Lactic Acid Fermentation, Muscle Contractions, and Other Processes:

Jump To:

The Chemical Energy and Process of Muscle Contraction

Chemical Energy for Humans

Our bodies, and more specifically the cells inside of our bodies, all require a continuous amount of energy to maintain our bodily functions. This energy can also be applied to other activities such as exercise. How do we go about getting this energy? And how does this work on a biological and chemical level?

As humans, we derive our chemical energy from complicated molecules, known as macromolecules. Macromolecules (Figure 1) are found in the food we eat and can be classified as proteins, carbohydrates (sugars), and lipids (fats) based on different structures. Proteins are typically found in eggs, meats, nuts, and various dairy products[1]. Carbohydrates can be found in fruits, starchy vegetables, and pasta/other grains[1]. Lipids are located in fats and oils and can come in both the healthy/ unsaturated form and unhealthy/saturated form[1].

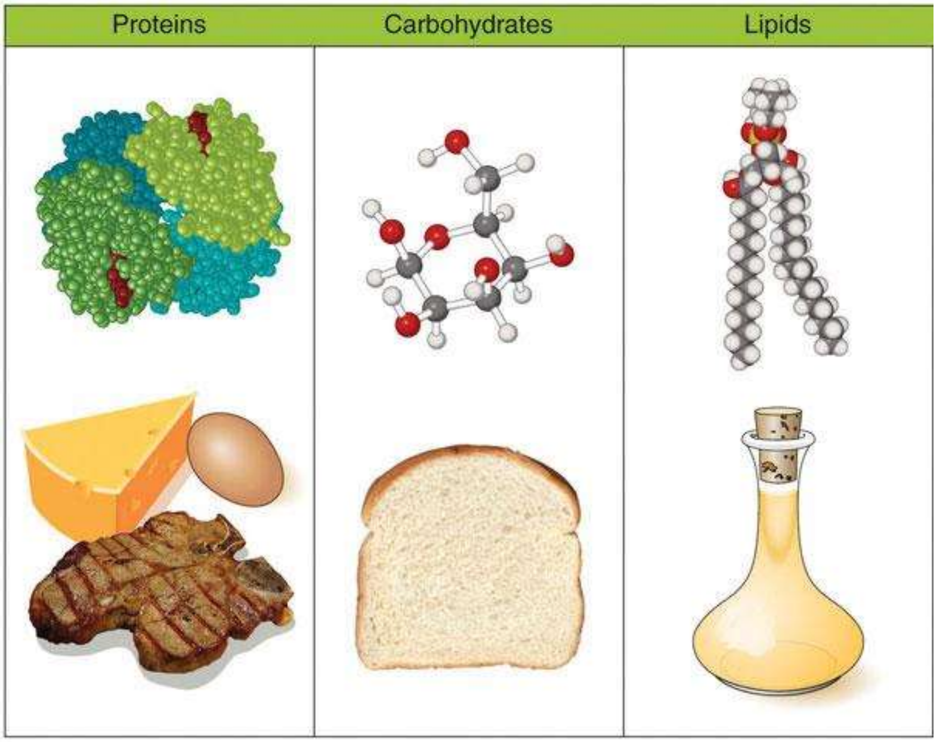


Figure 1: Different Macromolecule Structures and Examples [6]

To convert food into energy, these macromolecules must undergo a three-step process. In the first step, digestion, food consumed is broken down in the stomach and intestine by specialized enzymes. These enzymes convert the complex macromolecules into simpler substances (monomers) that the body can use and transport easily[2]. After digestion, these monomers are transported to the cells to be converted into energy[2]. The second and third steps, glycolysis and oxidation, are found later in this article and can be jumped to HERE. After oxidation, the cell is left with adenosine triphosphate as a product.

Adenosine triphosphate, better known as ATP, is the body's way of easily storing and transporting energy to various cells and reactions. ATP is made of an adenine base, a sugar (ribose), and three phosphate groups (Figure 2)[3].

There is a lot of energy found in the bond between the second and third phosphate groups of ATP. When energy is needed the bond between these phosphates are broken, forming adenosine diphosphate and inorganic phosphate[3]. The energy from this broken bond is then released for use by the cell or for a reaction. These reactions are shown by Figure 3 below.

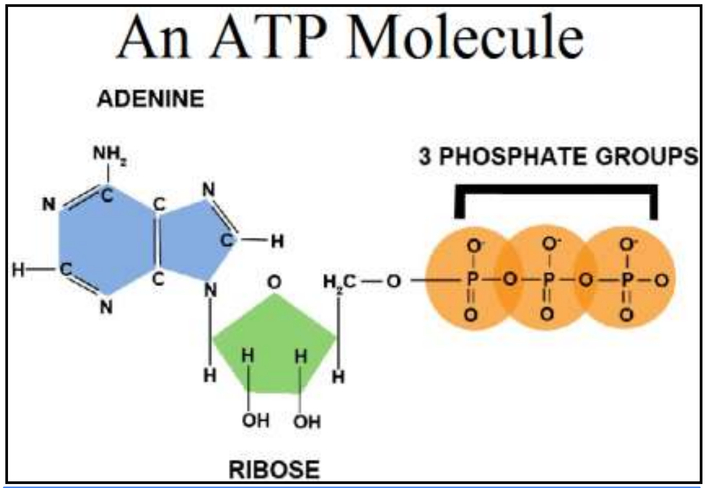


Figure 2: ATP Molecule and its Components [7]

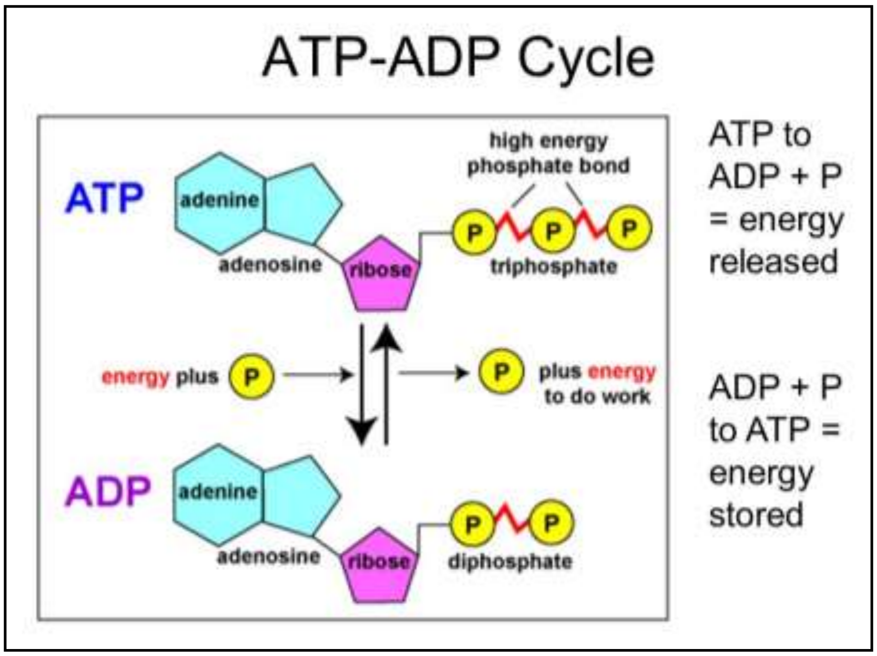


Figure 3: ATP Reactions [8]

In periods of rest, or when the body has excess energy, the energy is stored as ATP. ATP has many different functions as a source of energy, from copying DNA to cellular waste removal, so it is used up quickly and must be replenished frequently. This is why us humans are constantly eating food as a means to maintain the fuel necessary to complete our bodily functions even in times of relaxation. Knowing that ATP is the form of energy our body uses, one may wonder, “how is ATP used in exercise?”.

Muscle Contraction on a Microscopic Level

In our bodies there are three types of muscle, but skeletal muscle is the only type muscle we can voluntarily control. To exercise, we rely on the contraction and extension of these skeletal muscles to move our body parts and/or weights. Muscle contraction (Figure 6) is a very complicated process involving many different areas of the body, specifically muscle fiber (Figure 4). Muscle fiber is made of myofibril threads. These myofibrils are composed of the proteins actin and myosin. Actin protein forms thin filaments while myosin protein forms thick filaments. The layering of these two filaments results in a simple unit of a myofibril known as a sarcomere.

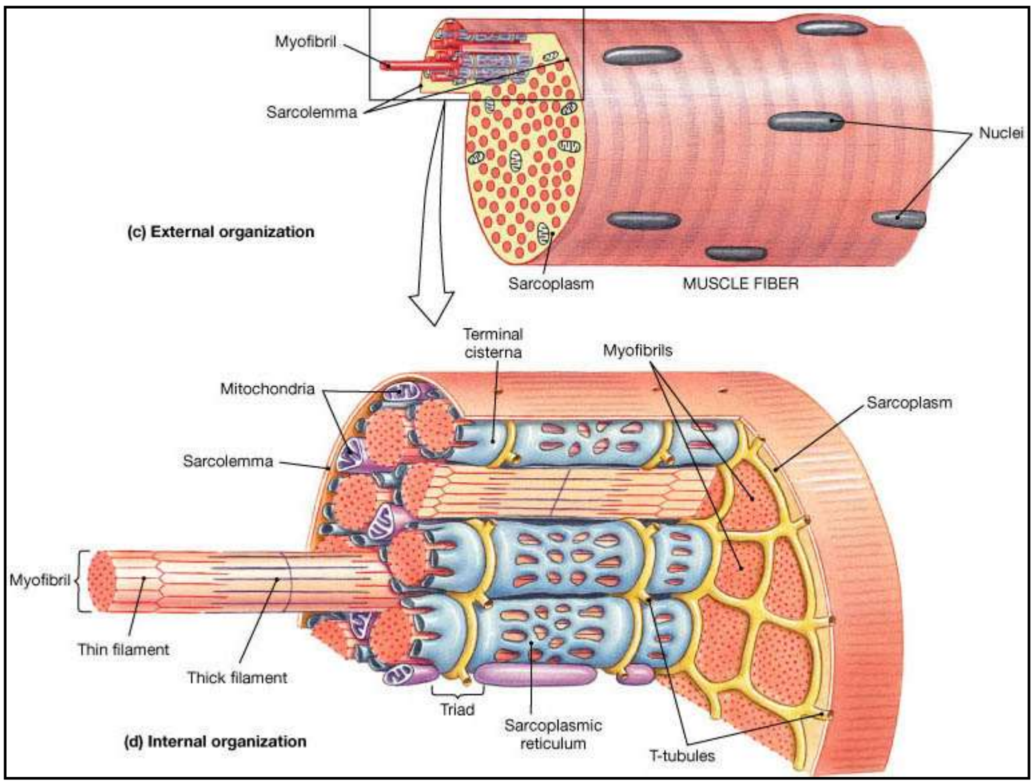


Figure 4: Labeled Muscle Fiber [9]

Since skeletal muscles are voluntary, a signal must be sent from the brain, along the spinal cord, and to the muscle in order for it to be put into action. This neural signal must then be passed through a gap called the neuromuscular junction. This is the gap formed by motor neurons of the spinal cord and the muscle. An electric signal from the brain triggers the release of Acetylcholine (ACh) in the neuron.[5] ACh functions as a neurotransmitter to send an activation signal across the neuromuscular junction.

ACh binds to receptors in the sarcolemma, or the muscle cell membrane[5]. This signals to open or “activate” different channels of sodium and potassium ions that generate an action potential. In simpler terms, this continues the electrical signal from before into the T-tubule (or passageway) in the muscle cell to unlock storage of calcium ions inside of the muscle fiber[4].

Calcium ions are then let out of the sarcoplasmic reticulum[4]. The sarcoplasmic reticulum is a specialized part of muscle cells, and its main purpose is to regulate these calcium ions. The ions then bind to a protein complex, named troponin, on the actin filament. This binding exposes part of the actin filament under another complex called tropomyosin[4]. This bonding allows for the myosin filaments to attach at these sites.

The myosin head of the thick filament attaches to the thin filament through the formation of chemical bonds known as cross-bridges. The cross-bridge starts with inorganic phosphate (P_i) and adenosine diphosphate (ADP) connected to the myosin head. The thick filaments then pull the actin strands past itself producing force, which is where your muscles contract. During this, the ADP and P_i detach from the myosin head. Meanwhile, one ATP connects to the myosin head[4]. This causes the the myosin head to then release actin filament. The ATP is then broken back down into ADP and P_i, releasing energy. The energy from this reaction is used to reset the myosin head to its original “cocked” position. In this position, a new cross-bridge is formed. The final result is the shortening of the sarcomere, and thus the contraction of the muscle fiber as a whole. This shortening causes tension in the muscle fiber which we recognize as contraction of the targeted muscle. The myosin keeps attaching, detaching, and reattaching to the actin until the sarcomere reaches its limit or the muscle is fully flexed. The actin-myosin interaction can be seen below in Figure 5.

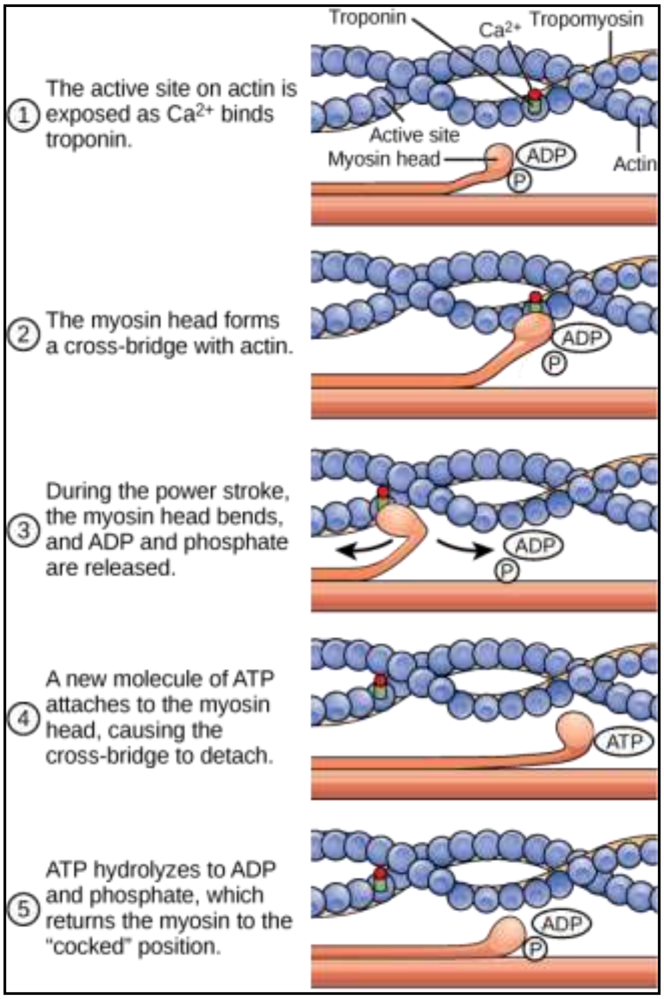


Figure 5: Actin and Myosin Filaments Interacting [10]

When the electrical signal from the brain stops, ACh is then broken down by an enzyme called Acetylcholinesterase (AChE)[4]. This means the muscle is not receiving a signal to release calcium ions or contract anymore. After this occurs, the calcium ions on actin are removed and leave through the sarcoplasmic reticulum[4]. With the exiting of the calcium ions, the actin filaments become covered up by tropomyosin and block the formation of cross-bridges. This is when the contraction of the muscle ends and the muscles return to the relaxed state.

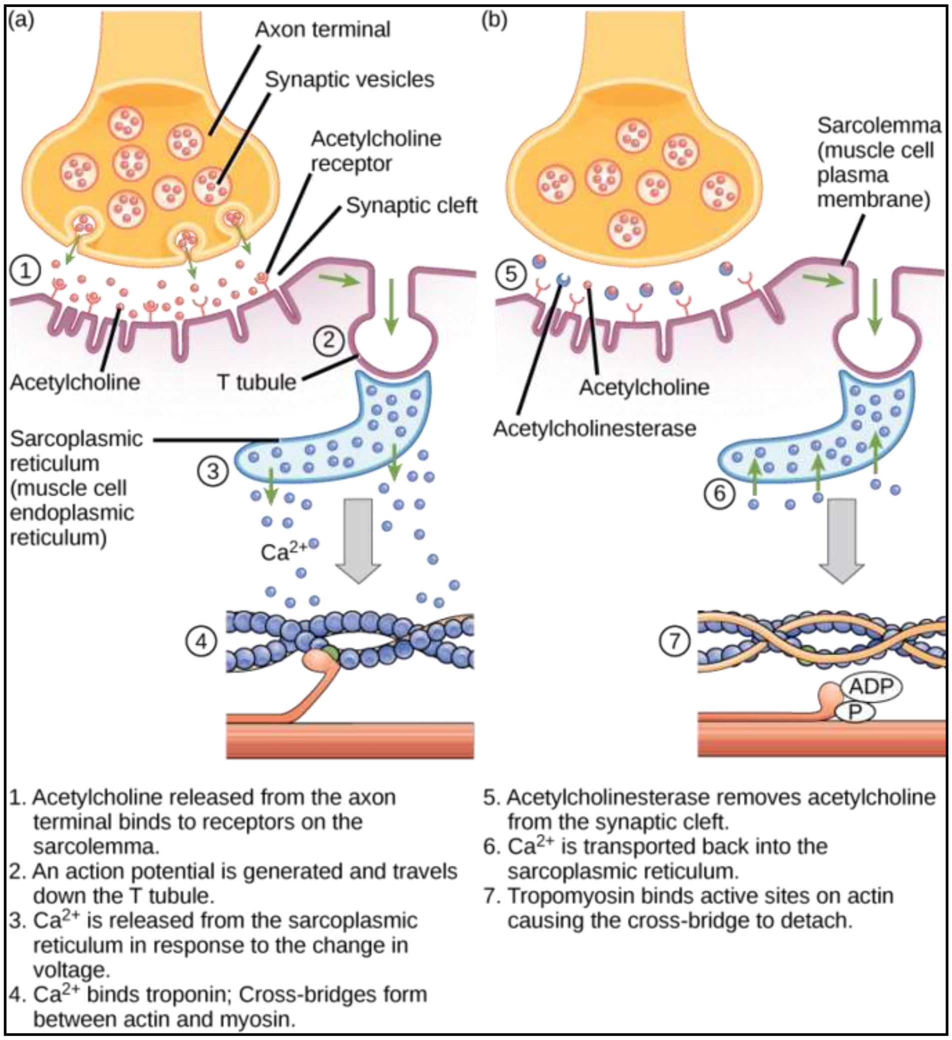


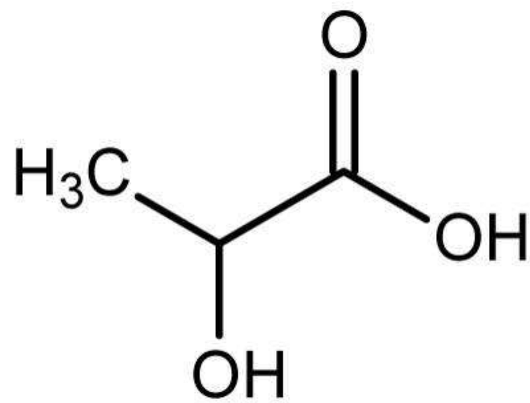
Figure 6: Muscle Contraction Process [11]

How do we go about converting food into energy needed for muscle contraction and other functions? Keep reading to find out!

What is Lactic Acid and Where Do We Get It?

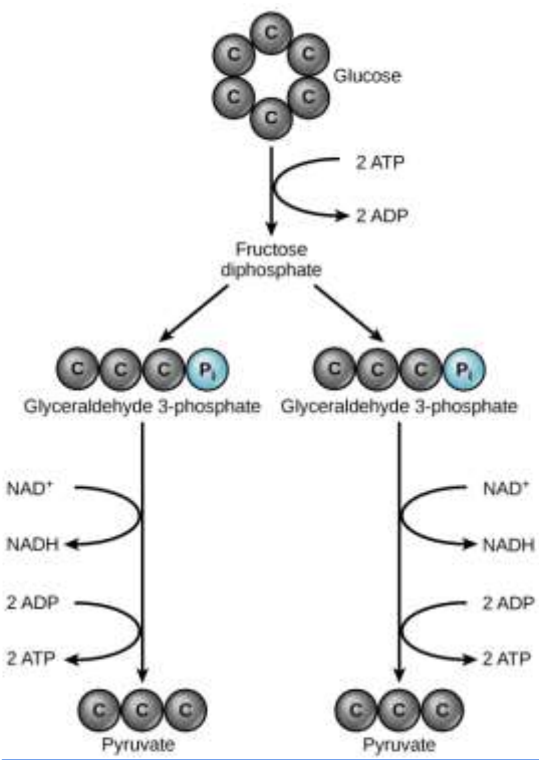
Have you ever been running or doing some intense exercise that causes you to breathe heavy and sweat and suddenly you feel your muscles begin to ache until, finally you can't continue? This muscle soreness that occurs during or shortly after intense exercise is a result of lactic acid and its buildup in the muscles.

You are probably wondering what lactic acid is and how it appears in our bodies. Firstly, lactic acid is an organic compound with the molecular formula $C_3H_6O_3$[12]. It was first discovered in 1780 by Swedish chemist Carl Wilhelm Scheele who isolated it from stale milk. Lactic acid's relation to milk gives it its name; *lact*- being the latin word for milk. Its discovery in muscles occurred later, in the year 1808, by Swedish chemist Jöns Jacob Berzelius[13].



The chemical structure of lactic acid[16].

Secondly, lactic acid is only produced through a process known as lactic fermentation[14]. Lactic fermentation occurs in many organisms, but only during a specific process known as anaerobic respiration. Muscles usually receive energy through a process known as cellular respiration[15], but when there is a lack of oxygen in the organism, muscles go through anaerobic respiration.

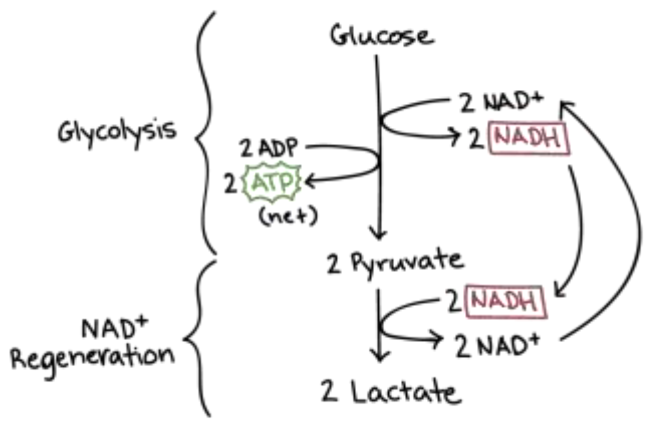


Basic diagram of the process of glycolysis[18].

Anaerobic respiration consists of glycolysis with a few extra reactions which allow it to repeat[17]. Glycolysis can be repeatedly carried out when exerting oneself due to its lack of oxygen dependence. The process begins by adding two phosphate groups to a glucose molecule, using two ATP to donate the phosphate groups. The result is a modified, unstable 6-carbon sugar named fructose-1,6-bisphosphate[19]. This unstable sugar molecule splits into two 3-carbon sugar isomers called dihydroxyacetone phosphate (DHAP) and glyceraldehyde-3-phosphate, which remain in equilibrium. However, only the glyceraldehyde -3-phosphate continues in glycolysis, so as glyceraldehyde-3-

phosphate is consumed in the following steps, the DHAP converts to the glyceraldehyde-3-phosphate until the entirety of both sugars is consumed.

The next part of glycolysis is referred to as the energy producing stage, as the glyceraldyhyde-3-phosphate molecules are used to produce energy carrying molecules. First the glyceraldehyde-3-phosphate reacts with an NAD^+ molecule, releasing energy and creating an energy holding molecule of NADH. The glyceraldehyde-3-phosphate gains another phosphate group as a result, and becomes 1,3-bisphosphoglycerate. The 1,3-isphosphogylcerate donates two phosphate groups to two separate ADP molecules, creating 2 ATP molecules and converting the 1,3-bisphosphoglycerate into a pyruvate molecule, which is usually used in the later processes of cellular respiration. The result of glycolysis is 2 pyruvate molecules, 4 ATP molecules and 2 NADH molecules.



Basic Diagram Lactic Fermentation [20].

The process of glycolysis requires 1 glucose molecule, 2 ATP molecules, and 2 NAD^+ molecules. The goal of anaerobic respiration is to repeat glycolysis until the organism is able to reintroduce oxygen into its system. The required glucose is provided by the food the organism has eaten and the ATP is a renewable part of the glycolysis reaction. The only non-renewable factor of glycolysis is the NAD^+.

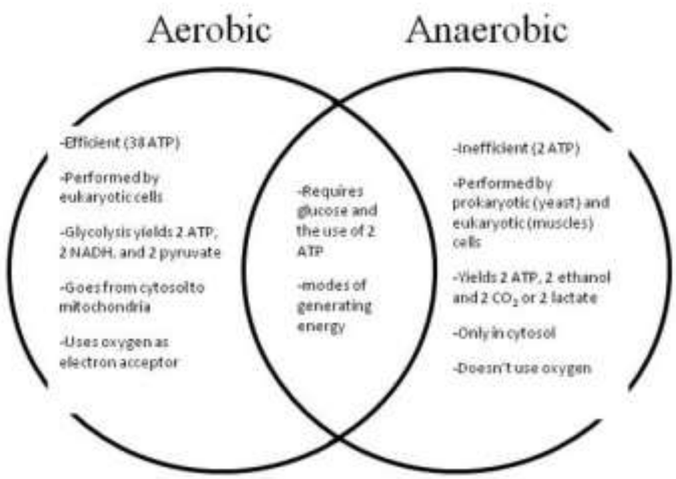
This complication is fixed through the method of lactic fermentation. Lactic fermentation is a minor process which occurs after glycolysis in anaerobic respiration. In it, an enzyme found in most every organism called lactate dehydrogenase catalyzes a reaction between the NADH produced from glycolysis with the pyruvate molecules to create the NAD^+ necessary to begin glycolysis. Lactate is then formed as a byproduct of this reaction. The lactate produced will eventually protonate into lactic acid. This lactic acid continues building up in the muscles until oxygen is reintroduced into the system and aerobic respiration can begin again. Once anaerobic exercise ends, the lactic acid is sent to the liver and converted back into pyruvate which can then be used in aerobic respiration.

Aerobic vs. Anaerobic Glycolysis:

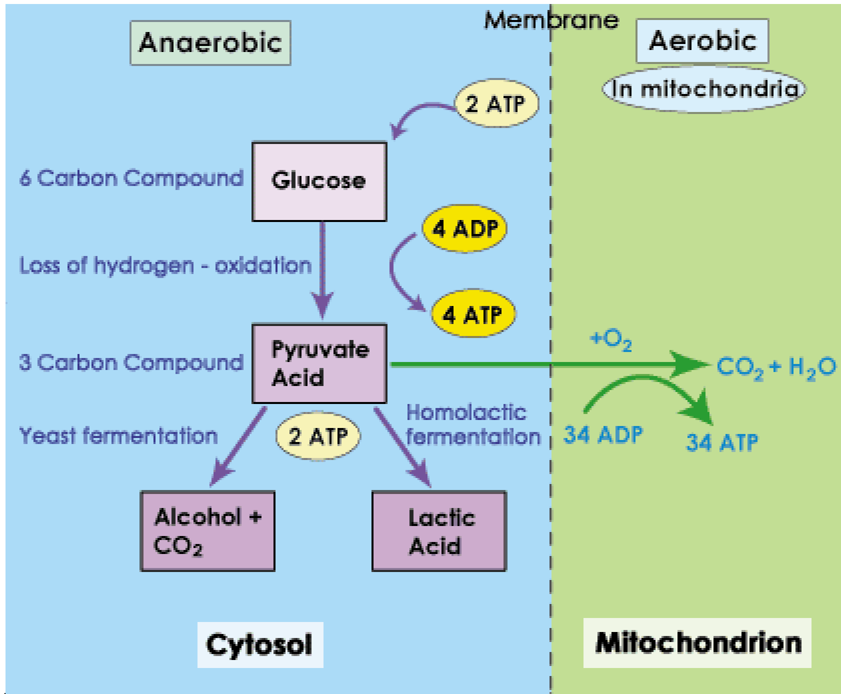
Glycolysis is the process in which the human body (as well as many other organisms) converts glucose into energy by reorganizing it into three pyruvate molecules[21]. Glycolysis is the first stage of many in cellular respiration, and usually occurs in the presence of oxygen. However, this is not always the case. Glycolysis can actually occur aerobically (in the presence of oxygen) and anaerobically (without the presence of oxygen)[22]. The differences between the processes and the products of these versions of glycolysis can be beneficial in different circumstances.

In the human body, aerobic glycolysis is the primary form of glycolysis carried out on a daily basis. In most daily situations, oxygen is plentiful, and since aerobic respiration produces up to 36 adenosine tri-phosphate molecules (ATP), it is an efficient and clean way to produce energy, creating little waste. Generally, the waste product of one glucose molecule being converted into 36 ATP molecules is 6 molecules CO_2, and 6 molecules of H_2O or water. When completing daily activities like going to class, working at a desk, driving a car, or walking around campus, the body can easily intake enough oxygen to continue aerobic respiration in the muscles, providing them with plenty of energy. As the body begins to undergo physical exertion, this begins to change. Whether it be running, biking, lifting weights, swimming, or any multitude of sports or physical activities, the muscles in the body require more energy to perform these activities. As more energy is called for from the muscles, the lungs can no longer keep up with the oxygen intake necessary, and the heart can only transport oxygen rich blood to the muscles so quickly. To make up for this lack of oxygen, anaerobic respiration, or fermentation, begins to take place.

Anaerobic equation also uses glucose, but it doesn't break it up as completely or efficiently as is possible with oxygen [23]. In fact, anaerobic respiration produces a total of 2 ATP molecules per glucose molecule, 18 times fewer than the aerobic process. The reason for this is that without oxygen, anaerobic respiration happens in the cytosol rather than in the mitochondria. The mitochondria is where the Krebs Cycle takes place, so without that, the cells are unable to produce the same amount of ATP per glucose[21]. Instead of being able to attach excess hydrogen molecules to oxygen to create water, the hydrogen molecules are instead placed back on the middle carbon of the pyruvate molecules to create lactate. This is why lactate is also known as lactic acid, because it has two hydrogens it can easily donate in water. Lactic acid commonly is referred to as a waste product of anaerobic respiration, but in fact it is not at all. Lactic acid instead acts as a storage unit. Lactate goes through what is known as the Cori cycle [21]. It is returned to the liver where it goes another process known as gluconeogenesis. Gluconeogenesis reverses glycolysis and fermentation, converting the lactate back into glucose. This has a cost though, because in order to do this, it has a net cost of 4 ATP molecules. As a result, anaerobic respiration is not a sustainable process. In some cases, usually in very unhealthy people, the



body cannot process the buildup of lactic acid. This leads to lactic acidosis, which causes nausea, vomiting, rapid deep breathing, and general weakness. Alcohol also inhibits the metabolizing of lactic acid. In fact, alcoholics typically experience sore muscles as a result of lactic acid buildup, even without exercising at all. Over prolonged periods of time, if alcohol continues to prevent this process, uric acid crystals begin to build up in the joints. Pain as a result is known as gout, which is why gout is often associated with large amounts of alcohol consumption[26].



The chart above shows the differences between aerobic and anaerobic respiration, as well as yeast fermentation[24].

With the obvious benefits of aerobic respiration compared to anaerobic respiration, it might seem odd that the human body undergoes anaerobic glycolysis at all. However, anaerobic respiration is still incredibly useful to humans. Any kind of intense exercise would not be possible without it. While it is possible to increase fitness so that the heart and lungs can provide more oxygen to the muscles, even the most elite athletes in the world require anaerobic glycolysis to perform. Evolutionarily, this process also makes sense. Since early humans required physical activity to hunt or to escape predators, being able to undergo anaerobic glycolysis for short spurts is an incredibly favorable trait. Many basic organisms that do not use oxygen rely solely on anaerobic respiration, as well as other similar animals to humans [25].

Disorders regarding cellular respiration:

Since cellular respiration is such an important function in the human body, any diseases or disorders that negatively affect this process are very catastrophic. One example of this disease is Huntington's disease [25]. Huntington's disease primarily affects parts of the brain associated with memory encoding, and typically leads to reduced cognitive functioning and loss of memories. However, due to recent research into this disease, medical researchers now believe that the huntington mutant protein can actually impair the abilities of mitochondria to function properly. While it is currently uncertain to the exact effects of the huntington protein, researchers believe that this error in mitochondrial functioning may cause incorrect transcription of proteins, or may cause problems through direct contact with organelles[27]. Many other diseases are known to be problematic when it comes to mitochondria and affecting aerobic and anaerobic respiration. These are generally known as mitochondrial diseases, and include mitochondrial myopathy, Leber's hereditary optic neuropathy, Leigh syndrome, as well as several others[28].

Why Bother with It?

Under standard conditions your body will use the entirety of cellular respiration to create usable energy for your cells. In this process, glucose is broken apart through chemical reactions to make adenine triphosphate, ATP, a molecule that can be readily used by the cells of your body to fuel important biochemical reactions through its high-energy phosphate bonds. ATP is used to fuel muscle contractions, allowing for the movement of your body and fueling exercise. One important part of cellular respiration is the last step, the electron transport chain (ETC). In the electron transport chain, electrons are ferried from one part of the transport chain to the next. This movement of electrons creates an electrochemical gradient with this difference in charge being used to fuel the creation of ATP.[30] However, cellular respiration, as the name implies, requires oxygen. Oxygen is necessary for this process because oxygen is used to accept the electrons that have passed through the electron transport chain. Oxygen is useful for this task as it has a high electronegativity, meaning it readily attracts the electrons of the electron transport chain. Each oxygen will accept 2 electrons, giving the oxygen a -2 overall charge. This reduced oxygen will then attract positively charged H+ ions, which combine with the oxygen to create H2O. This H2O is then removed, allowing new oxygens to accept the electrons of the ETC. Without oxygen to accept the electrons passing through, the electrons would have no where to go, and as such, would “clog” the cycle. This would force the electron transport chain to stop and thus, end the production of ATP in the electron transport chain. So, in situations where oxygen is not available in the required amounts, the cells of your body will use another process, lactic acid fermentation, to create the necessary energy.

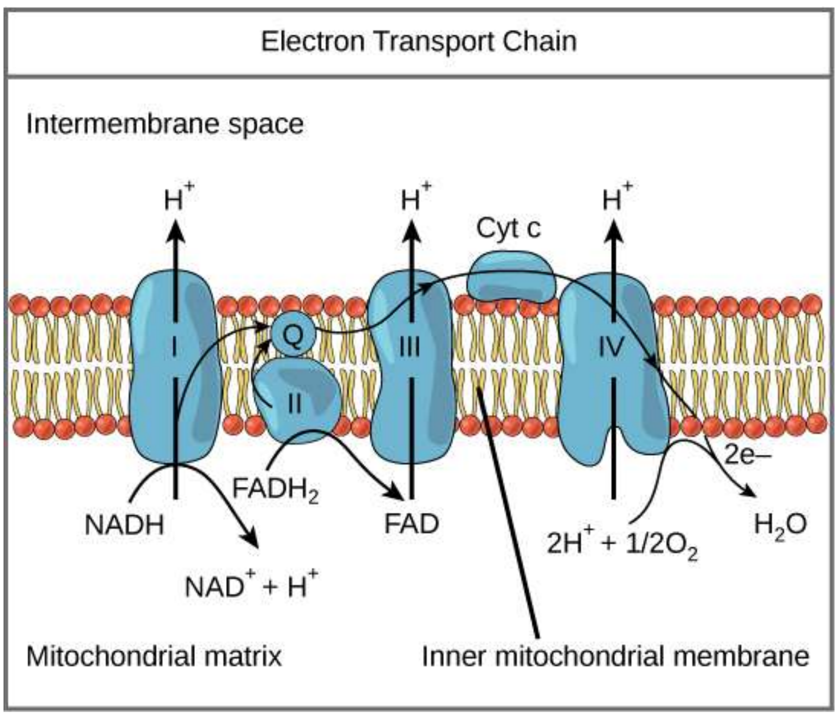


Figure 1: The Electron Transport Chain[31]

How would such a situation arise? After all, oxygen is readily available in the air. An example of a situation requiring oxygen-independent energy production would be weightlifting. Lactic acid fermentation is used by your body during short, intense activities like weightlifting because in such a situation, the cells of your body do not get enough oxygen from the bloodstream to undergo the lengthy process of cellular respiration.[32] As noted earlier, our bodies use the ATP produced in cellular respiration to fuel the muscle contractions that allow us to move and exercise. In this example, the rate of consumption of ATP (muscle contractions) is greater than the rate at which your cells can absorb oxygen and use it to make ATP. A one-hour weightlifting session will burn around 270 kilocalories for a 185-pound person.[33] 270 kilocalories are equal to around 1130 kilojoules while one mole of ATP molecules contains around 28-34 kilojoules.[34] This means that if we use the upper figure of ATP energy, said workout session will "burn" over 33 moles of ATP, that being equal to 2.00x1025 molecules of ATP! While the biochemical reactions of your body take place at an astonishing rate, it is still difficult for your cells to keep up with this energy consumption. Therefore, your cells need a quicker way to make energy without having to use oxygen.

This situation demonstrates the primary advantage of lactic acid fermentation, it being a quick way for the cells of your body to create energy without requiring oxygen. Lactic acid fermentation involves the first part of cellular respiration, glycolysis. In glycolysis, glucose is broken down into pyruvate through ten reactions. Through other reactions of cellular respiration, the products of glycolysis are processed further into molecules that can be used to create ATP. Glycolysis itself requires the consumption of 2 molecules of ATP but results in the production of 4 molecules of ATP, a net gain of 2 ATP. In addition, the reactions that make up lactic acid fermentation are 100 times faster than those of cellular respiration.[35] Therefore, in situations like extended exercise, lactic acid fermentation is used to provide quick energy.

However, lactic acid fermentation is not without its drawbacks. As discussed earlier, lactic acid fermentation, through glycolysis, creates 2 molecules of ATP from each glucose. This is far less than the 38 molecules of ATP produced from the same glucose through cellular respiration (while there is still dispute on the exact number of ATP molecules produced from one glucose through cellular respiration, most biology textbooks cite 38 as the number).[36] The inefficiency of lactic acid fermentation is its chief drawback, as it only produces about 5.26 percent of the ATP that could be made through cellular respiration. Lactic acid fermentation, as the name implies, produces 2 molecules of lactic acid for each glucose consumed. When this lactic acid builds up it can raise the acidity of the cells' environment. This increase in acidity can inhibit the processes that break down glucose, making it harder for the cell to produce ATP and usable energy. One commonly identified side effect of this increase in muscle acidity is the “burning” sensation felt in the muscles during intense exercise. This painful sensation is caused by lactic acid and other metabolites, although the roles of said products in this sensation are unknown.[37] In addition, extreme lactic acid buildup during or after exercise can result in a condition known as exercise related lactic acidosis. This condition can result in cramps, muscle ache, a burning feeling in the muscles, and even nausea and stomach pain. Exercise related lactic acidosis is caused by high levels of lactic acid in the bloodstream.[38]

Appendix

ATP- ATP stands for Adenosine TriPhosphate. It is an organic molecule used in cellular respiration and photosynthesis. It is considered the "batter" of the cell because it releases large amounts of energy when one of the phosphate groups is removed. It is essential to all living things.

Glucose- Glucose is a six-carbon sugar and is the simplest of sugars. In glycolysis it serves as the starting molecule which is manipulated to release more energy. It is formed through photosynthesis, the "reverse" reaction of cellular respiration.

References

[1] C.D.N., E.W., M.S., R.D. What Types of Foods Supply Carbohydrates, Proteins & Lipids? https://www.livestrong.com/article/517141-what-types-of-foods-supply-carbohydrates-proteins-lipids/ (accessed Nov 20, 2017).

[2] Alberts B., Johnson A., Lewis J., et al. Molecular Biology of the Cell. 4th edition. New York: Garland Science; 2002. How Cells Obtain Energy from Food. https://www.ncbi.nlm.nih.gov/books/NBK26882/ (accessed Nov 20, 2017)
.

[3] Freudenrich, P. D. C. How Exercise Works https://health.howstuffworks.com/wellness/diet-fitness/exercise/sports-physiology2.htm (accessed Nov 20, 2017).

[4] Freudenrich, P. D. C. How Muscles Work https://health.howstuffworks.com/human-body/systems/musculoskeletal/muscle3.htm (accessed Nov 20, 2017).

[5]N/A Muscular System: Stages of A Muscle Contractionhttp://legacy.owensboro.kctcs.edu/gcaplan/anat/notes/api%20notes%20j%20%20muscle%20contraction.htm (accessed Nov 20, 2017).

[6] Nauss, J. The 'Diet'-Brief Introduction to Macronutrients and Macronutrient Tracking http://evidencebasedhabit.com/index.php/2017/08/30/the-diet-brief-introduction-to-macronutrients-and-macronutrient-tracking/ (accessed Nov 20, 2017).

[7] Mastering AP Homework Chemistry Comes Alive http://www.easynotecards.com/print_list/56370 (accessed Nov 20, 2017).

[8] Investigation of Biological Oxidation, Oxidative Phosphorylation and ATP Synthesis. Inhibitors and Uncouplers of Oxidative Phosphorylation.

http://intranet.tdmu.edu.ua/data/kafedra/internal/chemistry/classes_stud/en/med/lik/ptn/2/03.%20Investigation%20of%20biological%20oxidation,%20oxidative%20phosphorylation.htm (accessed Nov 20, 2017).

[9] Woodfords Strength & Conditioning Principles https://alexsandalis.com/woodfords/ (accessed Nov 20, 2017).

[10] ATP Crossbridge Searches https://www.picquery.com/c/atp-crossbridge_DVeOwprv5fFB4viPjDLGV6ZKmTY2eKhxBfdD4UWjqw8/ (accessed Nov 20, 2017).

[11] OpenStax. Muscle contraction and locomotion By OpenStax (Page 5/25) https://www.quizover.com/biology3/course/muscle-contraction-and-locomotion-by-openstax?page=4 (accessed Nov 20, 2017).

[12] Lactic acid. https://en.wikipedia.org/wiki/Lactic_acid#Exercise_and_lactate (accessed Nov 18, 2017)

[13] Jöns Jacob Berzelius https://www.britannica.com/biography/Jons-Jacob-Berzelius (accessed Nov 18, 2017)

[14] Why Does Lactic Acid Build Up in Muscles? And Why Does It Cause Soreness? https://www.scientificamerican.com/article/why-does-lactic-acid-buil/ (accessed Nov 19, 2017)

[15] Cellular Respiration https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation/a/steps-of-cellular-respiration (accessed Oct 28, 2017)

[16] Pinterest https://i.pinimg.com/originals/ca/1d/98/ca1d98ea5d28ed351e125487d6c9442b.jpg (accessed Nov. 19, 2017)

[17] Fermentation and Anaerobic Respiration https://www.khanacademy.org/science/biology/cellular-respiration-and-

fermentation/variations-on-cellular-respiration/a/fermentation-and-anaerobic-respiration (accessed Nov.19, 2017)

[18] archive.cnx.org
https://archive.cnx.org/resources/20abe48ad463ab7b120a27a2ad706a7c98bb1e53/Figure_08_01.jpg (accessed Nov. 19, 2017)

[19] Glycolysis| Cellular Respiration
https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation/glycolysis/a/glycolysis (accessed Nov. 19, 2017)

[20] Fermentation and Anaerobic Respiration
https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation/variations-on-cellular-respiration/a/fermentation-and-anaerobic-respiration (accessed Nov.19, 2017)

[21]Glycolysis | Cellular respiration | Biology (article)
https://www.khanacademy.org/science/biology/cellular-respiration-and-fermentation/glycolysis/a/glycolysis (accessed Nov 18, 2017).

[22] ABA Keywords https://www.openanesthesia.org/aba_aerobic_vs/ (accessed Nov 18, 2017).

[23] GCSE Bitesize: Anaerobic respiration
http://www.bbc.co.uk/schools/gcsebitesize/science/add_aqa/respiration/respirationrev4.shtml (accessed Nov 18, 2017).

[24] Glycolysis
http://www.sparknotes.com/biology/cellrespiration/glycolysis/section3.rhtml (accessed Nov 18, 2017).

[25] About Abnormalities in Energy Metabolism
http://web.stanford.edu/group/hopes/cgi-bin/hopes_test/about-abnormalities-in-energy-metabolism/ (accessed Nov 18, 2017).

[26] Respiration - Real-life applications
http://www.scienceclarified.com/everyday/Real-Life-Physics-Vol-3-Biology-Vol-1/Respiration-Real-life-applications.html (accessed Nov 18, 2017).

[27] Bossy-Wetzel, E.; Petrilli, A.; Knott, A. B. Mutant huntingtin and mitochondrial dysfunction. https://www.ncbi.nlm.nih.gov/pubmed/18951640 (accessed Nov 18, 2017).

[28] Mitochondrial disease https://en.wikipedia.org/wiki/Mitochondrial_disease (accessed Nov 18, 2017).

[29] Nikita. Difference between Aerobic and Anaerobic Respiration http://www.differencebetween.info/difference-between-aerobic-and-anaerobic-respiration (accessed Nov 18, 2017).

[30] "2.10 – ATP Production II: The TCA Cycle and Oxidative Phosphorylation," ScienceDirect, http://www.sciencedirect.com/science/article/pii/B9780128008836000215, (accessed 11/17/17)

[31] Lumen Learning, https://s3-us-west-2.amazonaws.com/courses-images/wp-content/uploads/sites/110/2016/05/03200406/Figure_07_04_01.jpg, (accessed 11/17/17)

[32] "Electron transport chain," Wikipedia, https://en.wikipedia.org/wiki/Electron_transport_chain#Summary, (accessed 11/17/17)

[33] "Calories burned in 30 minutes for people of three different weights," Harvard Health Publishing, Harvard Medical School, https://www.health.harvard.edu/newsweek/Calories-burned-in-30-minutes-of-leisure-and-routine-activities.htm, (accessed 11/17/17)

[34] "How Much Energy is Released in ATP Hydrolysis?," Cell Biology by the Numbers, http://book.bionumbers.org/how-much-energy-is-released-in-atp-hydrolysis/, (accessed 11/17/17)

[35] "Anaerobic glycolysis," Wikipedia, https://en.wikipedia.org/wiki/Anaerobic_glycolysis, (accessed 11/18/17)

[36] "Cellular respiration," Wikipedia, https://en.wikipedia.org/wiki/Cellular_respiration, (accessed 11/18/17)

[37] “Why Does Lactic Acid Build Up in Muscles? And Why Does It Cause Soreness?,” Scientific American, https://www.scientificamerican.com/article/why-does-lactic-acid-buil/, (accessed 11/18/17)

[38] “Lactic Acidosis and Exercise: What You Need to Know,” WebMD, https://www.webmd.com/fitness-exercise/guide/exercise-and-lactic-acidosis#1, (accessed 11/18/17)