted into 2.5 molecules of ATP in the electron transport chain[14]. The second point, which we will come back to near the end of the semester, is that the glycerol backbone, needed to generate triglycerides is derived from DHAP, and when glycerol is broken down, it becomes DHAP and enters the glycolytic pathway.

Pyruvate kinase regulates conversion to pyruvate

$$Phosphoenolpyruvate + ADP \rightarrow Pyruvate + ATP \tag{9}$$

The last step catalyzes the irreversible reaction of phosphoenolpyruvate (PEP) to pyruvate is catalysed by Pyruvate Kinase. This is the last point of regulation in glycolysis. Fructose-1,6-bisphosphate (F1,6bP) is the product of PFK1, and functions as a *feed-forward* regulator of pyruvate kinase activity (see Figure 2). ATP, similar to its inhibitory role on PFK1, reduces glycolytic flux when energy is not needed. Alanine on the other hand is an amino acid that is easily interconverted with Pyruvate by the enzyme Alanine Aminotransferase (ALT)[15]. As a surrogate for both protein breakdown (and amino acid availability), Alanine reduces liver Pyruvate Kinase activity when amino acids are high, and there is less of a need to use glucose as fuel[16]. This is because the cell can use Alanine, rather than Phosphoenolpyruvate to generate Pyruvate.

SIMILAR TO PFK2, PYRUVATE KINASE IS INHIBITED BY PKA-DEPENDENT PROTEIN PHOSPHORYLATION. In the liver, glucagon

[13] Remember, since glucose was broken in two pieces at step 4, one glucose generates two ATP at this step.

[14] Discussed next lecture.

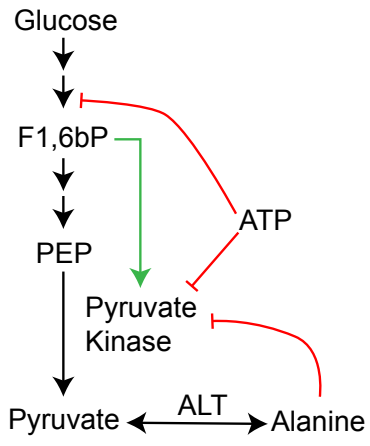

Figure 2: Regulation of pyruvate kinase in the liver. In the muscle, neither ATP nor Alanine play important roles. PKA indicates inhibitory phosphorylation of Pyruvate Kinase in response to glucagon or adrenaline.

[15] This will be discussed in the amino acid catabolism lecture in the middle of the semester.

[16] The muscle isoforms of Pyruvate Kinase is *not* inhibited by ATP or Alanine, but is still subject to feed-forward regulation by F1,6bP. The adipocyte isoform (PKM2) is also activated by Serine [Christofk et al., 2008] and is expressed in a variety of tumors.

or epinephrine can inhibit glycolysis at two steps, PFK2 (described above) and also at the Pyruvate kinase step. In both cases, this is important to prevent glycolysis and gluconeogenesis from occurring simultanously.

The fate of pyruvate

Pyruvate can go in one of four directions in the cell, depending on the activity of Pyruvate Dehydrogenase (PDH) and the relative levels of Alanine in the cell. The regulation of PDH is very important for aerobic respiration, and will be discussed next lecture. These fates are described in Table 3. In general, if Alanine is in sufficient and PDH activity is low or absent, then pyruvate is converted to lactate via Lactate Dehydrogenase and released from the cell. This is known as anaerobic respiration and is important for fast-twitch muscle fibers and in conditions where oxygen levels are low. Pyruvate can also be easily converted to and from Alanine, via ALT[17]. Finally, as we will cover in the lectures on the TCA cycle, when acetyl-CoA levels are high[18], Pyruvate can be converted to Oxaloacetate, a process known as anaplerosis.

[17] We will cover how amino acids are synthesized in the second unit of this course.

[18] Indicating reduced TCA/ETC flux, but sufficient acetyl-CoA production. Think about under which conditions this might occur.

Pyruvate Fate	Conditions	Key Enzyme
TCA cycle	High PDH Activity	Pyruvate Dehydrogenase
Lactate	Low PDH Activity	Pyruvate Dehydrogenase
Alanine	Low Ala, High Glu	Alanine Aminotransferase
Oxaloacetate	High Acetyl-CoA	Pyruvate Carboxylase

Table 3: Potential fates of pyruvate. While several of these enzymes and processes have not been covered yet, we will discuss all of these later in the semester.

Energy production by glycolysis

Glycolysis occurs in three phases:

1. An investment phase, which uses two molecules of ATP (see steps 1 and 3) are consumed. This "charges" the glucose molecule, providing it with enough energy to be split into two-3 carbon molecules. **At this stage there is a net usage of two ATP molecules per molecule of glucose.**

2. The cleavage step, performed by aldolase A, immediately after the highly regulated PFK1 step (see step 4). This is a very energetically costly step, as breaking a carbon-carbon bond is quite difficult[19]. This cleavage means that one glucose molecule will eventually generate **two** Pyruvate molecules.

3. The catabolism of each molecule of glyceraldehyde-3-phosphate (GA3P) to pyruvate generates two molecules of ATP via substrate-level phosphorylation[20] (see steps 6 and 9). There is also the re-

[19] The standard free energy of this step is +28 kcal/mol, making it highly endothermic. For more details on how Fructose-1,6-bisphosphate buildup allows this difficult reaction to occur, see `http://sandwalk.blogspot.com/2007/10/aldolase-reaction-and-steady-state.html`

[20] Substrate level phosphorylation is the production of ATP by direct transfer from another phosphorylated compound.

duction of one NAD+ molecule into NADH (see step 5). NADH, as we will discuss in the unit on the electron transport chain is equivalent to 2.5 ATP molecules. Therefore this phase produces a total of 4.5 ATP molecules per GA3P, or **9 molecules per glucose molecule**.

Glycolysis down to the level of pyruvate therefore uses up two ATP molecules, and generates the equivalent of 9 ATP molecules for a **net gain of 7 molecules of ATP per molecule of glucose.** Full oxidation of glucose to CO_2 will eventually produce 36 molecules of ATP/glucose so at this stage there is quite a lot of energy remaining in pyruvate.

Hormonal regulation of glycolysis

INSULIN PROMOTES GLYCOLYSIS BY SEVERAL MECHANISMS. First, in muscle and adipose tissue, insulin promotes the translocation of GLUT4 to the plasma membrane, allowing for glucose entry into the cell. This increases the levels of glucose, and glucose-6-phosphate in the cell. Insulin also promotes the dephosphoryation of both PFK2 and Pyruvate Kinase [Probst and Unthan-Fechner, 1985]. Recall that in both cases, the dephosphorylated forms are *more active*, so this increases the flux by which glucose gets converted to pyruvate or lactate. The mechanisms by which insulin promotes these dephosphorylation events are still murky.

GLYCOLYSIS IS REGULATED DIFFERENTLY IN MUSCLE THAN IN LIVER TISSUES. There are splice variants[21] of PFK2 that are expressed in a tissue specific manner. In liver tissue the L-PFK2 isoform can be phosphorylated on Serine 32 resulting in its inhibition. This residue is *absent* in the muscle, brain and adipocyte isoforms. Therefore, adrenaline/glucagon-mediated inhibition[22] and insulin-mediated activation (via dephosphorylation) is *only* relevant for the liver isoform of PFK2. The muscle and adipocyte PFK2 isoforms are not regulated by these hormones. This means that glucagon or adrenaline will prevent glycolysis in liver cells but that adrenaline will not prevent glycolysis in muscle cells[23]. Similarly, Pyruvate Kinase is inhibited by ATP and Alanine, but only in the liver but all Pyruvate Kinase isoforms are regulated positively by F1,6bP. This means that the downstream negative feedback by Alanine and ATP is not a factor in the regulation of adipocyte or muscle glycolysis.

[21] Splice variants are different mRNA's which lead to different proteins, transcribed from the same gene.

[22] Via PKA-dependent phosphorylation

[23] There is a physiological advantage to this, think about what the consequence would be if adrenaline *prevented* glycolysis in muscle cells, and why it would be advantageous to do this in liver cells

ANOTHER LEVEL OF CONTROL OF GLYCOLYSIS IS TRANSCRIPTIONAL. There are certain conditions where it is helpful to increase

glycolysis in a chronic and less rapidly reversible manner. This occurs by transcription factors which can synthesize new glycolytic proteins, increasing the capacity by which glycolysis can occur. There are several examples of this such as:

- Hypoxia, or reduced oxygen, via the transcription factor HIF[24].
- Chronically elevated glucose levels (via the transcription factor ChREBP).
- Chronic glucagon stimulation (via the transcription factor CREB).

[24] Think about why glycolysis may be advantageous during oxygen deprivation.

These transcriptional changes often affect the expression of the enzymes Pyruvate Kinase, Glucokinase and PFK2 [Semenza et al., 1994, Kawaguchi et al., 2001]. These changes are slower and more energetically costly than allosteric or post-translational changes. As such, they are both longer lasting and harder to undo.

Fructose metabolism

Fructose, the other component of sucrose is largely metabolized within the liver, compared to glucose which is metabolized in multiple tissues. Within the liver, fructose enters the hepatocyte via facilitative GLUT5 channels, which are constitutively present on the plasma membrane. In terms of metabolism, fructose undergoes the folowing steps, catalyzed by fructokinase, aldolase B then triose kinase[25,26].

$$Fructose + ATP \rightarrow Fructose - 1 - phosphate \tag{10}$$

$$Fructose - 1 - phosphate \leftrightarrow Glyceraldehyde + DHAP \tag{11}$$

$$Glyceraldehyde + ATP \rightarrow GA3P \tag{12}$$

[25] Be careful here, fructose becomes F16bP then DHAP/G3P wheras glucose becomes F6P then F16bP then DHAP/GA3P. These routes can be easily confused.

[26] As an exercise, consider the pathways by which glucose and fructose become lactate, calculate whether the ATP production is similar for these two monosaccharides.

Fructose catabolism is independent of PFK1

The products (DHAP and Glyceraldehyde-3-phosphate) are the same that occur for the glycolytic step in reaction 4. Importantly this step occurs *after* the two key glycolytic regulatory steps at PFK1 and Glucokinase. This has very important ramifications for how fructolysis[27] is regulated relative to glycolysis. Since the regulatory steps that can control the flow of glucose are uncontrolled for fructose, fructose is converted rapidly to its end-products, whether there is demand or not. This is biochemical basis by which fructose is thought to be more prone to become acetyl-CoA then fatty acids[28]. Similarly, as we will discuss for unit on gluconeogenesis, fructose can very easily become glucose with little metabolic control [Kim et al., 2016].

[27] The breakdown of fructose into pyruvate/lactate.

[28] Think about how citrate can control glucose but not fructose breakdown.

Fructose consumption has been linked to both obesity and liver disease

Fructose is normally present at high levels in fruit, or as the disaccharide sucrose, which has a 1:1 ratio of glucose:fructose. For ease of handling and production, high fructose corn syrup (HFCS) has been in widespread use since the 1970s, particularly in sugar-sweetened beverages. HFCS generally contains 45-60% fructose with the remaining as glucose. While as recently as 2014, the Food and Drug Administration has declared HFCS safe as a food ingredient, epidemiological studies suggested HFCS may be associated with both obesity, and non-alcoholic fatty liver disease[29]. A recent meta-analysis in this area was inconclusive, as it was difficult to separate the effects of added calories due to HFCS from direct metabolic effects of this sweetener [Chung et al., 2014].

[29] A liver disease that starts with lipid accumulation and inflammation of the liver, which can result in impaired liver function or eventually cirrhosis or some liver cancers.

Disorders of fructose metabolism

There are two inborn errors of fructose metabolism, defects in either Fructokinase or Aldolase B. In the case of Fructokinase deficiency, this is generally not pathological, since Fructose is not phosphorylated, and therefore is not trapped in cells. Patients with Fructokinase deficiency have very high circulating levels of Fructose in their blood, but are otherwise normal. On the other hand, Aldolase B deficiency means that Fructose becomes trapped at the Fructose-1-phosphate step [Cross et al., 1988][30]. This occurs in approximately 1 in 20,000 to 30,000 individuals. This intermediary metabolite builds up, wasting ATP and resulting in liver cirrhosis, hypoglycemia and kidney damage[31].

[30] If you want to explore mutations in any of the enzymes we discuss in more detail, I suggest going to the website `http://exac.broadinstitute.org`, enter the gene name, scroll down, click on LOF (loss of function) then click on any of the variants to see their incidence in various populations. The gene name for Aldolase B for example is *ALDOB*.

[31] Think about, from a dietary perspective how this disease could be managed.

Galactose metabolism

Galactose, the other monosaccharide in lactose is taken up in the liver via GLUT2. In contrast to Fructose, Galactose enters glycolysis near the early steps of glycolysis and is subject to similar regulatory steps. The initial steps of galactolysis are catalyzed by the enzymes galactokinase, GALT or phosphoglucomutase and result in the production of Glucose-6-phosphate:

$$Galactose + ATP \rightarrow Galactose - 1 - phosphate \tag{13}$$

$$Galactose - 1 - phosphate + UDP - Glucose \leftrightarrow Glucose - 1 - phosphate + UDP - Galactose \tag{14}$$

$$Glucose - 1 - phosphate \leftrightarrow Glucose - 6 - phosphate \tag{15}$$

Glucose-6-phosphate then proceeds as normal, becoming dephosphorylated to glucose, or processed through glycolysis, glycogenesis or the pentose phosphate pathway. Inborn errors of GALT lead to galactose intolerane and a buildup of Galactose-1-phosphate in tissues and the blood.

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