

Teacher Notes for "How do muscles get the energy they need for athletic activities?"¹

In this analysis and discussion activity, students learn how muscle cells produce ATP by aerobic cellular respiration, anaerobic fermentation, and hydrolysis of creatine phosphate. Students use their understanding of these three processes to analyze their relative importance when racing different distances. Students learn how multiple body systems work together to supply the oxygen and glucose needed for aerobic cellular respiration. Finally, students use what they have learned to analyze how regular aerobic exercise can improve athletic performance.

As preparation for this activity, I recommend our analysis and discussion activity "How do organisms use energy?" (<https://serendipstudio.org/exchange/bioactivities/energy>).²

Learning Goals

In accord with the Next Generation Science Standards³, this activity:

- helps students to learn the Disciplinary Core Ideas:
 - LS1.C, "Cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken", carbon dioxide and water are formed, and the energy released is used in the production of ATP from ADP and P. Then, the hydrolysis of ATP molecules provides the energy needed for muscle contraction.
 - LS2.B, "... cellular respiration (including anaerobic processes) provide most of the energy for life processes."
 - LS1.A, "Multicellular organisms have a hierarchical structural organization, in which any one system is made up of numerous parts and is itself a component of the next level."
- engages students in the Scientific Practices:
 - "Constructing Explanations: Apply scientific ideas, principles, and/or evidence to provide an explanation of phenomena..."
 - "Developing and Using Models: Develop and/or use a model... to support explanations, predict phenomena, analyze systems...."
- illustrates the Crosscutting Concept, "Energy and matter: Flows, Cycles and Conservation: Within a natural... system, the transfer of energy drives the motion... of matter."
- helps students to prepare for Performance Expectation, HS-LS1-7, "Use a model to illustrate that cellular respiration is a chemical process whereby the bonds of food molecules and oxygen molecules are broken and the bonds in new compounds are formed resulting in a net transfer of energy."

Instructional Suggestions and Background Information

To maximize student participation and learning, I suggest that you have your students work individually or in pairs to complete groups of related questions and then have a class discussion after each group of related questions. In each discussion, you can probe student thinking and help them develop a sound understanding of the concepts and information covered before moving on to the next group of related questions.

If your students are learning online, I recommend that they use the Google Doc version of the

¹ By Dr. Ingrid Waldron, Department of Biology University of Pennsylvania, 2024. These Teacher Notes and the Student Handout are available at <https://serendipstudio.org/exchange/bioactivities/energyathlete>.

² For additional background, you may want to have your students complete "Using Models to Understand Cellular Respiration" (<https://serendipstudio.org/exchange/bioactivities/modelCR>).

³ Quotations are from <https://www.nextgenscience.org/> and <https://www.nextgenscience.org/sites/default/files/HS%20LS%20topics%20combined%206.13.13.pdf>.

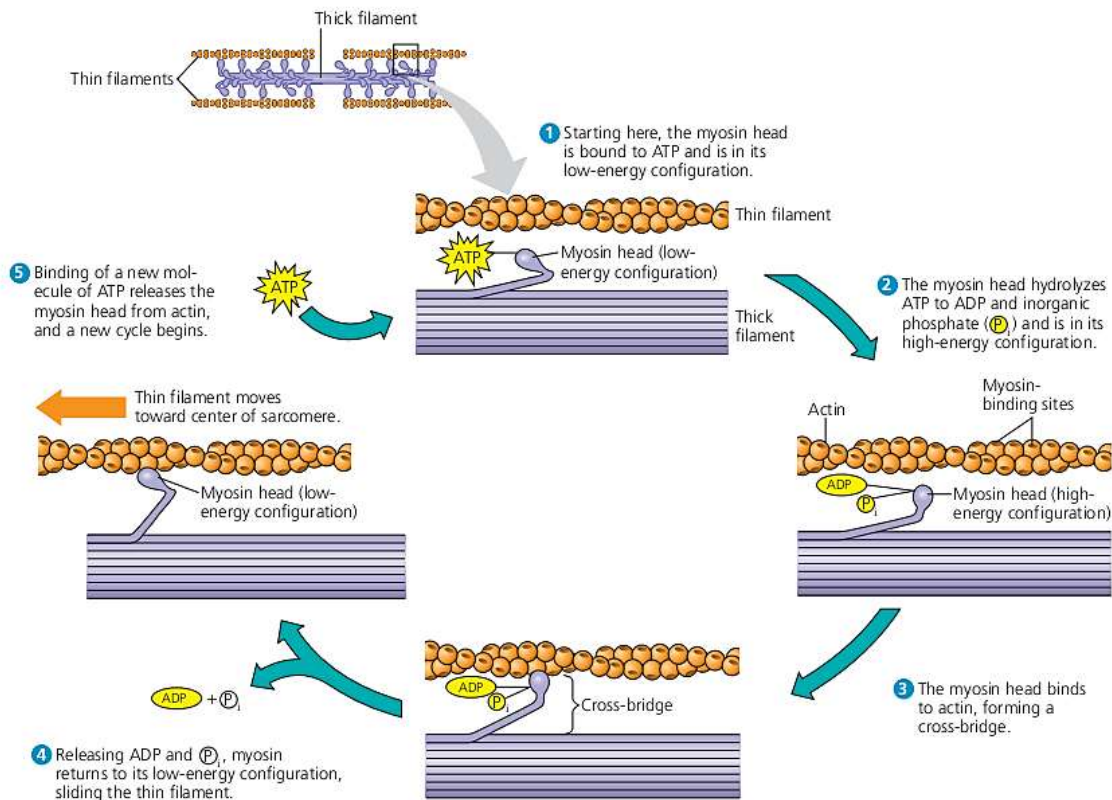
Student Handout available at <https://serendipstudio.org/exchange/bioactivities/energyathlete>. To answer questions 2-4 and 9, students can either print the relevant pages, draw on them and send pictures to you, or they will need to know how to modify a drawing online. To answer online, they can double-click on the relevant drawing in the Google Doc to open a drawing window. Then, they can use the editing tools to answer the questions.

You can use the Word document for the Student Handout to prepare a revised version that may be more suitable for your students. If you use the Word document, please check the format by viewing the PDF.

A key for this activity is available upon request to Ingrid Waldron (iwaldron@upenn.edu). The following paragraphs provide additional instructional suggestions and background information for your interest and possible use in class discussions.

Question 1 is intended to activate previous student knowledge to help students relate it to their learning during this activity. Student answers to question 1 will allow you to gauge the knowledge of your students and adjust your discussion accordingly. If your students mention food as the ultimate source of energy for physical activity, you can confirm that and then say that we will circle back to food on page 4 of the Student Handout.

Question 2 focuses on the hydrolysis of ATP to provide the energy for muscle contraction. If your students are not familiar with the term “hydrolysis of ATP”, you can explain that hydro- means water and -lysis means breaking down, so hydrolysis refers to a chemical reaction in which a molecule is split into smaller molecules by reacting with water. If your students are not familiar with the term “coupled reactions”, you might want to have them read “Coupled chemical reactions” (<https://www.britannica.com/science/cell-biology/Coupled-chemical-reactions>). The figure below provides more detail about the role of ATP in muscle contraction.



▲ **Figure 50.28 Myosin-actin interactions underlying muscle fiber contraction.**

? When ATP binds, what prevents the filaments from sliding back into their original positions?



Visit the Study Area at www.masteringbiology.com for the BioFlix® 3-D Animation on Muscle Contraction.

(http://classconnection.s3.amazonaws.com/938/flashcards/1810938/png/screen_shot_2012-10-22_at_14201_am1350884481342.png)

For question 3, it should be relatively easy for students to copy the information about cellular respiration from the figure above in the Student Handout. Some students may find it more challenging to show how the hydrolysis of ATP provides energy for muscle contraction since the arrows in their answers will point from right to left, instead of from left to right. To facilitate class discussion of student answers to question 3, you may want to have each small group of students prepare their consensus answer on a whiteboard,⁴ so they can more effectively present and compare their answers.

Although this activity focuses on muscles, students should be aware that most types of cells are constantly using aerobic cellular respiration of organic molecules like glucose to make ATP and using hydrolysis of ATP to provide the energy for biological processes (e.g. synthesizing molecules, pumping ions into and out of cells, and moving molecules within cells). On average,

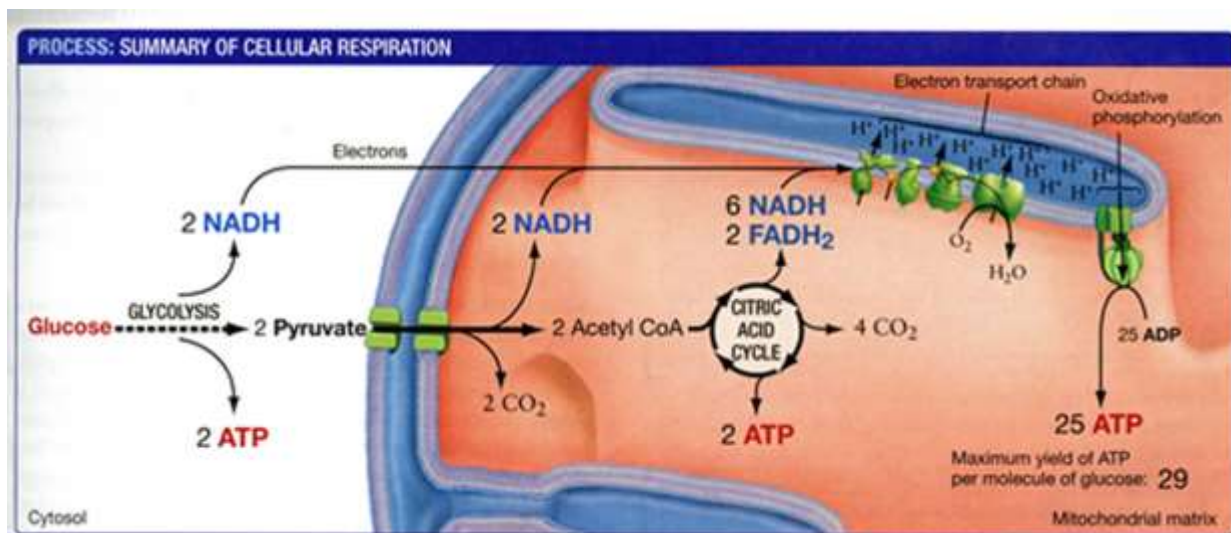
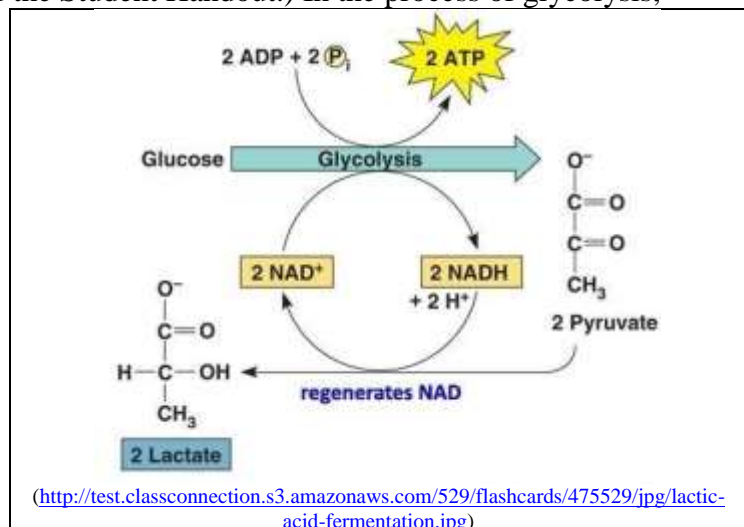
⁴ For information about how to make inexpensive whiteboards and use them in your teaching, see "The \$2 interactive whiteboard" and "Resources for whiteboarding" in <https://fnoschese.wordpress.com/2010/08/06/the-2-interactive-whiteboard/>. You can go to Home Depot and ask them to cut a 8' x 4' whiteboard (e.g. EUCATILE Hardboard Thrifty White Tile Board) into six pieces with the dimension 32" x 24". They should have a power saw rig that allows their employees to cut the pieces very easily. They should not charge to cut them and the product cost is reasonable. Some additional tips are:

- Coat the white boards with Endust (or similar product) before using. Every once in a while wipe them clean and reapply Endust.
- Do not use markers that are old or almost empty. The ink from these are more difficult to erase.
- Black markers erase easiest.
- Best if boards are erased immediately after use.
- Teacher and/or students can take a picture of the information on the whiteboard if they want to save it.

each ATP molecule in a human body is used and re-synthesized more than 30 times per minute when a person is at rest and more than 500 times per minute during strenuous exercise.

Both aerobic cellular respiration and anaerobic fermentation begin with glycolysis, when glucose is broken down to 2 pyruvate and 2 ATP are produced. (See the figure immediately below and the diagrams on the top half of page 2 of the Student Handout.) In the process of glycolysis,

NAD⁺ is reduced to NADH. For glycolysis to continue, NADH must be oxidized back to NAD⁺. When O₂ is available as an electron acceptor, NADH enters the electron transport chain and is oxidized to NAD⁺ in a process that contributes to the production of ATP (as part of aerobic cellular respiration; see figure below). In anaerobic fermentation, the pyruvate produced by glycolysis reacts with NADH to produce lactate and NAD⁺. The lactate is mainly secreted into the blood and carried to the heart (where it can be used in aerobic cellular respiration) and the liver (where it can be converted back to pyruvate or glucose for use in aerobic cellular respiration).⁵



(From "Biological Science" by Scott Freeman, Benjamin Cummings, 2011)

The figure above provides additional information about the multiple steps of cellular respiration, although it omits many of the specific steps. Notice that "citric acid cycle" is another name for the Krebs cycle shown in the figure on the upper half of page 2 of the Student Handout.

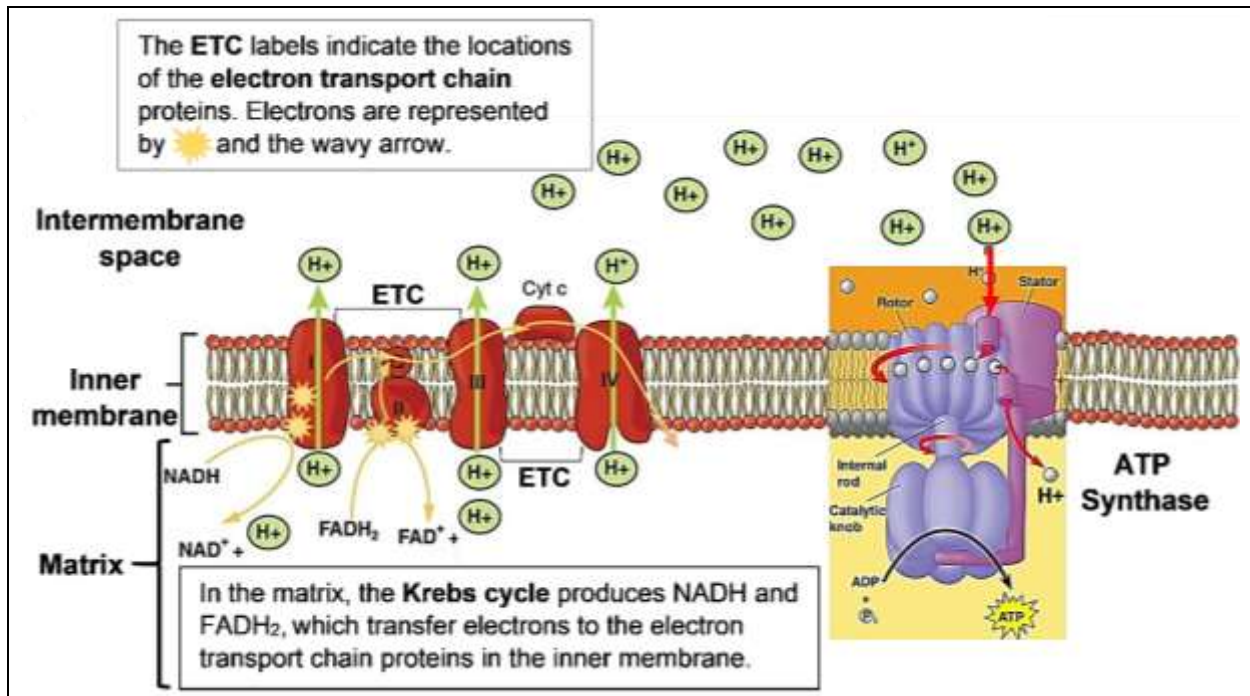
The equations and figures indicate that cellular respiration generates ~29 molecules of ATP for each glucose molecule; this number is less than previously believed (and often erroneously stated

⁵ Anaerobic fermentation is associated with increased acidity; for an explanation, see "Biochemistry of exercise-induced metabolic acidosis" (<https://www.physiology.org/doi/full/10.1152/ajpregu.00114.2004>).

Some organisms use a slightly different type of anaerobic fermentation that produces ethanol; see e.g. our hands-on activity "Alcoholic Fermentation in Yeast" (http://serendipstudio.org/sci_edu/waldron/#fermentation).

in textbooks). This revised estimate is based on recently discovered complexities and inefficiencies in the function of the electron transport chain and ATP synthase enzyme. The number of ATP molecules produced per molecule of glucose is variable because of variability in the efficiency of the electron transport chain proton pumps and the ATP synthase.⁶ These findings are interesting as an example of how science progresses by a series of successively more accurate approximations to the truth.

The oxidation of glucose is coupled with the production of ATP by a complex sequence of processes that take time, which explains why cellular respiration is slower than anaerobic fermentation. This figure shows how the electron transport chain functions, together with ATP synthase. The bulleted prose below provides an explanation.



(modified from <https://biologydictionary.net/wp-content/uploads/2018/08/The-Electron-Transport-Chain.jpg> and <https://slideplayer.com/slide/14082775/86/images/57/Figure+9.14+ATP+synthase%2C+a+molecular+mill.jpg>)

- NADH and FADH₂ transport electrons (mainly from the Krebs cycle and some from earlier steps of aerobic cellular respiration) to the electron transport chain (ETC) in the inner membrane of the mitochondria.⁷
- When activated by NADH and FADH₂, the electron transport chain proteins pump H⁺ from the matrix to the intermembrane space. As a result, the concentration of H⁺ is higher in the intermembrane space and lower in the matrix.
- Because of this difference in H⁺ concentration, H⁺ tends to diffuse across the inner membrane from the intermembrane space to the matrix. The only place that H⁺ can diffuse across the inner membrane is through the channels in the ATP synthase molecules.
- The movement of H⁺ through ATP synthase provides the energy to make ATP. This is similar to how the flow of water through a turbine provides the energy to generate electricity.

⁶ "Approximate Yield of ATP from Glucose, Designed by Donald Nicholson" by Brand, 2003, Biochemistry and Molecular Biology Education 31:2-4 (available at <http://www.bambed.org>).

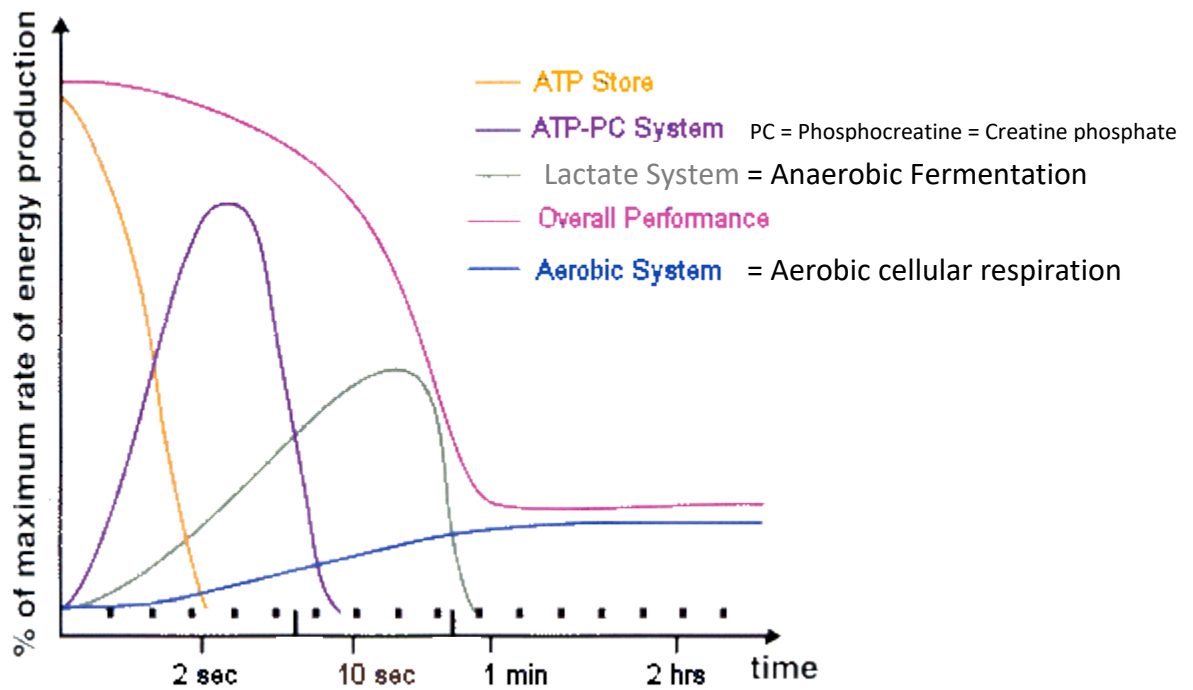
⁷ For more information, see the advanced version of "Using Models to Understand Cellular Respiration" (<https://serendipstudio.org/exchange/bioactivities/modelCR>).

Hydrolysis of creatine phosphate (also called phosphocreatine) can be used to make ATP during muscle contraction (shown on the bottom of page 2 of the Student Handout). During rest (after physical activity or between bouts of intense physical activity), aerobic cellular respiration produces ATP, which is used to reverse the reactions shown at the bottom of page 2 in the Student Handout, which restores the muscle cell's creatine phosphate supply.

Muscle cells have extreme increases in metabolic demands, with up to 100-fold increases in the rate of hydrolysis of ATP when muscles are active. Therefore, it is not surprising that skeletal muscles contain most of the body's creatine phosphate (~95% of the total body creatine). Meat and fish provide dietary sources of creatine. Use of oral creatine supplements can lead to increased creatine in skeletal muscles and ~10-15% improvement in performance in brief high-intensity athletic events; use of these supplements can also contribute to improved performance in intermittent high-intensity sports. Use of creatine supplements that do not have contaminants does not appear to result in serious side effects, although weight gain (mainly lean body mass) is common (<http://link.springer.com/article/10.2165/00007256-200232140-00003>; <http://www.jissn.com/content/pdf/1550-2783-4-6.pdf>).⁸

Aerobic cellular respiration, anaerobic fermentation, and hydrolysis of creatine phosphate all contribute to ATP production during any physical activity, but the relative contributions vary substantially over time and between different types of physical activity. (See figure below.) For very brief, high-intensity events, the supply of ATP is heavily dependent on the hydrolysis of creatine phosphate and anaerobic fermentation which can supply ATP very rapidly and do not require O₂; when the intensity of muscle activity is very high, the rate of ATP use exceeds the capacity of the circulatory system to supply the muscles with O₂ for aerobic cellular respiration. However, both the hydrolysis of creatine phosphate and anaerobic fermentation are limited to relatively short time periods, and aerobic cellular respiration is the primary energy source after a minute or two.

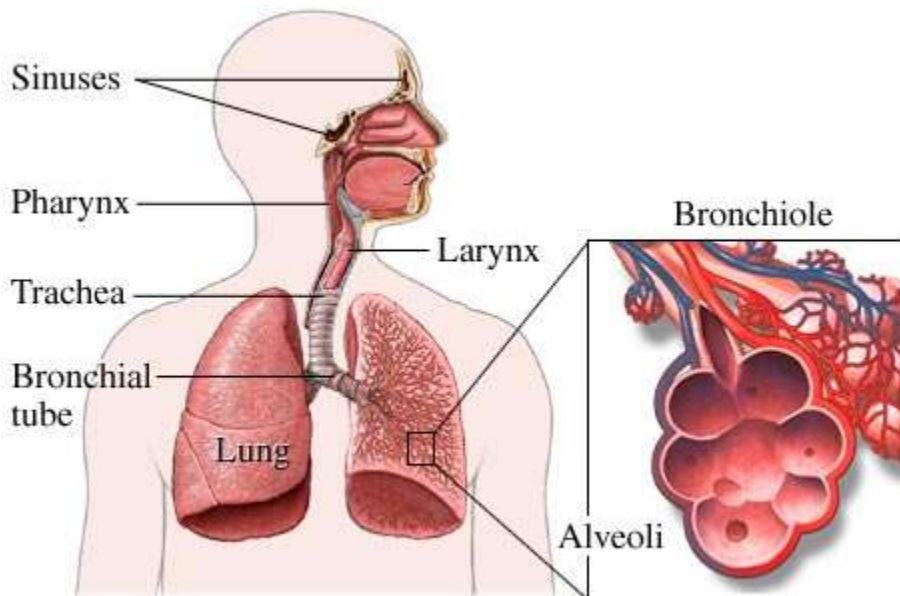
⁸ Anabolic androgen steroids are the most commonly used performance-enhancing drugs. These drugs are often used by bodybuilding young men to increase muscle size and "improve appearance". Anabolic androgen steroids have harmful effects on the circulatory system, mood and behavior (<https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4026349/>).



(<http://www.brianmac.co.uk/pictures/physiology/energy.gif>)

How Oxygen and Glucose Get to Your Muscles

This section provides the opportunity to reinforce the general point that interactions between body systems are important for accomplishing the activities of life. The digestive system and circulatory system cooperate to bring glucose and oxygen to muscles.⁹ The respiratory and circulatory systems cooperate to provide oxygen to the muscles. The respiratory system is shown in the figure below.

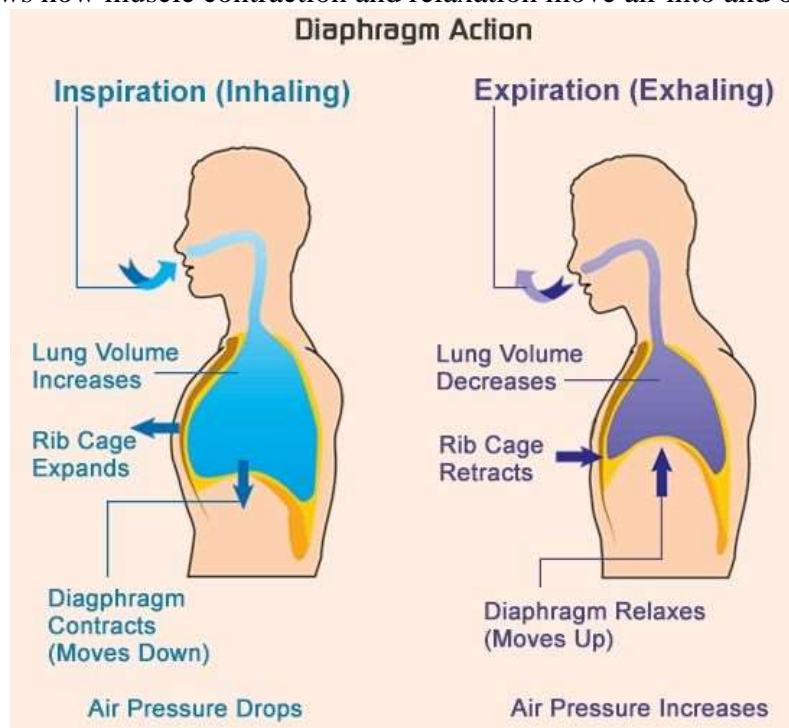


(https://megansbiologyportfolio.weebly.com/uploads/1/3/8/2/13822667/6761185_orig.jpg)

O₂ diffuses from the inhaled air in the alveoli to the blood in the network of capillaries that

⁹ Students learn how the digestive and circulatory systems cooperate to provide glucose to the muscles in "How do food molecules reach our muscles? – Structure and Function of Organ Systems, Organs and Cells" (<https://serendipstudio.org/exchange/bioactivities/SFCellOrgan>). For diagrams of the digestive system and circulatory system, see the Student Handout of that activity.

surrounds the alveoli. The heart pumps the oxygenated blood to the muscles, where the O_2 diffuses from the blood into the muscles. For simplicity, the Student Handout does not discuss how CO_2 diffuses into the blood in the capillaries, and then is carried by the blood to the lungs where CO_2 diffuses from the blood into the air in the alveoli, and ultimately is exhaled. The figure below shows how muscle contraction and relaxation move air into and out of the lungs.



(<https://i.pinimg.com/originals/0d/7f/3a/0d7f3ab710f71252b88c0e62f605e246.jpg>)

How Regular Aerobic Exercise Can Improve Athletic Performance

Regular aerobic exercise results in changes in the body which are called training effects. The supply of O_2 to the muscle is limiting for prolonged physical activity. Improved heart function (e.g. increased stroke volume) and increased capillaries in muscles deliver more O_2 .¹⁰ In addition, regular aerobic exercise results in an increase in the number of mitochondria in muscles, increased blood volume, and increased maximum breathing capacity. Each of these training effects contributes to increased capacity for aerobic cellular respiration in active muscle cells. Increased capacity for aerobic cellular respiration can improve athletic performance, especially in sports that rely primarily on aerobic cellular respiration (e.g. longer running, swimming, or bicycling races).

This introductory activity does not discuss glycogen (a polymer of glucose which can provide additional glucose molecules for aerobic cellular respiration and anaerobic fermentation) or fat (which can be broken down to fatty acids and glycerol which muscle cells can use as input for aerobic cellular respiration).¹¹ As a result of regular aerobic exercise, muscle cells have more stored glycogen and more of the molecules that facilitate uptake of glucose and fatty acids into cells. Increased capacity for aerobic cellular respiration reduces the need for anaerobic

¹⁰ Diffusion of oxygen across capillary walls is proportional to the surface area of the capillary walls, and more capillaries have more surface area.

¹¹ There is a relatively limited supply of glycogen in skeletal muscle (enough for less than an hour of moderate intensity activity). A slightly larger amount of energy is available from the fat in muscles. In comparison, there is three times as much glycogen in the liver and roughly 20 times as much fat in adipose tissue.

It appears that neither amino acids nor nucleic acids are significant inputs for aerobic cellular respiration in well-nourished individuals.

fermentation, which conserves glycogen stores. Depletion of the glycogen in skeletal muscles is associated with fatigue, so increased capacity for aerobic cellular respiration can delay fatigue and increase endurance.¹²

There are multiple additional effects of training which contribute to both improved athletic performance and health. More information on the effects of training, as well as are more information on the complexities of energy metabolism, is available in "The Surgeon General's Report on Physical Activity and Health" (<http://www.cdc.gov/nccdphp/sgr/chap3.htm>).

This activity illustrates how analysis at different levels – from molecular to body systems – contributes to our understanding of biological phenomena.

Possible Extension Activity

If your students have questions about other aspects of energy metabolism and athletic activity, you may want to encourage them to investigate these questions and engage in the NGSS-recommended science practices of "asking questions" and "obtaining, evaluating, and communicating information". Possible sources include those already referred to in these Teacher Notes and physiology textbooks. If your students are unfamiliar with how to evaluate the reliability of various sources, this important skill can be introduced, using the last page of these Teacher Notes.

Related Learning Activities

- "Cellular Respiration and Photosynthesis – Important Concepts, Common Misconceptions, and Learning Activities" (<https://serendipstudio.org/exchange/bioactivities/cellrespiration>) offers multiple learning activities concerning energy metabolism. For example, "Food, Physical Activity, and Body Weight" (<https://serendipstudio.org/exchange/bioactivities/foodenergy>) discusses the contribution of exercise to weight loss (or prevention of weight gain).
- "How do food molecules reach our muscles? – Structure and Function of Organ Systems, Organs and Cells" (<https://serendipstudio.org/exchange/bioactivities/SFCellOrgan>)
- "Should you drink sports drinks? When? Why?" (<https://serendipstudio.org/exchange/bioactivities/sportsdrinks>)

Sources of Figures in Student Handout

- Silhouettes of sports figures – modified from <https://koohsports.files.wordpress.com/2017/04/33.jpg>
- Aerobic Cellular Respiration and Anaerobic Fermentation – modified from https://images.slideplayer.com/32/10058702/slides/slide_14.jpg

Other figures were prepared by the author.

¹² For endurance events it is helpful to reduce the rate of utilization of muscle glycogen by consuming food which can supply glucose for muscle cell aerobic cellular respiration. In this connection, you may be interested in the evidence that carbohydrate ingestion before and during endurance events that last longer than an hour can help to prevent fatigue and improve performance (see "Carbohydrate Consumption, Athletic Performance and Health – Using Science Process Skills to Understand the Evidence"; <https://serendipstudio.org/exchange/bioactivities/sciproc>). In contrast, consumption of fats immediately before or during athletic competitions is not recommended, because long chain fatty acids take too long to digest and medium chain fatty acids cause gastrointestinal distress when consumed in sufficient quantity to provide significant energy.

Instructions for Evaluating Sources

Rubric for Evaluating Sources ¹³	Additional Points
<div style="border: 1px solid black; padding: 10px; margin-bottom: 10px;"> <p>Q1: Is the provider of information credible?</p> <p>Are they unbiased and free of any conflict of interest: for example, do the individuals or organizations lack any economic or political reason for promoting their views?</p> <p>Do they provide evidence from sources that are scientifically reliable (for example, multiple peer-reviewed publications) to support their claim?</p> </div> <div style="display: flex; justify-content: space-around; margin-bottom: 10px;"> <div style="text-align: center;"> <p>NO</p> <p style="border: 1px solid black; padding: 2px;">Reject the claim</p> </div> <div style="text-align: center;"> <p>YES</p> </div> </div> <div style="border: 1px solid black; padding: 10px; margin-bottom: 10px;"> <p>Q2: Does the provider of the information have the expertise to vouch for the claim?</p> <p>Do they have training, a track record, and expertise in a relevant field of science?</p> <p>Do they have a good reputation among their peers?</p> </div> <div style="display: flex; justify-content: space-around; margin-bottom: 10px;"> <div style="text-align: center;"> <p>NO</p> <p style="border: 1px solid black; padding: 2px;">Reject the claim</p> </div> <div style="text-align: center;"> <p>YES</p> </div> </div> <div style="border: 1px solid black; padding: 10px; margin-bottom: 10px;"> <p>Q3: Is there a consensus among relevant scientific experts?</p> </div> <div style="display: flex; justify-content: space-between;"> <div style="width: 45%; text-align: center;"> <p>NO</p> <div style="border: 1px solid black; padding: 10px; margin-top: 5px;"> <p>The claim requires further investigation.</p> <p>What is uncertain and what do the experts agree on?</p> <p>What other explanations might be plausible?</p> <p>What additional information would be needed to support the claim?</p> </div> </div> <div style="width: 45%; text-align: center;"> <p>YES</p> <div style="border: 1px solid black; padding: 10px; margin-top: 5px;"> <p>The claim is likely to be correct.</p> </div> </div> </div>	<p>To find out whether sources may have a conflict of interest, use Wikipedia or fact-checking sources such as Snopes. Do <i>not</i> use “.org” as a sign of reliability. Be cautious about any source that uses emotional language.</p> <p>Experts in one subject are often unreliable when they write about another subject.</p> <p>What are the risks of accepting a claim that is ultimately proven to be wrong? What are the risks of not accepting a claim that is ultimately proven to be correct?</p>

¹³ This rubric is from https://sciedandmisinfo.stanford.edu/sites/g/files/sbiybj25316/files/media/file/why_trust_science-ecb.pdf.