Chapter 11.5

Muscle Energy and Metabolism

How ATP is created throughout a race?


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The level of activity (how fast the muscle fiber uses glucose and oxygen) determines the physiologic state of the muscle fibers. To support a high level of muscle contractions, you need to increase the blood supply (delivery of glucose and oxygen) to the muscle fiber.

As you move from a resting state to an active state, there is a “ramping-up process” as the cardiovascular and respiratory systems increases their functions to meet the demands of the now more active muscle organ. This will take several seconds and depends upon the fitness of the individual.

Therefore, the muscle fiber must have a mechanism to “bridge” the muscle's energy requirement from a resting state to an active state.

A dynamic transition occurs between the resting to walking to running states.

Muscle “Energy” Metabolism

- The ATP needed for skeletal muscle contraction is proportional to the level of skeletal muscle activity. ATP must be made “on demand” to power muscle contraction.

- A resting skeletal muscle cells keeps some oxygen inside cell attached to myoglobin. This molecule holds “in reserve” a small amount of oxygen in the sarcoplasm.

- The resting skeletal muscle fiber also has creatine phosphate which maybe used to re-phosphorylate ADP to ATP. Any excess ATP will be used to phosphorylate ADP if it is available.

- When at rest, the muscle fiber makes ATP by glycolysis and Kreb'sCycle/Electron Transport. Cardiovascular and respiratory system's delivers enough nutrients (glucose and oxygen) to support the muscle activity when at resting state.

- If you start to run from a resting state, then there is not enough glucose and oxygen being delivered to support the higher level of muscle contraction. Time is required for the cardiovascular and respiratory systems to to increase their functions to supply enough nutrients to support the increase in muscle activity.

- Muscle fibers now must use creatine phosphate and myogobin's oxygen to support ATP production. The reserve of myoglobin and creatitine phosphate will be exhausted within the first few seconds of the race. Now the muscle fiber continues to make ATP using aerobic fermentation with the buildup of lactic acid. A shift back to aerobic respiration occurs after cardiopulmonary systems is able to deliver adequate glucose and oxygen.

How do we use ATP in skeletal muscle?

- We need ATP to preload myosin heads with energy // cock the myosin head
- After a contraction cycle we will need more ATP to break the myosin-actin cross bridges
- When the muscle relaxes more ATP is required to pump calcium back into the sarcoplasmic reticulum
- ATP is constantly being consumed and produced during a muscle contracton.
- ATP is not stored.
- ATP in sarcoplasma last about one second. ATP is immediately consumed or its energy is transferred to another molecule. (creatine phosphate)

Muscle “Energy” Metabolism

- *Ability to make small amount of ATP using glycolsis depends on availability of a reduced organic molecule (e.g. glucose)*

- *Ability to make large amounts of ATP depends on availability of a reduced organic molecule (e.g. pyruvic acid from splitting glucose and/or acetyl groups produced by beta-oxidation of fatty acids) plus the presence of oxygen.*

  – Glycolysis vs Kreb's Cycle + Electron Transport System (note: Kreb's Cycle also called the citric acid cycle)

    - Glcolysis enzymes are in cytosol // anaerobic // produce 2ATP plus pyruvate if oxygen is available or lactic acid if no oxygen is available.

    - KC-ETS enzymes are inside mitochondria // areobic // produces 38 ATP, metabolic water, carbon dioxide

Muscle Metabolism

- Two main pathways for ATP synthesis
  - First metabolic pathway = anaerobic fermentation (glycolysis)
    - enables cells to produce ATP in the absence of oxygen / takes place in cytoplasm
    - yields little ATP // but immediately available
    - by product is toxic lactic acid /// believed to be factor in muscle fatigue

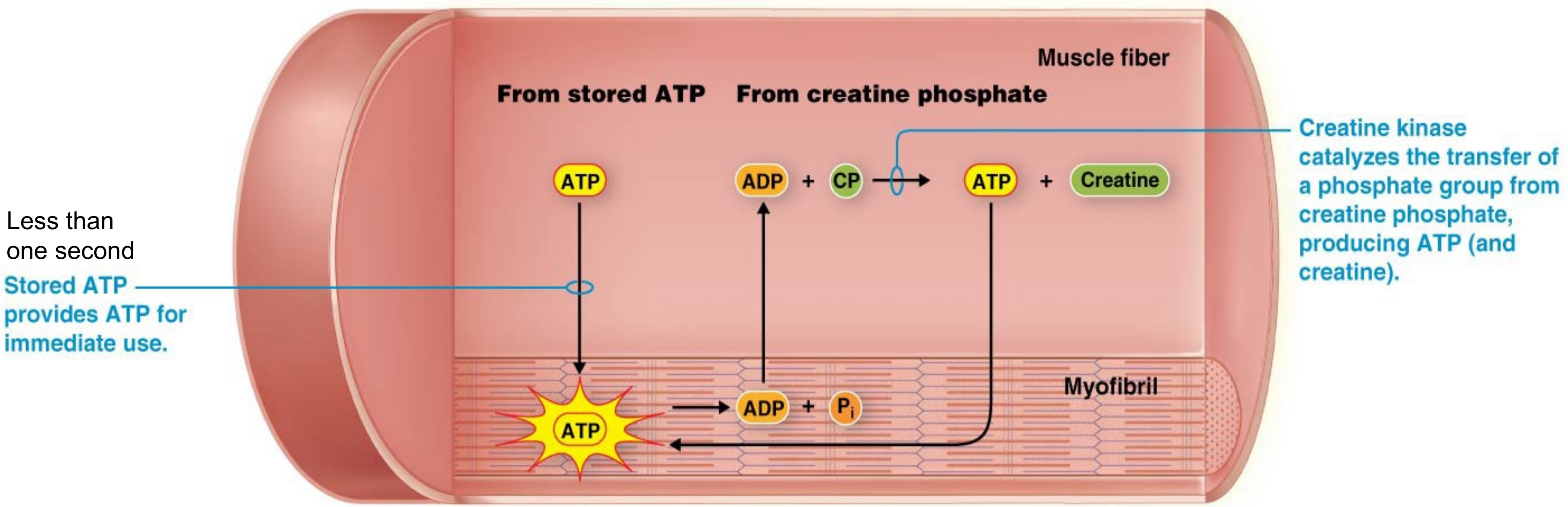
Muscle Metabolism

- Second metabolic pathway: aerobic respiration (Krebs Cycle also called Citrus Acid Cycle with ETS)

  - takes place in the mitochondria
  - requires oxygen
  - produces much more ATP // glycolysis = 2 vs Kreb's Cycle = 36 to 38
  - toxic end product = CO_2
  - produces H+ (acid) but use oxygen to make water with H+ (called metabolic water)
  - Kreb's cycle reduces FAD and NAD / these reduced co-enzymes are then oxidized via electron transport system
  - Reduced co-enzymes transfer protons and electrons to ETS which produces most of the ATP using ATP Synthetase /// two ADP are directly phosphorlated within mitochondria during each "Krebs Cycle

Sources of energy for muscle fibers.

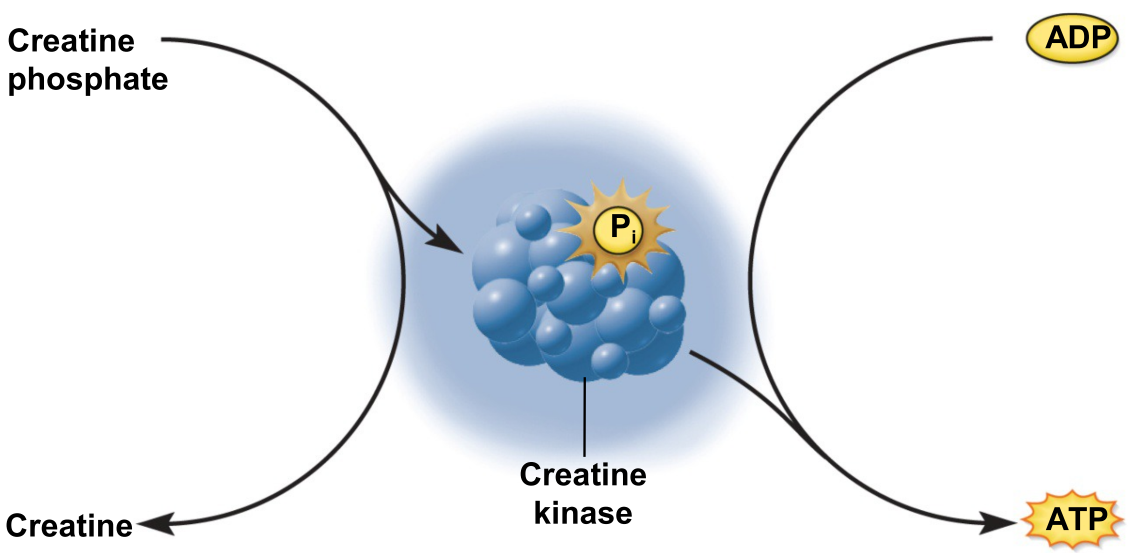
Less than
one second

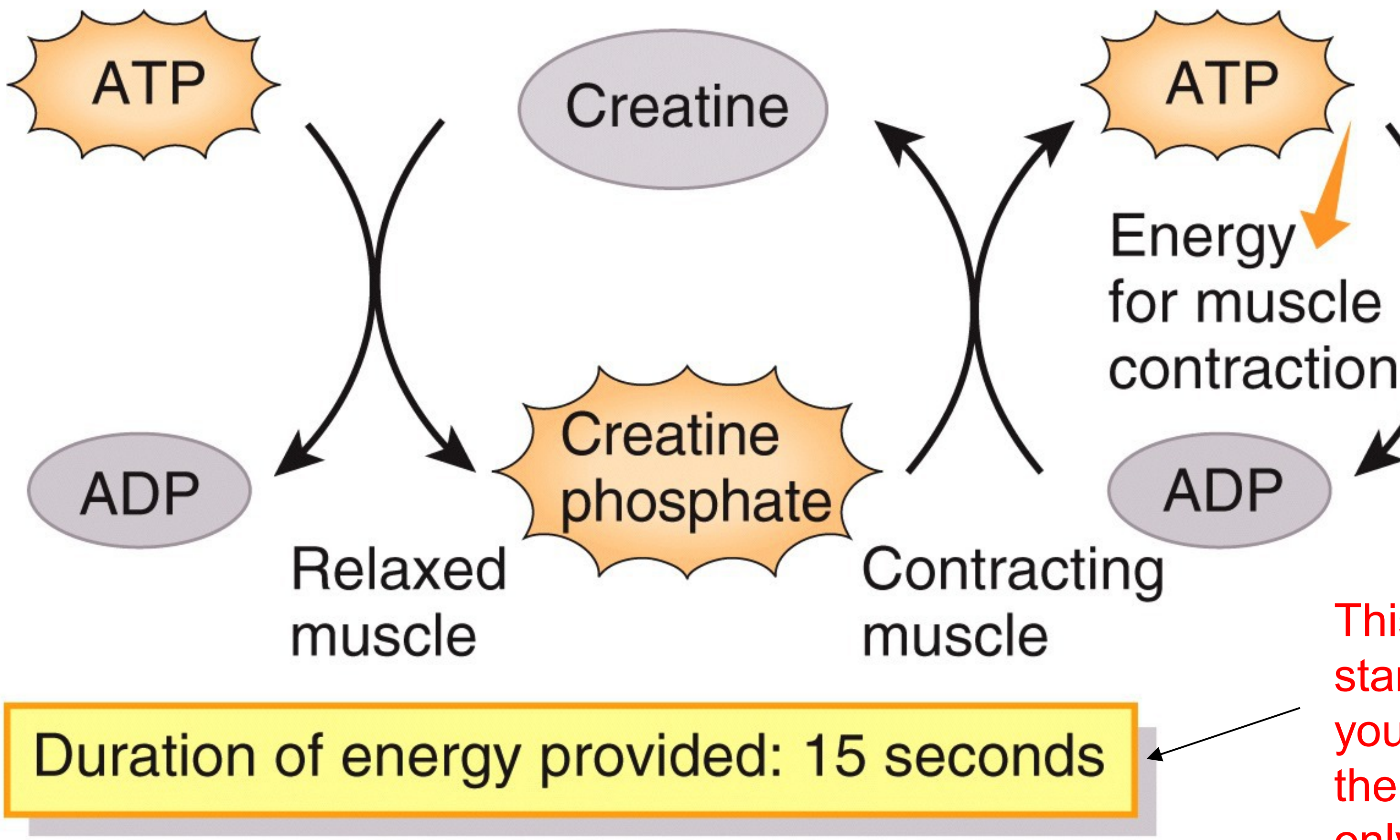


(a) Immediate energy sources

ATP is always being made within cytosol but when you start to exercise this small amount of ATP is consumed within a second. ADP can be “re-energized” by borrowing a phosphate from creatine phosphate (i.e. like getting a jump start to a battery). /// When the muscle fiber has an excess ATP, it may use it to energize creatine and at a later time use creatine phosphate to energize ADP!

Immediate Energy Needs



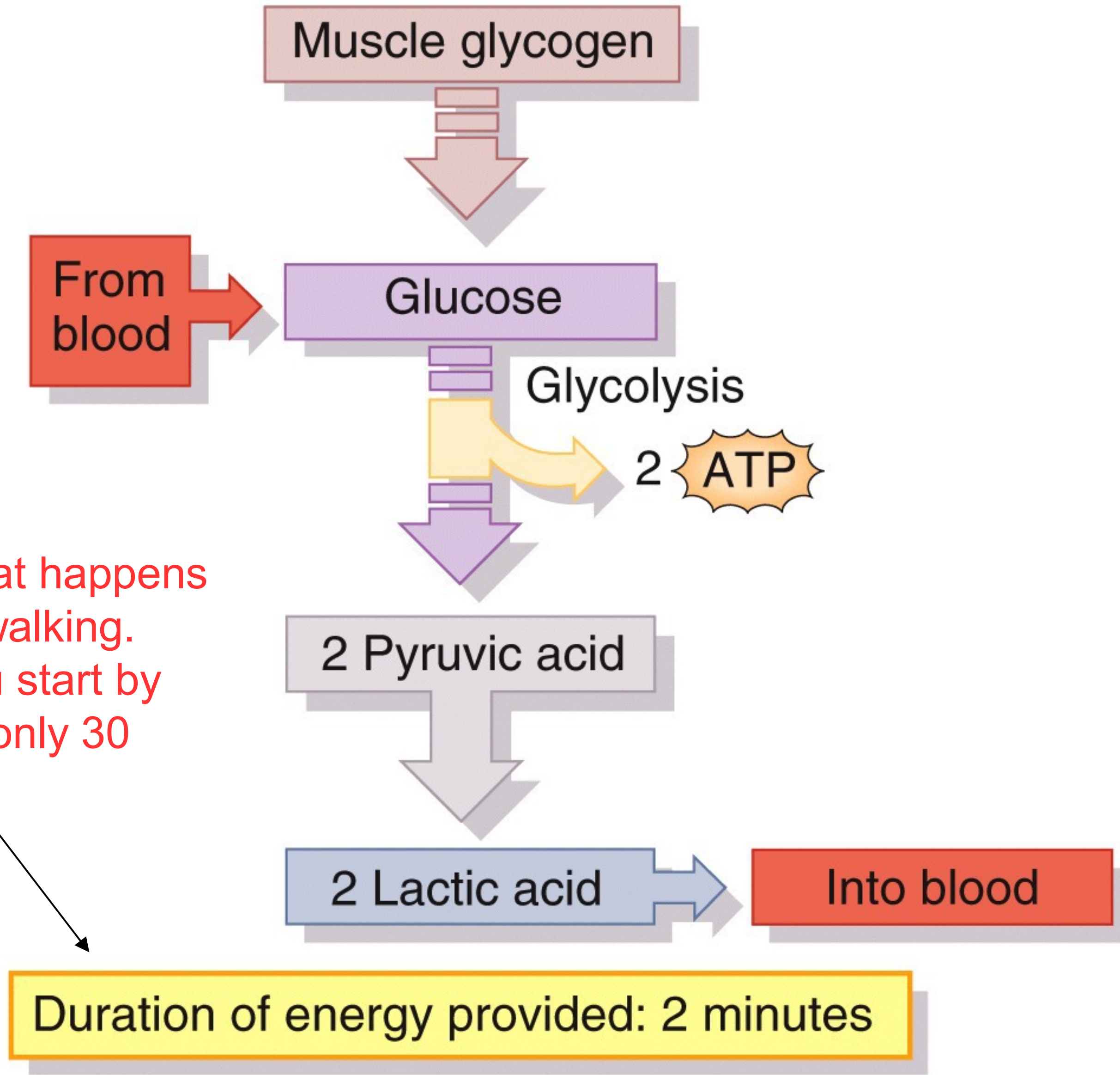


(a) ATP from creatine phosphate

This applies when you start to walk. But if you start by "running" then CP-ATP may last only 2 to 3 seconds

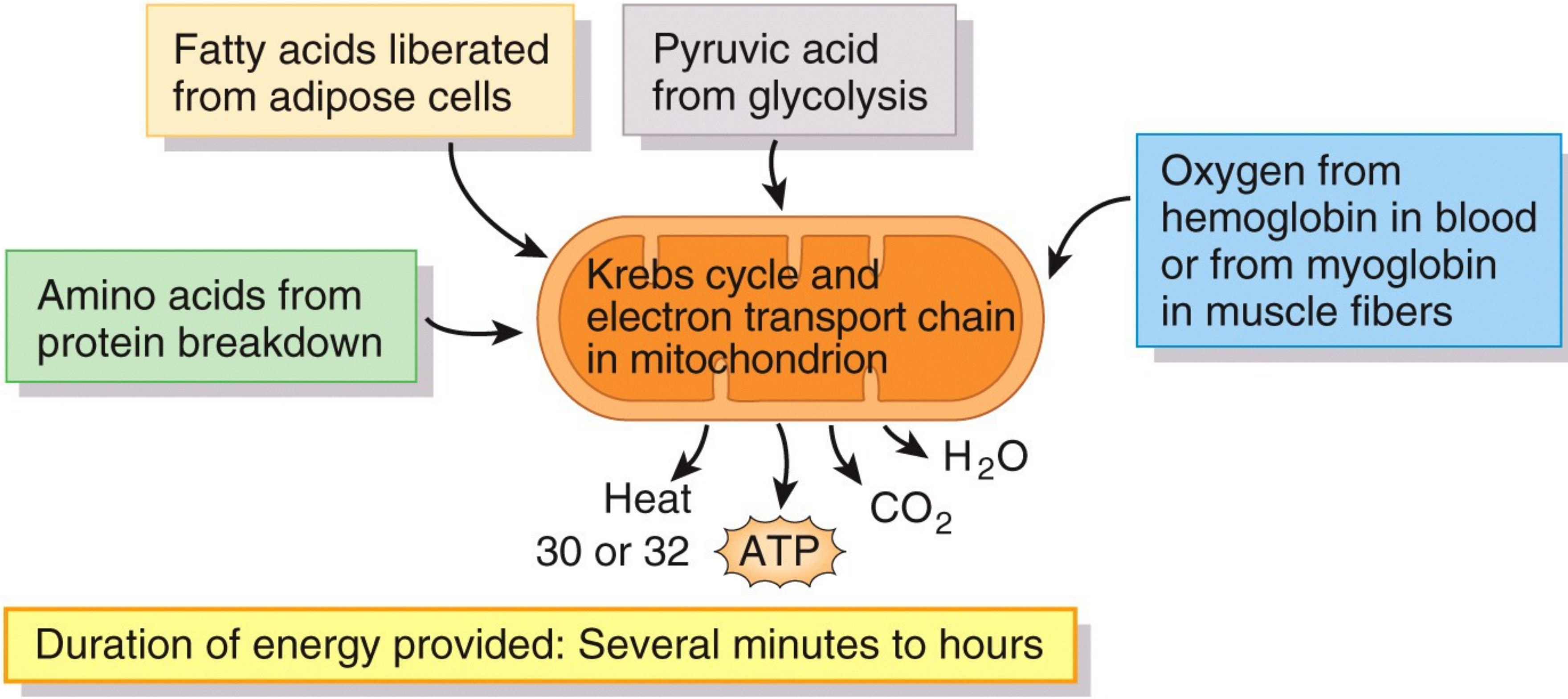
Myoglobin is a muscle fiber cytoplasmic protein. // Like hemoglobin, myoglobin binds and stores oxygen and may release oxygen so mitochondria can use this myoglobin's oxygen to produce limited amount of ATP. This is only enough to support Krebs Cycle for one second. Now the creatine phosphate (phosphogen system) may supplement ATP production after myoglobin is depleted of oxygen .

This shows what happens when you are walking. However, if you start by “running” then only 30 seconds +/-



(b) ATP from anaerobic glycolysis

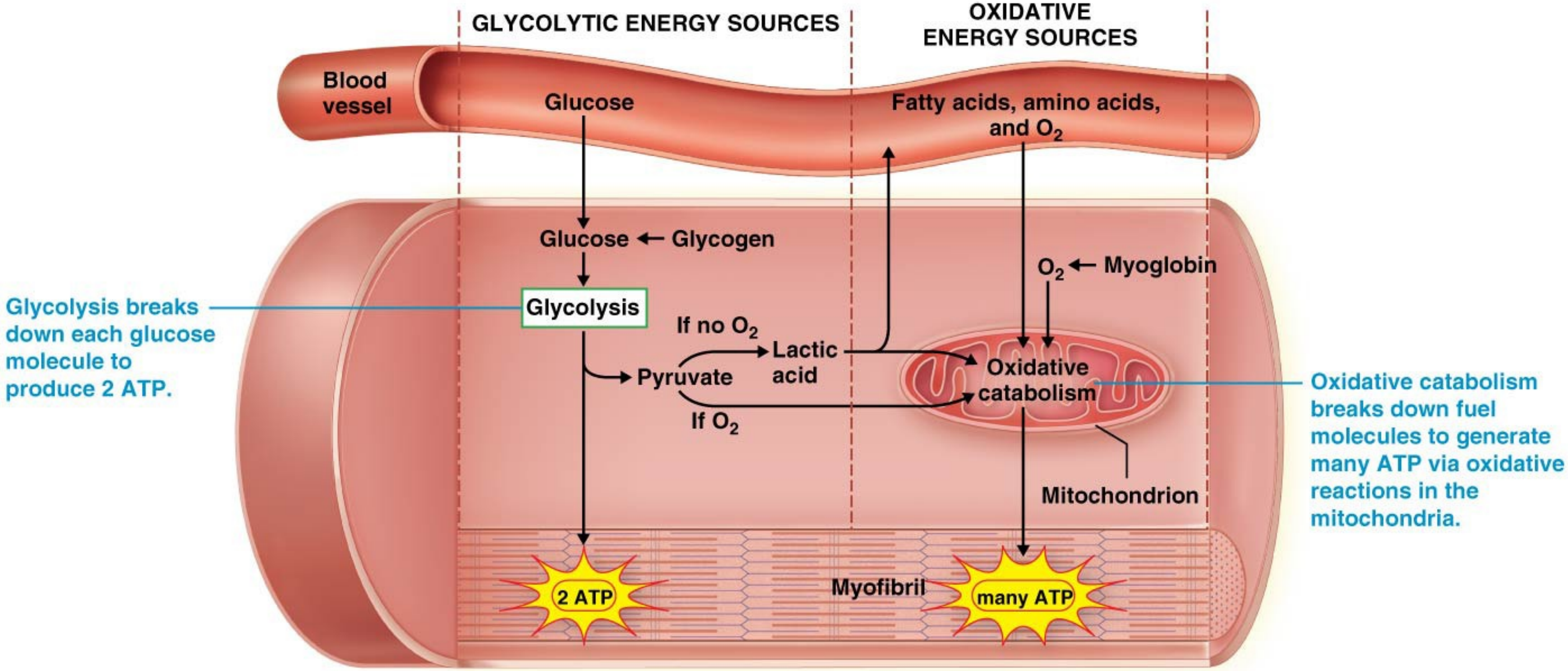
Different types of reduced molecles are modified so they may enter the Kreb's cycle at different entry points.   This allows for alternative fuel sources when glucose is not available.



(c) ATP from aerobic respiration

Note: How is skeletal muscle ATP managed if you want to run a long race? The next slides will outline the steps.

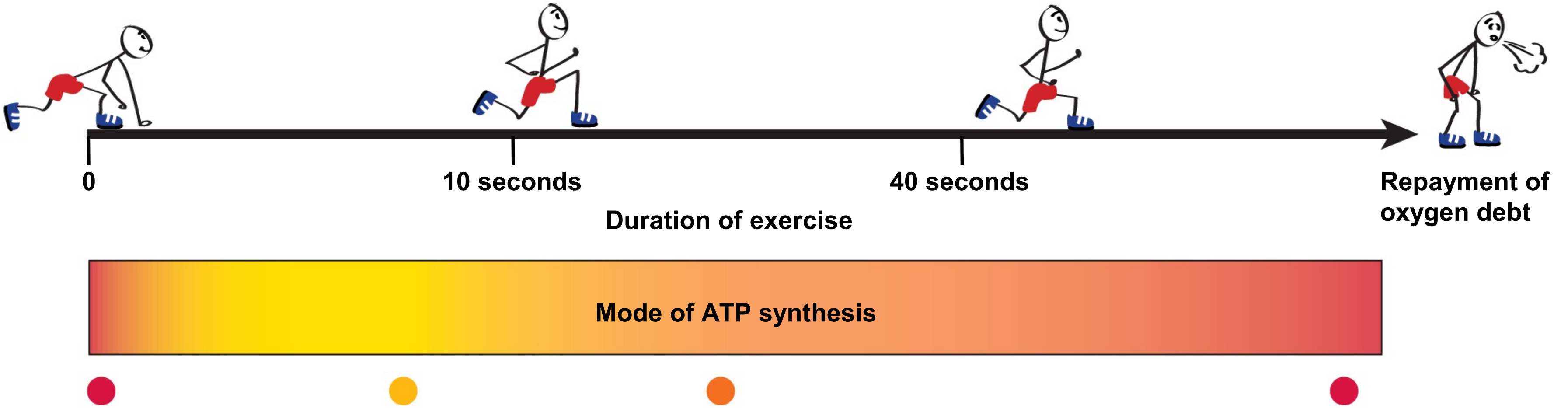
Sources of energy for muscle fibers.



(b) Glycolytic and oxidative energy sources

Muscle fibers store a small amount of oxygen bound to myoglobin. So at the start of exercise, oxidative catabolism starts but the stored oxygen is depleted in a second and more oxygen from lungs must be delivered. This process takes time. How is ATP produced during this “period”?

Modes of ATP Synthesis During Extreme Exercise



ATP in cytosol plus aerobic respiration using oxygen from Myoglobin 1 to 2 seconds

Phosphagen system another 6 to 8 seconds

Catabolize cytoplasmic Glycogen to lactic acid system // (anaerobic fermentation) 30 to 40 sec

Aerobic respiration Now possible due to cardiopulmonary function now able to supply necessary glucose and oxygen reached after 40 sec

After race post exercise oxygen consumption remains high so the ATP "borrowed" at the start of race may now be replaced.

At rest we oxidize fatty acids to supply energy for our skeletal muscles (note: our brains continue to oxidize glucose / brain cells and RBCs only ferment glucose)

As level of activity increases, skeletal muscles will shift from fat to glucose as an energy source.

Only after glucose reserves are exhausted will we shift back to fat metabolism

What is Oxygen Debt?

- Why does heavy breathing continues after strenuous exercise?
  - excess post-exercise oxygen consumption (EPOC) – the difference between the resting rate of oxygen consumption and the elevated rate following exercise.
  - typically about 11 liters extra is needed after strenuous exercise
  - oxygen debt occurs because we need to replace the ATP consumed to restore myoglobin and replenish CP

Oxygen Debt

- Oxygen need in excess of current muscle activity for the following reasons:
  - **replace oxygen to the myoglobin //** depleted in the first minute of exercise
    - oxygen bound to myoglobin and blood hemoglobin
    - oxygen dissolved in blood plasma and other extracellular fluid
    - oxygen in the air in the lungs
  - **replenishing the phosphagen system**
    - Synthesize extra ATP to replace phosphate “borrowed” from creatine-phosphate at the start of the race

Oxygen Debt

- Furthermore, additional oxygen needed for

- **Metabolize lactic acid**

    - 80% of lactic acid produced by muscles enter bloodstream
    - much of this lactic acid ends up in liver
    - converted back to pyruvic acid in the kidneys, cardiac muscle, and especially the liver
    - liver converts most of the pyruvic acid back to glucose to replenish the glycogen stored in the skeletal muscles or liver.
    - This requires ATP and explains continued demand for oxygen even after strenuous exercise stops!

  - **Serving the elevated metabolic rate**

    - occurs while the body temperature remains elevated by exercise and consumes more oxygen

Endurance

- Endurance – the ability to maintain high-intensity exercise for more than 4 to 5 minutes
  - determined in large part by one's maximum oxygen uptake (VO_2max)
  - maximum oxygen uptake – the point at which the rate of oxygen consumption reaches a plateau and does not increase further with an added workload
    - proportional to body size
    - peaks at around age 20
    - usually greater in males than females
    - <u>can be twice as great in trained endurance athletes as in untrained person</u>
    - May result in twice the ATP production

Muscle Fatigue

- Characterized by progressive weakness and loss of contractility from prolonged use of the muscles
  - To experience muscle fatigue try this:
    - repeated squeezing of rubber ball
    - rapidly opening and closing your hand as if making a fist (one minute)
    - holding text book out level to the floor

Fatigue

- Causes of muscle fatigue
  - ATP synthesis declines as glycogen is consumed
  - ATP shortage slows down the Na^+ - K^+ pumps
    - compromises their ability to maintain the resting membrane potential and excitability of the muscle fibers
  - Lactic acid lowers pH of sarcoplasm
    - inhibits enzymes involved in contraction, ATP synthesis, and other aspects of muscle function

Fatigue

- Causes of muscle fatigue (cont)
  - release of K^+ with each action potential causes the accumulation of extracellular K^+ /// hyperpolarizes the cell and makes the muscle fiber less excitable
  - motor nerve fibers use up their Ach /// less capable of stimulating muscle fibers – junctional fatigue
  - central nervous system, where all motor commands originate, fatigues by unknown processes, so there is less signal output to the skeletal muscles

Beating Muscle Fatigue

- Taking **oral creatine** increases level of creatine phosphate in muscle tissue and increases speed of ATP regeneration
  - useful in burst type exercises – weight-lifting
  - risks are not well known
    - muscle cramping, electrolyte imbalances, dehydration, water retention, stroke
    - kidney disease from overloading kidney with metabolite creatinine

Beating Muscle Fatigue

- carbohydrate loading – a form of dietary regimen
  - Loads maximum amount of glycogen into muscle cells
  - extra glycogen is hydrophilic and adds 2.7 g water/ g glycogen
    - athletes feel sense of heaviness outweighs benefits of extra available glycogen