Teacher Notes for "How do muscles get the energy they need for athletic activity?":

In this activity, students analyze how aerobic cellular respiration and anaerobic fermentation contribute to ATP production in muscle cells during different types of athletic activity. In addition, students gain understanding of general principles such as the conservation of energy and the importance of interactions between body systems to accomplish functions such as supplying the energy that muscles need for physical activity. Students apply this knowledge to an analysis of how the training effects of regular aerobic exercise contribute to an increase in muscle cells’ capacity for aerobic respiration.

Learning Goals
In accord with the Next Generation Science Standards, 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 many biological processes.
  - LS2.B, "Photosynthesis and 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 recommended Scientific Practices, including constructing explanations and arguing from evidence
- illustrates the Crosscutting Concept, Energy and matter: Flows, cycles and conservation, including “Energy cannot be created or destroyed – only moves between one place and another place, between objects and/or fields, or between systems.”
- helps students to prepare for Performance Expectations:
  - 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."
  - HS-LS2-3, "Construct and revise an explanation based on evidence for the cycling of matter and flow of energy in aerobic and anaerobic conditions."
  - HS-LS1-2, "Develop and use a model to illustrate the hierarchical organization of interacting systems that provide specific functions within multicellular organisms."

Instructional Suggestions and Background Information
Before beginning this activity, students should have a basic understanding of cellular respiration and the importance of ATP. For this purpose, I recommend our analysis and discussion activity "How do biological organisms use energy?" (http://serendip.brynmawr.edu/exchange/bioactivities/energy).

To maximize student participation and learning, I suggest that you have your students work in pairs (or individually or in groups of three) 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 to develop a sound understanding of the concepts and information covered before moving on to the next group of related questions.

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1 By Dr. Ingrid Waldron, Department of Biology University of Pennsylvania, 2016. These Teacher Notes and the Student Handout are available at http://serendip.brynmawr.edu/exchange/bioactivities/energyathlete.
This activity focuses on energy metabolism in skeletal muscle in humans. The following figure illustrates the role of ATP in muscle contraction.

Although this activity focuses on the production and use of ATP during muscle contraction, students should be aware that all of our cells are constantly using cellular respiration of organic molecules like glucose to make ATP and using hydrolysis of ATP to provide the energy for biological processes such as synthesizing molecules, pumping ions into and out of cells, and moving molecules within cells. On average, each ATP molecule in our body is used and resynthesized more than 30 times per minute when a person is at rest and more than 500 times per minute during strenuous exercise.

The constant molecular activity within body cells and constant changes within our bodies can be illustrated using:
- the figure on page 1 of the Student Handout that shows the constant breakdown and resynthesis of ATP
- the repeated breakdown and resynthesis of glycogen (shown on the top of page 3 of the Student Handout)
• question 9 concerning training effects, and
• question 13 concerning recovery processes.

Both anaerobic fermentation and aerobic respiration begin with glycolysis, when glucose breaks down to 2 pyruvate and produces 2 ATP. (See top part of this figure and left part of the figure on the next page.)

![Glycolysis Diagram](http://test.classconnection.s3.amazonaws.com/529/flashcards/475529/jpg/lactic-acid-fermentation.jpg)

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 respiration). When O₂ is not available, the pyruvate produced by glycolysis reacts with NADH to produce lactate (lactic acid) and NAD+ (in anaerobic fermentation). Eventually, lactate can be used to produce ATP, either when lactate is used by heart muscle cells as input for aerobic respiration or when lactate is converted back to glucose which can undergo aerobic respiration (see question 13). 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://serendip.brynmawr.edu/sci_edu/waldron/#fermentation](http://serendip.brynmawr.edu/sci_edu/waldron/#fermentation)).

The figure on the next page of these Teacher Notes summarizes the multiple steps of aerobic respiration (also known as cellular respiration); obviously, many specific steps are omitted. Notice that O₂ does not interact directly with glucose, but rather combines with an electron and H+ at the end of the electron transport chain to form water. Notice also that aerobic respiration generates ~29 molecules of ATP for each glucose molecule; this number is less than previously believed (and still often erroneously stated in textbooks). Brief explanations are provided in:

• "Cellular Respiration and Photosynthesis – Important Concepts, common Misconceptions, and Learning Activities" (available at [http://serendip.brynmawr.edu/exchange/bioactivities/cellrespiration](http://serendip.brynmawr.edu/exchange/bioactivities/cellrespiration))
• "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](http://www.bambed.org)).

These recent findings are interesting as an example of how science progresses by a series of successively more accurate approximations to the truth.
Creatine phosphate (also called phosphocreatine) can be used to make ATP during muscle contraction (shown on page 2 of the Student Handout). After muscle contraction, ATP produced by cellular respiration is used to reverse these reactions and restore 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 the 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)

Question 6 provides the opportunity to emphasize the conservation of energy. Question 7 reinforces the important point that all types of energy transformation are inefficient and result in the production of heat.

The discussion of how the muscles get glucose on page 3 of the Student Handout provides the opportunity to reinforce the important point that interactions between body systems are important for accomplishing the activities of life.

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.

Depletion of glycogen within skeletal muscles is associated with fatigue, so it is important to reduce the rate of utilization of muscle glycogen by having external sources of glucose for aerobic respiration in the muscle cells. In this connection, you may be interested in the evidence that carbohydrate ingestion before and during endurance events lasting 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"; http://serendip.brynmawr.edu/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.

Fat molecules are broken down to fatty acids (and glycerol) which muscle cells can use for aerobic respiration. Aerobic respiration of fatty acids is especially important for longer duration, low intensity or moderately vigorous physical activity. For high-intensity physical activity, the supply of O$_2$ to the muscle is limiting, so muscle cells reduce aerobic respiration of fatty acids which requires more O$_2$ per ATP molecule produced than aerobic respiration of glucose. Fatty acids cannot be used for anaerobic fermentation; they are converted to Acetyl CoA and enter the citric acid cycle in the mitochondria (after glycolysis). It appears that neither amino acids nor nucleic acids are a significant input for aerobic respiration in well-nourished individuals.

You may want to relate aerobic respiration of fatty acids to the contribution of aerobic exercise to weight loss (or prevention of weight gain; see "Food, Energy and Body Weight"; http://serendip.brynmawr.edu/exchange/bioactivities/foodenergy). During weight loss, it appears that resistance exercise can help to ensure that lean body mass (including muscles) is maintained while adipose tissue mass is reduced; this is desirable for both health and athletic competition.
Training effects of regular aerobic exercise contribute to increased capacity for aerobic respiration in muscle cells. Increased capacity for aerobic respiration improves athletic performance, especially in sports that rely primarily on aerobic respiration (e.g. longer running, swimming, or bicycling races). Increased capacity for aerobic respiration reduces the need for anaerobic fermentation; this conserves glycogen stores and prevents the production of lactic acid, thus delaying fatigue and increasing endurance. Other effects of regular aerobic exercise include increased blood volume, stroke volume and maximum breathing capacity, and stronger bones. 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 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).

Creatine phosphate, anaerobic fermentation and aerobic respiration all contribute to ATP production during any physical activity, but the relative contributions vary substantially over time and between different types of physical activity. For high-intensity brief 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 respiration. However, both the hydrolysis of creatine phosphate and anaerobic fermentation are limited to relatively short time periods, and aerobic respiration is the primary energy source after a minute or two.

Many sports involve intermittent high-intensity activity which depends on creatine phosphate and anaerobic fermentation for rapid supply of ATP. During the intervals between these bursts of high-intensity activity, aerobic respiration produces ATP which can be used to restore the supply of creatine phosphate. Lactate produced by alcoholic fermentation is mainly secreted into the blood and carried to the liver (where it is converted back to pyruvate or glucose) and the heart (where it is used in aerobic respiration). These rapid recovery processes are somewhat similar to the more long-term recovery processes after a marathon, as discussed in question 13.
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, other online sources, and physiology textbooks. If your students are unfamiliar with how to evaluate the reliability of various sources, this important skill can be introduced with resources available at [http://www.library.georgetown.edu/tutorials/research-guides/evaluating-internet-content](http://www.library.georgetown.edu/tutorials/research-guides/evaluating-internet-content) and [http://www.virtualsalt.com/evalu8it.htm](http://www.virtualsalt.com/evalu8it.htm).

Related Learning Activities
- "Alcoholic Fermentation in Yeast – A Bioengineering Design Challenge" ([http://serendip.brynmawr.edu/sci_edu/waldron/#fermentation](http://serendip.brynmawr.edu/sci_edu/waldron/#fermentation))