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Muscle Metabolism: Aerobic vs. Anaerobic

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Four different types of muscle fibers will be discussed here. However, only the aerobic slow-twitch fiber and the anaerobic fast-twitch fiber are found in human skeletal muscle. For the purpose of gaining additional insight provided by comparative study, the cardiac muscle fiber and aerobic fast-twitch fiber will also be discussed.

Aerobic means with oxygen. In body metabolism, it also means with mitochondria. The mitochondrial structure acts as a substrate to bring reactants together and catalyze reactions. The structure also helps control and neutralize the radicals, which also occur in oxidative reactions. The mitochondria also produce enzymes, which further catalyze the reactions so that they will occur at body temperature.

Three of the four fibers are aerobic, with the mitochondria in each being different from the other two. The aerobic fast-twitch fiber is really no longer a muscle, but a bag full of mitochondria with a few contractile fibers remaining. The mitochondria in this fiber are one-third the size of those in the aerobic slow-twitch fiber. These smaller mitochondria can only oxidize the components of glucose, not fatty acids or ketones as the larger mitochondria can.

The mitochondria in the cardiac muscle fibers is three times the size of the aerobic slow-twitch fiber (nine times the aerobic fast-twitch fiber) and has the added capability of oxidizing lactic acid back into pyruvic acid and pyruvate back into glucose. The only other organ which contains the largest mitochondria is the liver. The smallest mitochondria appear bright red in color like the myoglobeen, which accompanies it; the intermediate mitochondria are brownish red, and the largest mitochondria are purplish. The presence of large numbers of the largest mitochondria give the heart and liver tissues their purplish color.

The anaerobic muscle fiber contains mitochondrial fragments that produce the enzymes needed to reduce glucose to pyruvate and pyruvate to lactate. In photomicrographs of stained aerobic and anaerobic cells abutted against each other and with a capillary in the corridor between them, the mitochondria of the aerobic fibers are seen bunched near the capillary like moths around a flame, while the anaerobic fiber shows no such activity.

Comparison of aerobic and anaerobic fibers might lead to calling the aerobic ectomorphic and the anaerobic endomorphic. This is because everything other than muscle fibers is concentrated along the periphery of the aerobic fiber, but spread in the interior of the anaerobic fiber.

The mitochondria are naturally at the periphery of the aerobic fiber but are spread in the interior of the anaerobic fiber. The mitochondria are naturally at the periphery, because the oxygen they need can only come from outside the cell. The fatty acid stores are then placed near the mitochondria, because that is where they will be metabolized. The myoglobin needs to be near the periphery and the mitochondria.

Myoglobin has the same red color as hemoglobin and results in these aerobic fibers being referred to as red muscle fibers. The anaerobic fibers have no need for myoglobin since they have no mitochondria and as such are referred to as pale muscle fiber.

Aerobic fibers use large adenosine molecules as energy transporters, with AMP moving out to the mitochondria to be recharged to ATP, then lumbering back to the interior to activate calcium ion release. The mitochondria of the aerobic fibers must also serve the oxidative needs of the anaerobic fibers, so it is busy oxidizing pyruvate as well as fatty acids. (This is why the mix of the two different fibers does not vary much beyond 50/50, even though anaerobic fibers are three to six times larger than aerobic fibers.)

The fat molecular produces almost eight times the energy of a pyruvate molecule, but the mitochondria can metabolize pyruvate nine times faster than fat. In the anaerobic fibers, the large adenosine molecules are locked into the matrix of the sarcoplasmic reticular cisterns next to the calcium ion mechanisms the ATP must activate. Likewise, the glycogeneral stores are located next to the adenosine, which the glycolysis must recharge.

The mitochondrial fragments, which produce the enzymes to catalyze reactions, are also located here. Energy transport is handled by small fast creatine molecules, which can readily pass through the membranes to reach the mitochondria in the aerobic fibers. Just as the mitochondria will selectively metabolize pyruvate ahead of fat, it will also phosphorylate creatine and glucose molecules ahead of AMP.

When a runner reaches a speed of about eight and a half miles per hour, the respiratory quotient rises to one, which indicates no fat metabolism is happening. Speeds above 8.5 mph are produced only by the anaerobic fast-twitch fibers, which can contract three times faster than slow-twitch fibers (25 milliseconds versus 75 milliseconds). The fast-twitch fibers can produce a speed in excess of 25 miles per hour, which is attained in the 100 and 200-meter dashes.

It should also be clear that lower animals that don’t have a 50/50 mix of aerobic slow-twitch and anaerobic fast-twitch fibers are in need of aerobic fast-twitch fibers (essentially bags of mitochondria) capable of oxidizing pyruvate from the anaerobic fibers.

The flight muscles of a bird are of necessity mostly all fast-twitch fibers. A photomicrograph shows that out of a sample of 30 fibers, 18 are anaerobic fast-twitch, with the anaerobic fibers being five to nine times larger than the aerobic fibers. If you have ever cut raw chicken or turkey breast, you will probably have noticed the tiny bright red dots located throughout the pale fibers.

The reverse situation exists in the cat soleus muscle, in that it is made up entirely of aerobic slow-twitch fibers. This allows the cat to move with incredibly smooth slow motion when in stealth mode. To provide the quick leap when pounce mode comes, the gastrocnemius is mostly fast-twitch fibers. A sample of 30 cat gastrocnemius fibers reveals seven aerobic slow-twitch fibers, 17 anaerobic fast-twitch fibers, and six aerobic fast-twitch fibers.

This heritage shows up in the human soleus being weighted slightly towards slow-twitch fibers and the human gastrocnemius being weighted slightly toward the fast-twitch, but still close to a 50/50 mix.

Glycolysis provides anaerobic energy by splitting glucose into pyruvate and hydrogen ions. These cannot be oxidized until they reach the mitochondria in the aerobic fibers. The concentration in the anaerobic fibers will rise until the hydrogen free radicals threaten to shut down the process, at which time enzymes trigger the combination of hydrogen with pyruvate to form lactate, which will level off at a concentration high enough to cause a gradient sufficient to drive the lactate into the bloodstream as fast as it is being produced.

This usually produces a 10:1 ratio in favor of lactate to pyruvate. Extremely fast activity can drive the lactate concentration high enough to shut down the process. The 10:1 ratio of lactate to pyruvate is a consequence of the slow clearing of venous blood from the fascicular arrangement of muscle fibers. The actual conversion ratio is one lactate molecule for each pyruvate molecule. The pyruvate travels across to the slow-twitch fiber to be oxidized to carbon dioxide and water. The carbon dioxide and water then become more concentrated, like the lactate waiting to be cleared from the cell.

Venous waste pickup is as important as arterial supply for muscle operation. If the venous drainage is choked down by hypertonic muscles undermining the rhythmic pumping, the arterial blood flow will divert through the shunts so that both supply and pickup will be compromised. The energy contained in the lactate is temporarily lost to the muscle cells when it is dumped into the bloodstream, but upon reaching the liver, four-fifths of the lactate is reconverted back to glucose and returned to the muscles.

When glucose enters the muscle cell, it is phosphorylated by the mitochondrial energy so that the glucose phosphate supplements the creatine phosphate in carrying anaerobic phosphate energy within the cell.

After a period of maximum exercise has depleted the oxygen and anaerobic energy stores of the muscles, only three minutes and two and a half liters of oxygen are required to recharge the creatine to creatine phosphate and AMP to ATP, and to reload the myoglobin with oxygen. However, it takes one hour and eight liters of oxygen for the liver to clear the accumulated lactate.

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