

Muscle Metabolism

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Page 1. Introduction

- Skeletal muscle must continuously make ATP to provide the energy for muscle contraction.

Page 2. Goals

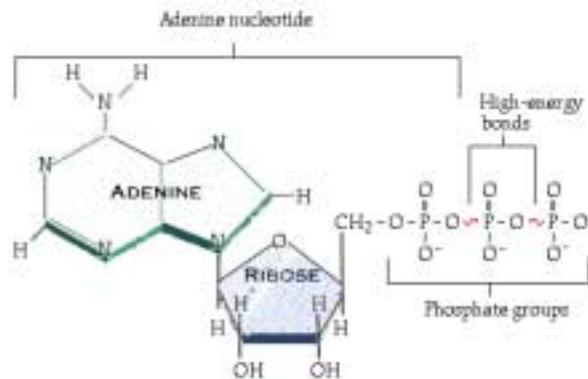
- To understand the cellular processes for synthesis of ATP.
- To compare and contrast aerobic and anaerobic processes in the muscle cell.
- To examine the differences in ATP synthesis among different types of muscle cells.

Page 3. Role of ATP

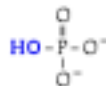
- Important roles of ATP in muscle contraction:
 1. ATP binds to myosin heads and upon hydrolysis into ADP and Pi, transfers its energy to the cross bridge, energizing it.
 2. ATP is responsible for disconnecting the myosin cross bridge at the conclusion of a power stroke.
 3. ATP provides the energy for the calcium ion pump which actively transports calcium ions back into the sarcoplasmic reticulum.

Page 4. Structure of Adenosine Triphosphate (ATP)

- Structure of ATP:



Note: ATP has three phosphate groups. The structure of a phosphate group (Pi) is:



- The bond between the last two phosphate groups is high energy and therefore blinking yellow.

Page 5. Hydrolysis of ATP

- This animation shows the hydrolysis of ATP.
- Summary of the hydrolysis of ATP:



- The hydrolytic enzyme binds the ATP and catalyzes the reaction. Two examples of hydrolytic enzymes within the muscle are:

- The myosin head functions as a hydrolytic enzyme when it hydrolyzes ATP into ADP and Pi. The energy released is used to prop the myosin cross bridge up into its high energy position.

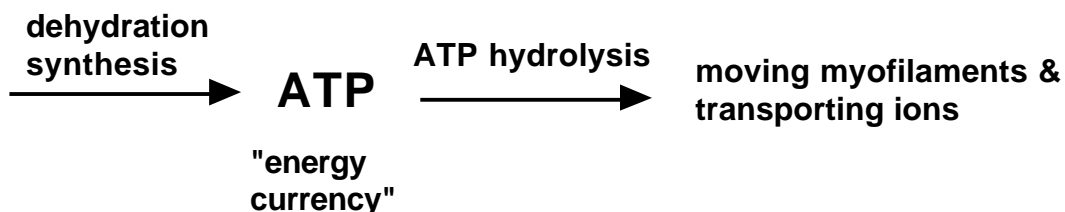
- The calcium ion pump which actively transports calcium ions back into the sarcoplasmic reticulum will act as a hydrolytic enzyme when it hydrolyzes ATP into ADP and Pi. The energy released is used to change the shape of the pump allowing the calcium ions to go back into the SR.
- During the reaction, the water (shown in blue) breaks the high energy bond between the last two phosphate groups. The water splits apart and the OH from the water ends up on the inorganic phosphate (sometimes abbreviated Pi) and the other H from the water goes onto the phosphate group which remains attached to the ADP.
- ADP is called adenosine diphosphate because only two phosphate groups remain on it.
- The energy contained in the bond between the last two phosphates on ATP has been released and is shown here as a glowing "E". There is still one additional high energy bond left in the ADP. (That high energy bond will not be important in this module.)
- The energy released from the ATP hydrolysis will be used to
 - Disconnect the myosin cross bridge from the binding site on actin at the conclusion of a power stroke.
 - Energize the power stroke of the myosin cross bridge.
 - Energize the calcium ion pump which actively transports calcium ions back into the sarcoplasmic reticulum.

Page 6. Dehydration Synthesis of ATP

- This animation shows the dehydration synthesis of ATP. It is called "dehydration synthesis" because water is removed (dehydration) and a bigger molecule is synthesized from two smaller ones. Some textbooks call this process "condensation" because a water molecule is released.
- Summary of the dehydration synthesis of ATP:

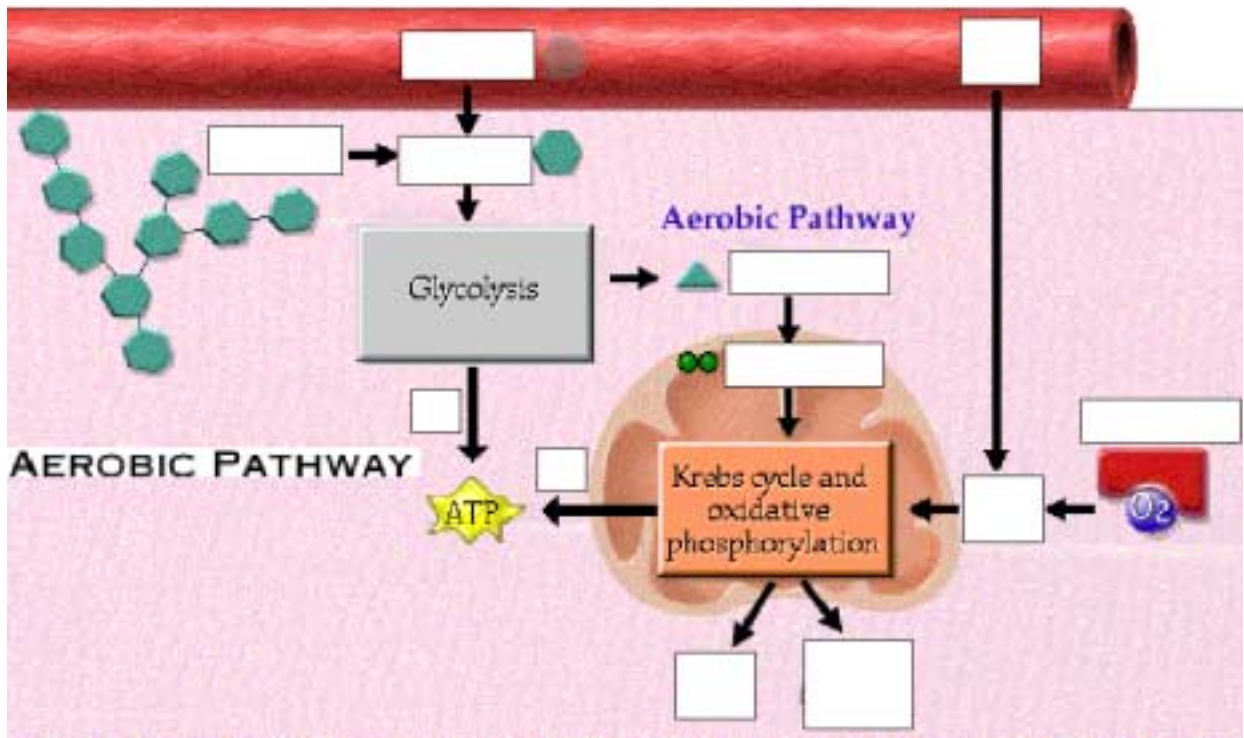
$$\text{ADP} + \text{Pi} + \text{energy} \longrightarrow \text{ATP} + \text{H}_2\text{O}$$
- The synthetic enzyme binds the ADP and catalyzes the reaction. During the reaction, water (shown attached to the ADP and phosphate groups in blue) splits off and the inorganic phosphate (Pi) attaches to the ADP to form ATP.
- This process requires energy since a high energy bond is formed. The energy is shown here as a glowing yellow ball which appears. One of the main functions of this section is to examine where that energy comes from.

Page 7. ATP as "Energy Currency"



Page 8. Overview of "Energy Currency"

- Muscle cells synthesize ATP these three ways:
 1. Hydrolysis of creatine phosphate
 2. Glycolysis
 3. The Krebs cycle & oxidative phosphorylation



Page 15. Summary of ATP Production

- This animation summarizes the three processes for producing ATP:
 - Creatine phosphate pathway
 - Glycolysis/anaerobic pathway
 - Aerobic pathway
- It also reminds us that ATP is needed by the muscle cell for the power stroke of the myosin cross bridge, for disconnecting the cross bridge from the binding site on actin, and for transporting calcium ions back into the SR.

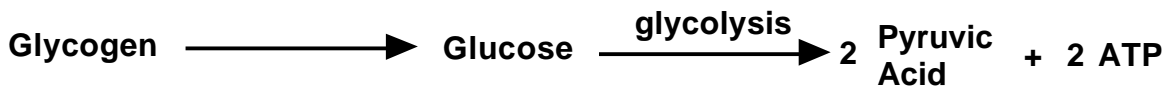
Page 16. Creatine Phosphate "Factory"

- This animation dramatically illustrates this process:



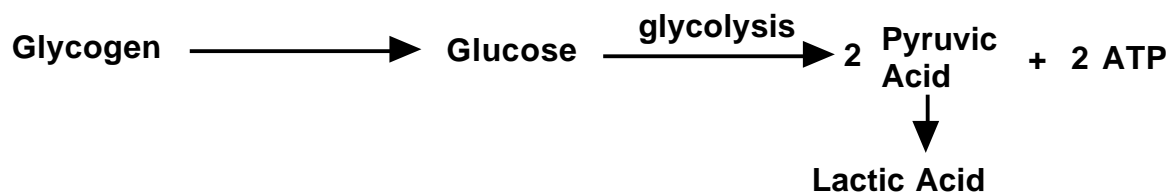
Page 17. Glycolysis "Factory"

- This animation dramatically illustrates the process of glycolysis from glycogen:



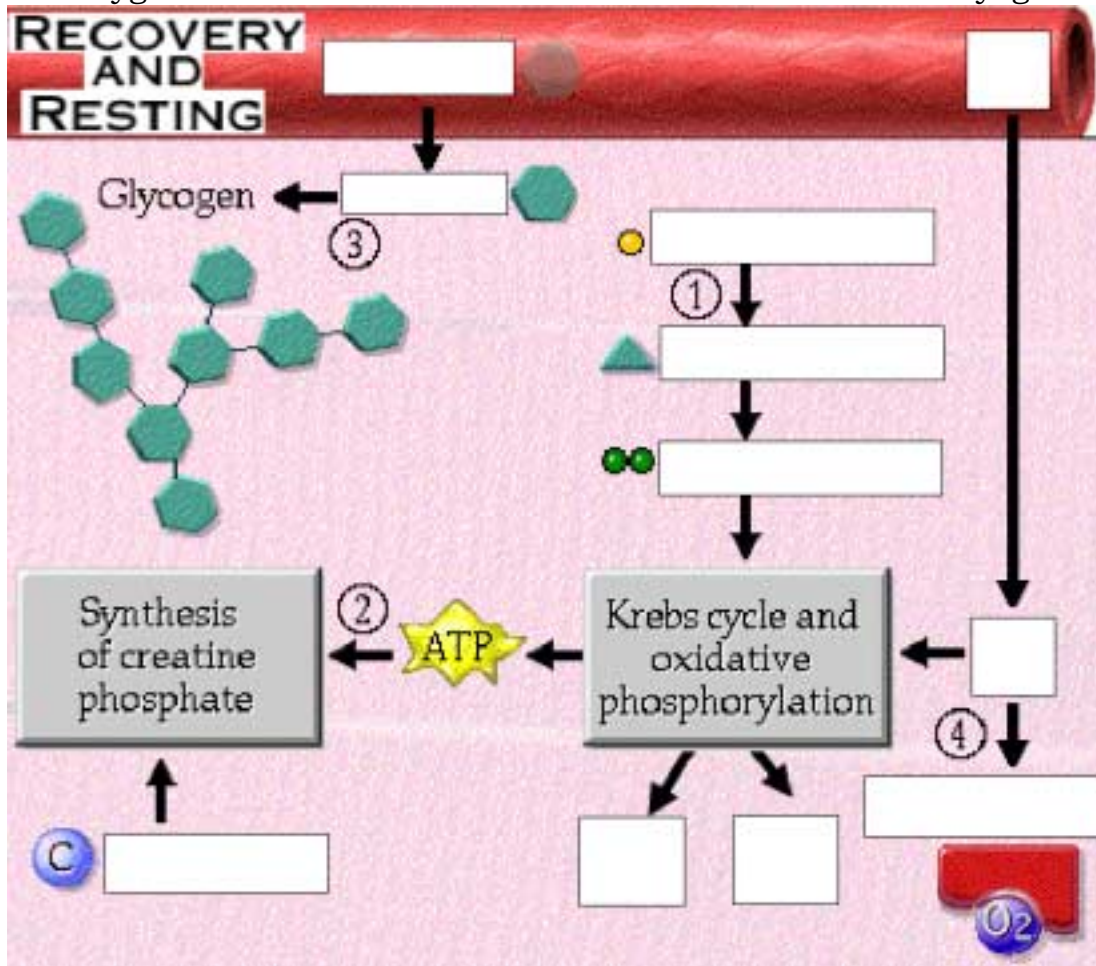
Page 18. Anaerobic Pathway "Factory"

- This animation dramatically illustrates lactic acid formation:



- Notice how some of the lactic acid stays in the muscle, and some goes back out

Oxygen enters the cell from the blood and reattaches to myoglobin (4).



Page 24. Metabolic Variations of Muscle Fiber Types

- There are two types of muscle cells within a given muscle, white muscle fibers and red muscle fibers, which differ in size, coloration and metabolism.

Page 25. Features of White Muscle Fibers

- Characteristics of white muscle fibers:
 - Large in diameter
 - Light in color due to reduced or absent myoglobin
 - Surrounded by only a few capillaries
 - Have relatively few mitochondria
 - Have a high glycogen content
 - Synthesize ATP mainly by glycolysis

Page 26. Metabolism in White Muscle Fibers

- Metabolic characteristics of white muscle fibers:
 - Use glycolysis, which synthesizes ATP quickly, resulting in fast contractions.
 - Allow for power contractions due to large numbers of myofilaments because they have a large diameter.
 - They fatigue rapidly due to build-up of lactic acid and depletion of glycogen.
 - They are well suited for activities requiring power and speed for a short duration.
- White muscle fibers are also called "fast-twitch glycolytic fibers."

Page 27. Features of Red Muscle Fibers

- Characteristics of red muscle fibers:
 - Half the diameter of white muscle fibers
 - Dark red in color due to a large quantity of myoglobin
 - Surrounded by many capillaries
 - Have many mitochondria
 - Have a low glycogen content
 - Synthesize ATP mainly by the Krebs cycle and oxidative phosphorylation

Page 28. Metabolism in Red Muscle Fibers

- Metabolic characteristics of red muscle fibers:
 - Use Krebs cycle and oxidative phosphorylation, which synthesizes ATP relatively slowly compared to glycolysis, resulting in prolonged contractions.
 - They are fatigue resistant.
 - They are well suited for activities requiring endurance and continuous contraction.
- Red muscle fibers are also called "slow-twitch oxidative fibers".

Page 29. Comparison of Muscles

- Individuals that engage in fast, intense, sporadic activities, such as sprinting, tend to have more white, fast twitch, fatigue-prone fibers. Individuals that engage in slower, longer muscular activities, such as jogging, have more red, slow twitch, fatigue resistant fibers.

Page 30. Summary

- ATP must be synthesized in muscle cells to replace ATP used for muscle contraction.
- ATP is synthesized by hydrolysis of creatine phosphate, glycolysis, and the Krebs cycle and oxidative phosphorylation.
- White muscle fibers mainly use glycolysis for synthesizing ATP; these fibers are quick and powerful, but fatigue rapidly.
- Red muscle fibers mainly use the Krebs cycle and oxidative phosphorylation for synthesizing ATP; these fibers are fatigue resistant and have a high endurance.

** Now is a good time to go to quiz questions 5 and 6:

- Click the Quiz button on the left side of the screen.
- Click on the scrolling page list at the top of the screen and choose "5. Muscle Metabolism Mania".
- Work through quiz questions 5-6.

Notes on Quiz Questions:

Quiz Question #1: Sequence of Metabolic Pathway

- This question allows you to predict the sequence of steps in the aerobic synthesis of ATP, starting with glycogen.
- Lactic acid is not used since this is an aerobic pathway.

Quiz Question #2: Anaerobic Process

- This question asks you to predict what part of the sequence in question 1 is anaerobic.

Quiz Question #3: Aerobic Process

- This questions asks you to predict what part of the sequence in question 1 is aerobic.

Quiz Question #4: Storehouse of Glucose

- This question asks you to predict what part of the sequence in question 1 stores glucose in muscle cells.

Quiz Question #5: Muscle Metabolism Mania

- This question allows you to chose the energy sources, oxygen requirements, ATP production, end products, and muscle fiber types for each of the three important metabolic pathways in muscle cells.
- Please note, there may be a typographical error in three of the answer boxes if you are playing alone. Under energy source for hydrolysis of creatine phosphate, glycolysis, and Krebs cycle and oxidative phosphorylation, the answers choices should read: Glucose, creatine phosphate, oxygen, and acetyl CoA, unless you get a "Metabolic Multiplier", in which case the answer choices will be fine.

Quiz Question #6. White and Red Muscle Fiber Puzzles

- In this question you decide which points are characteristics of white muscle and which are characteristic of red muscle.

Study Questions on Muscle Metabolism:

1. (Page 1.) Why is it necessary for muscle to have mechanisms to make ATP quickly?
2. (Page 3.) Which of these is not an important role of ATP in skeletal muscle contraction?
 - a. Disconnecting the myosin cross bridge from the binding site on actin at the conclusion of a power stroke.
 - b. Exposure of the myosin binding sites on actin.
 - c. Energizing the power stroke of the myosin cross bridge.
 - d. Energizing the calcium ion pump which actively transports calcium ions back into the sarcoplasmic reticulum.
3. (Page 4.) Which of these is not a part of the ATP molecule?
 - a. adenine nucleotide
 - b. phosphate groups
 - c. ammonia
 - d. high energy phosphate bonds
4. (Page 5.) Fill in the blanks in the following equation for the hydrolysis of ATP.
 ATP + _____ → _____ + _____ + _____
5. (Page 5.) Why is the reaction that releases energy from ATP termed a "hydrolysis" reaction?
6. (Page 5.) Give a specific example of a hydrolytic enzyme that hydrolyzes ATP into ADP and Pi in muscle cells.

7. (Page 6.) Fill in the blanks in the following equation for the dehydration synthesis of ATP.



8. (Page 6.) Why is the production of ATP from ADP termed a "dehydration synthesis" reaction?

9. (Page 7.) Why is ATP often called "energy currency"?

10. (Page 7.) Muscle cells have only enough ATP to last for _____ during an active contraction period.

11. (Page 8.) List three processes that muscle cells use to make ATP when it is needed for muscle contraction.

12. (Page 9.) What is the most immediate source of energy for rebuilding ATP within muscle cells?

13. (Page 9.) Fill in the following blanks to show the production of ATP from Creatine phosphate:



14. (Page 10.) What are the two sources of glucose to muscle cells?

15. (Page 11.) What are the end products of glycolysis?

16. (Page 12.) What happens to pyruvic acid in the absence of oxygen?

17. (Page 12.) What happens if a muscle is deprived of oxygen for too long when it is physically active?

18. (Page 13.) What is the name of the oxygen binding protein within muscle?

19. (Page 14.) Where, within a muscle cell, will the Krebs cycle and oxidative phosphorylation occur?

20. (Page 14.) What are the end products of the aerobic pathway?

21. (Page 14.) The total energy harvest from glycolysis, the Krebs cycle and oxidative phosphorylation is 38 ATP molecules for each glucose molecule metabolized.

a. How much of that ATP is generated during glycolysis?

b. How much of that ATP is generated during the Krebs cycle and oxidative phosphorylation?

22. (Page 22.) During which of these activities would creatine phosphate and anaerobic metabolism be more important. During which of these activities would aerobic respiration (Krebs cycle and oxidative phosphorylation) be more important. Why?

a. very fast sprinting for a short distance

b. slow jogging for a long distance

23. (Page 23.) After the exercise period is concluded, what reserves have been depleted within the muscle cells? In addition, what by-product tends to build-up in the muscle cell?
24. (Page 23.) To restore the _____ after exercise, muscle cells convert _____, present in the cytosol, back into pyruvic acid, which enters the Krebs cycle, producing _____, which is used to re-phosphorylate creatine into creatine phosphate. Glycogen is also synthesized from _____ and additional oxygen re-binds to _____.
25. (Page 24.) What are the names of the two different types of muscle cells?
26. (Page 25.) List several structural features that white muscle cells have that explains why these muscle fibers mainly use glycolysis to synthesize ATP (as opposed to the Krebs cycle and oxidative phosphorylation).
27. (Page 26.) Why are white muscle fibers also called "fast-twitch glycolytic fibers?"
28. (Page 27.) List several structural features that red muscle cells have that explains why these muscle fibers mainly use Krebs cycle and oxidative phosphorylation to synthesize ATP (as opposed to anaerobic metabolism).
29. (Page 28.) Why are red muscle fibers also called "slow-twitch oxidative fibers?"