Mini-symposium

Bioenergetic provision of energy for muscular activity

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SUMMARY

A complex series of metabolic pathways are present in human muscle that break down substrates from nutritional sources to produce energy for different types of muscular activity. However, depending on the activity in which an individual is engaged, the body will make use of different energy systems that have been adapted for the particular activity. More specifically, utilization of bioenergetic substrates depends on the type, intensity, and duration of the exercise. The aerobic oxidative system is used for longer duration activities of low to moderate intensity, the anaerobic glycolytic system is used for short to moderate duration activities of higher intensity, and the high energy phosphagen system is used for short duration activities of high intensity. The efficiency and effectiveness of these pathways can be enhanced through physical activity and training. It is these bioenergetic pathways that are the focus of this review.

INTRODUCTION

Humans are capable of performing amazing feats. Sprinters run down the track with astonishing speed and power; power lifters make hundreds of kilograms look like a sack of potatoes; swimmers traverse an entire lake or channel against the elements; hurdlers gracefully clear all obstacles in their way; and some basketball players even seem to defy the laws of gravity. Before muscles can produce movement by pulling on their attachments to bones, they must first obtain a source of energy to sustain such a movement. A complex series of metabolic pathways are present in human muscle that break down substrates from nutritional sources to produce energy for different types of muscular activity. However, depending on the activity in which an individual is engaged, the body will make use of different energy systems that have been adapted for the particular activity (see Fig. 1). More specifically, utilization of bioenergetic substrates depends on the type, intensity, and duration of the exercise. The aerobic oxidative system is used for longer duration activities of low to moderate intensity, the anaerobic glycolytic system is used for short to moderate duration activities of higher intensity, and the high energy phosphagen system is used for short duration activities of high intensity. The efficiency and effectiveness of these pathways can be enhanced through physical activity and training. It is these bioenergetic pathways that are the focus of this review.

AN OVERVIEW OF MUSCLE PHYSIOLOGY

Muscle tissue - the contraction specialist - provides a prime example of how the structure of a tissue is well-adapted to perform a specific function. With approximately 324 muscles, and with muscle constituting 30-35% and 42-47% of body mass in women and men, respectively the importance of muscular activity is obvious. The various types of muscle tissue support numerous life functions such as ventilation, physical activity and exercise, digestion, and of course, pumping life-sustaining blood throughout the body via specialized cardiac muscle. Skeletal muscle (also termed striated muscle) connects the various parts of the skeleton through one or more connective tissue tendons and is the type of muscle used to produce movement during exercise. During muscle contraction, skeletal muscle shortens and, as a result of the tendinous attachments, functions to move the various parts of the skeleton with respect to one another via joints. This allows changes in position of one skeletal segment in relation to another, thus creating movement. Skeletal muscle is comprised of numerous multinucleated cylinder-shaped cells called muscle fibres (myofibrils), and each fibre is made up of a number of myofilaments. Physically, they range in size from under a hundred microns in diameter and a few millimeters in length to a few hundred microns across and a few centimetres in length. Each cell (fibre) is surrounded by a connective tissue sheath called the sarcolemma, and a variable number of fibres are enclosed together by a thicker connective tissue sheath (the perimysium) to form a bundle of

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fibres called fascicles. Each fibre contains not only the contractile machinery needed to develop force (sarcomeres), but also the cell organelles necessary for cellular respiration (mitochondria). Each fibre is activated through electrical impulses transmitted by nerves, the motor nerves and motoneurones in particular. A group of fibres activated via the same nerve is termed a motor unit. Also located outside each fibre is a supply of capillaries from which the cell obtains nutrients and eliminates waste.

Within each myofibril, a number of contractile units called sarcomeres, are organized in series, i.e., attached end to end. Each sarcomere is comprised of three types of protein myofilaments: the thick filament system is composed of myosin protein which is connected from the M-line to the Z-disc by the protein titin. It also contains myosin-binding protein C which binds at one end to the thick filament and the other end to the protein actin. The thin filaments are assembled by actin monomers bound to nebulin, in a process that also involves tropomyosin. Nebulin and titin give stability and structure to the sarcomere (see Fig. 2). When a signal comes from the motor nerve activating the fibre, the neurotransmitter acetylcholine is released and travels across the neuromuscular junction. The action potential then travels along T (transverse) tubules until it reaches the sarcoplasmic reticulum. The action potential causes calcium ions to be released from the sarcoplasmic reticulum, allowing the flow of calcium ions into the sarcomere. Outflow of calcium from the sarcoplasmic reticulum allows the heads of the myosin filaments to temporarily attach themselves to the actin filaments, a process termed “cross bridge formation”. The movement of the cross bridges causes a movement of the myosin filaments in relation to the actin filaments, leading to shortening of the sarcomere, and muscle contraction. Human skeletal muscle is composed of a mixture of two contractile fibre types: slow twitch and fast twitch fibres. Each of the fibre types can be described on the basis of its predominant metabolic pathway by which it derives energy, with the type I slow twitch fibres being described as oxidative (Type I or SO), and the fast twitch fibres being subdivided into two subgroups, fast twitch oxidative-glycolytic (Type IIa or FOG) and fast twitch glycolytic (Type IIb or FG). Each of the three fibre types described above have distinctive morphological, contractile, and metabolic characteristics (see Table 1).

The Chemistry of Energy Production in Human Muscle

All energy in the human body is derived from the breakdown of complex nutrients such as carbohydrates, fats, and proteins. The end result of the breakdown of these substances is the production of the adenosine triphosphate (ATP) molecule, the energy currency of the body. ATP provides all the energy for fuelling biochemical processes of the body such as muscular work or the digestion of food. The capacity to perform muscular work (work = force exerted x distance moved) is dependent on supplying sufficient energy at the required rate for the duration of the activity.

Energy is liberated for work when the chemical bond between ATP and its phosphate sub-group is broken through hydrolysis when catalyzed by the enzyme ATPase:

\[ \text{ATP breakdown: } \text{ATP} \rightarrow \text{ADP} + \text{Pi} + \text{Energy} \] (1)

ATP is broken down in a process called “ATP turnover”. Water (H₂O) hydrolyzes the unstable chemical bonds of the phosphate groups of the ATP molecule, yielding an inorganic phosphate group and adenosine diphosphate (ADP). The energy released is used to perform work or other cellular processes.

Table 1: Functional Characteristics of Human Muscle Fibres

<table>
<thead>
<tr>
<th>Fibre Type</th>
<th>Type I</th>
<th>Type IIa</th>
<th>Type IIb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alternate name</td>
<td>Slow Oxidative</td>
<td>Fast Oxidative Glycolytic</td>
<td>Fast Glycolytic</td>
</tr>
<tr>
<td>Primary source of ATP</td>
<td>Aerobic Oxidation</td>
<td>Aerobic Oxidation &amp; Anaerobic Glycolysis</td>
<td>Anaerobic Glycolysis</td>
</tr>
<tr>
<td>Myosin- ATPase activity</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Glycolytic enzyme content</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Glycogen content</td>
<td>Low</td>
<td>Intermediate</td>
<td>High</td>
</tr>
<tr>
<td>Number of mitochondria</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Myoglobin content</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Capillary density</td>
<td>High</td>
<td>Intermediate</td>
<td>Low</td>
</tr>
<tr>
<td>Speed of contraction</td>
<td>Slow</td>
<td>Fast</td>
<td>Fast</td>
</tr>
<tr>
<td>Rate of fatigue</td>
<td>Slow</td>
<td>Intermediate</td>
<td>Fast</td>
</tr>
</tbody>
</table>

molecule (Pi) and adenosine diphosphate (ADP). The released energy is about 38-42 kilojoules (kJ) or 9-10 kilocalories (kcal) per mole of ATP.4

The body harnesses this energy when the free Pi group is transferred to another molecule. When this other molecule is joined with the new free phosphate group, it is said to be phosphorylated. All muscular work done in the body depends upon these phosphorylated molecules. For example, ATP powers the movement of muscles by transferring phosphates to contractile proteins, which leads to the contraction of muscle fibres.4

When the body performs work, it needs a continuous supply of ATP, but the initial stores of ATP in the muscles are used up very quickly. Therefore, ATP must be regenerated. ATP is a renewable resource that can be regenerated by the recombination of ADP and Pi. The metabolic process that results in the recombination of ADP and Pi to form ATP is termed ATP resynthesis (see Eq.(2)). ATP can also be resynthesized through the combination of phosphocreatine (PCR) and ADP as shown in Eq.(3). This reaction can occur at a very fast pace in the body. The resynthesis of ATP is described in the reactions below:

\[
\text{ATP resynthesis : ADP} + \text{Pi} + \text{energy} \rightarrow \text{ATP} 
\]

\[
\text{ATP resynthesis : PCR} + \text{ADP} + \text{energy} \rightarrow \text{ATP} + \text{Cr} 
\]

The regeneration of ATP, however, requires energy. This energy is supplied by the breakdown of complex food molecules such as carbohydrates and fats in metabolic energy systems of the human body. These energy systems will now be presented in more detail.

**THE ENERGY SYSTEMS**

The turnover and resynthesis of ATP involves three energy systems, each of which employs a different means of energy production. These energy systems are (1) the high-energy phosphagen system, (2) the anaerobic glycolytic system, and (3) the aerobic oxidative system (Table 2 and Fig. 3). These sources of energy for muscular contraction and other types of work are designated as aerobic or anaerobic, depending on whether they

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**Table 2**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>High energy phosphate</th>
<th>Anaerobic glycolytic</th>
<th>Aerobic oxidative</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel source(s)</td>
<td>stored ATP, phosphocreatine (PCR)</td>
<td>stored glycogen, blood glucose</td>
<td>glycogen, glucose, fats, proteins</td>
</tr>
<tr>
<td>Enzyme system used in breakdown</td>
<td>ATPase</td>
<td>HK, PFK, LDH, PDH, others</td>
<td>CS, MDH, SDH, others</td>
</tr>
<tr>
<td>Muscle fibre type(s) recruited</td>
<td>Type I, Type IIa, Type IIb</td>
<td>Type I, Type IIa, Type IIb</td>
<td>Type I, Type IIa</td>
</tr>
<tr>
<td>Power output requirement</td>
<td>high</td>
<td>moderate - high</td>
<td>low - moderate</td>
</tr>
<tr>
<td>Metabolic byproducts</td>
<td>ADP, P, Cr</td>
<td>lactic acid</td>
<td>CO2, H2O</td>
</tr>
<tr>
<td>Maximum rate of ATP production (mmol/min)</td>
<td>3.6</td>
<td>1.6</td>
<td>1</td>
</tr>
<tr>
<td>Time to maximal ATP production</td>
<td>1 sec</td>
<td>5-10 sec</td>
<td>2-3 min</td>
</tr>
<tr>
<td>Maintenance time of maximal ATP production</td>
<td>6-10 sec</td>
<td>20-30 sec</td>
<td>3 min</td>
</tr>
<tr>
<td>Time to exhaustion of system</td>
<td>12-15 sec</td>
<td>45-90 sec</td>
<td>theoretically unlimited</td>
</tr>
<tr>
<td>Ultimate limiting factor(s)</td>
<td>Depletion of ATP/PCR stores</td>
<td>Lactic acid accumulation</td>
<td>Depletion of carbohydrate stores, insufficient oxygen, heat accumulation</td>
</tr>
<tr>
<td>Time for total recovery (sec)</td>
<td>3 min</td>
<td>1-2 hr</td>
<td>30-60 min</td>
</tr>
<tr>
<td>Time for one half recovery (sec)</td>
<td>20-30 sec</td>
<td>15-20 min</td>
<td>5-10 min</td>
</tr>
<tr>
<td>Relative % ATP contribution to efforts of 10 sec</td>
<td>50</td>
<td>35</td>
<td>15</td>
</tr>
<tr>
<td>Relative % ATP contribution to efforts of 30 sec</td>
<td>15</td>
<td>65</td>
<td>20</td>
</tr>
<tr>
<td>Relative % ATP contribution to efforts of 2 min</td>
<td>4</td>
<td>46</td>
<td>50</td>
</tr>
<tr>
<td>Relative % ATP contribution to efforts of 10 min</td>
<td>1</td>
<td>9</td>
<td>90</td>
</tr>
</tbody>
</table>

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**Figure 3.** A general representation of aerobic, anaerobic and high energy phosphate bioenergetic pathways.
require the presence of oxygen to provide energy. The high-energy phosphagens and the anaerobic glycolytic systems do not use oxygen. The aerobic oxidative system depends on oxygen to produce energy. The three bioenergetic systems that are used in human physiology to produce energy for muscular activity are explained in detail in the following sections.

The High-Energy Phosphate System

The high-energy phosphate system (also known as the phosphagen or anaerobic alactic system) is characterized by the substrates that the system uses to produce energy. This system can provide energy for muscles in the initial 1 to 15 seconds of high intensity activity. The high-energy phosphate substrates that are the primary energy source for the high-energy phosphate system are adenosine triphosphate (ATP) and phosphocreatine (PCr).

During the initial stages of high intensity exercise, ATP is broken down via the enzyme ATPase, and phosphocreatine is broken down via the enzyme creatine kinase to supply inorganic phosphate for ATP resynthesis (Eqs. (2) and (3), respectively). ATP resynthesis may occur through anaerobic glycolysis or aerobic oxidation, and the power output drops accordingly.

The high-energy phosphate system is the primary energy system that is used in sporting events such as weight lifting, high jump, long jump, 100-metre run, or 25-metre swim. These high power output activities require a high rate of energy production as the work is done over a short time interval (power = work / time). It is also used for high intensity activities of daily living such as jumping, or short runs. If individuals are to continue the activity beyond a 15-second period, they must produce energy from another system at a lower power output.

Training may result in changes in levels of stored ATP and PCr in muscle. Strength training (repeated muscular efforts against a resistance or opposing force) may result in increases of approximately 20% in ATP, and PCr. Sprint training (short high intensity intervals separated by long rest periods) does not appear to result in increased stores of ATP or PCr. Strength and sprint training modalities also appear to affect the enzymes associated with the high energy phosphate system, more specifically ATPase and creatine kinase.

The Anaerobic Glycolytic System

The body relies primarily on anaerobic metabolism for the energy required to perform intensive exercise of greater than 12-15 seconds and less than 3 minutes duration. Anaerobic glycolysis is the primary energy system that is used in sporting events such as the 800-metre run, 200-metre swim, downhill ski racing, and the 1500-metre speed skating and in other activities such as sprints during soccer or hockey games. Metabolically, energy production via glycolysis is accomplished in the cytoplasm of skeletal muscle by the catabolism of carbohydrate, in the form of blood glucose or muscle glycogen (the storage form of glucose, consisting of many molecules of glucose), to pyruvate, through 10 separate but linked steps of the anaerobic glycolytic pathway (Fig. 4). This biochemical process results in the release of energy in the form of ATP, which is then used for muscle contraction. During glycolysis certain enzymes break down the chemical bonds in glucose in the absence of oxygen (hence the term anaerobic). Each molecule of glucose ultimately yields 2 lactic acid molecules and 2 molecules of ATP, the latter is then used for muscle contraction.

Although the peak rate of energy production is high (1.6 mol ATP·min⁻¹), the system is inefficient, as only 2 mol of ATP are produced for every one mol of glucose that is broken down. Most of the energy generated in glycolysis does not result in ATP resynthesis. Instead it is dissipated as heat. Further, two molecules of ATP contribute to the initial phosphorylation of the glucose molecule, glycolysis generates a net gain of two ATP molecules. This represents an endergonic conservation of 14.6 kcal/mol. Glycolysis generates only about 5% of the total ATP generated during the complete breakdown of the glucose molecule. However, owing to the high concentration of glycolytic enzymes and the speed of these reactions, significant energy for muscle action is generated rapidly during glycolysis. Further, when the rate of muscle work is high, pyruvate can accumulate faster than the aerobic oxidative system can process, and it is then converted into lactic acid. The conversion of pyruvate to lactic acid production is used to maintain the rate of anaerobic glycolysis and energy...
production. This process has recently been reviewed and was the subject of a comprehensive symposium. The exercise intensity at which lactic acid begins to accumulate within the blood has been commonly referred to as the anaerobic threshold. In practical terms, the anaerobic threshold can be thought of as the point during exercise when the person begins to feel discomfort and a burning sensation in their muscles. It can be identified during clinical incremental exercise tests as the point when carbon dioxide production (VCO2) exceeds oxygen consumption (VO2) with the resulting respiratory exchange ratio (RER) greater than one. Some investigators believe that accumulation of lactic acid, which breaks down into lactate and hydrogen ions, will eventually contribute to muscle fatigue. However, this would not account for the muscle fatigue, cramps and contractures seen during high-intensity, short-burst exercise in people with glycolytic/glycogenolytic disorders, in which glycolysis, and thus lactate production, is blocked. Thus, there are likely many different variables in the microenvironment of the muscle that contribute to muscle fatigue under different conditions. For example, hydrogen ions may interfere with the actin-myosin coupling and thereby ultimately impede muscle contraction. Further, the pH change associated with the accumulation of hydrogen ions may decrease the rate of glycolysis through its effect on the rate-limiting enzyme phosphofructokinase (PFK). These mechanisms are reviewed in detail elsewhere. Lactic acid accumulation is a commonly measured variable in sports physiology and typical values range from 2 mmol/L at rest, to 4 mmol/L in moderate sustainable exercise to 16 mmol/L in maximal anaerobic exercise (i.e. 2 minute maximal effort sprinting). Efficient lactate removal from the Type II glycolytic muscle fibres, where lactic acid is predominantly produced, to Type I oxidative fibres, where lactate can be oxidized in mitochondria, can allow individuals to continue to exercise at higher intensities for longer periods of time. This transfer of lactic acid in and out of muscle fibres is accomplished via monocarboxylate lactate transporters on the surface of the muscle cell. A graphical representation of the physiology of lactic acid transport is presented in Fig. 5.

Exercise training has significant effects on the anaerobic glycolytic system. High intensity interval training (e.g. 60 second maximal efforts alternating with 2-3 minutes of rest) can increase the rate of flux through the glycolytic pathway, thus increasing the ATP production rate, but also increasing the rate of lactic acid production. This increased flux through the glycolytic pathway is accomplished through upregulation of anaerobic enzymes. Muscle and blood buffering capacity can also be increased through anaerobic sprint or interval training. Trained individuals have also been shown to remove lactate faster from exercising muscle, suggesting an increase in the number and/or efficiency of the lactate transporters present in the specific muscle tissue (Type I or Type II). Aerobic endurance training can also increase the rate of lactate elimination by increasing the rate of pyruvate processing in the Krebs cycle in mitochondria. This increases the work rate that can be achieved exclusively through aerobic metabolism, and thus decreases the production of lactic acid for a given work level. Aerobic endurance training can result in other adaptations that can lead to an increased rate of lactate removal from the muscle following training, including increased muscle blood flow and increased ability to metabolize lactate in the heart, the liver and in non-working muscle. Blood flow is increased in trained individuals through an increase in the number of blood vessels in the muscle, altered neural and endocrine function, more red blood cells, greater total blood volume, and increased cardiac output. The aerobic oxidative energy system is a very important energy system in the human body, as it is the primary source of energy for a very broad range of activities. Daily activities such as walking, jogging, swimming, household chores, and walking up stairs all use energy provided by the aerobic oxidative system. Exercise that is performed at an intensity lower than that of the anaerobic threshold relies exclusively on the aerobic system for energy production. Thus, blood lactate levels remain relatively low (2-6 mmol/L blood) during purely aerobic exercise. As the duration of intensive activity increases, the relative contribution of the aerobic oxidative system to total energy production increases (see Fig. 1). During intense exercise, well trained individuals can elevate their rate of oxygen consumption up to 20 times above resting values. Under conditions of heavy exercise, the skeletal muscle cells set

![Figure 5](https://example.com/figure5.png)

**Figure 5.** Representation of lactate transport metabolism in different muscle fibre types. Adapted from 34.
the aerobic demand for oxygen, as 90% of the oxygen in the body is consumed in the mitochondria in the muscle cell. The aerobic energy system is the primary energy system that is used in exercise provided that (a) the working muscles have sufficient mitochondria to meet energy requirements, (b) sufficient oxygen is supplied to the mitochondria, and (c) enzymes or intermediate products do not limit the rate of energy flux through the Kreb's cycle and respiratory chain – the bioenergetic pathways that produce ATP within the mitochondria.

The pathway for oxygen transport involves three main structures; the lungs, the circulation, and the muscle. Oxygen follows a simple linear pathway without branches. Respiration is a regulated process matched to the instantaneous demands of aerobic metabolism: as muscle ATP consumption increases, O2 demand is increased proportionally. Increases in oxygen transport that occur during exercise are brought about as a result of an increase in ventilation and uptake of oxygen into the blood, an increased cardiac output and O2 transport by the blood, and an increased extraction of O2 by the muscle due to increased O2 metabolism in the mitochondria. Respiration is a limited function, and the limit of the maximal rate of oxygen that can be consumed to produce energy in the muscle is termed VO2max. Any additional energy requirements beyond that intensity will be fulfilled via anaerobic metabolism. VO2max is higher in athletes than non-athletes, and to an extent is malleable and can be elevated by training.

Further, the pathway for oxygen transport from the environment to the mitochondria in the skeletal muscle cells is linear. The actual process of respiration is the integrated function involving the coordinated action of all of the structures that make up the pathway for delivery of O2 from the lungs to the respiratory chain enzymes in the mitochondria of the muscle cell. A metaphor for understanding the respiratory pathway can be developed using an electric circuit as the example. In this case the individual steps can be viewed as resistors in series, and the total resistance can be estimated by the difference in arterial and venous O2 levels. The oxygen flux (VO2) can be thought of as current, and total oxygen transport (cardiac output) as voltage. Since voltage = current x resistance, the equation becomes VO2 = cardiac output x (arterial-venous O2 difference). The relative contribution of the individual steps in the respiratory pathway has been a subject of some debate, however, using the above electrical circuit model, it has been shown that for humans exercising in normoxia, approximately 75% of VO2max is set by central O2 transport and the remaining 25% by the periphery. Thus, it is now generally accepted that it is the integrated, interactive steps in the respiratory pathway that help set VO2max.

In human muscle mitochondria, a complex biochemical process known as oxidative phosphorylation is used to resynthesize ATP. Mitochondria are energy-generating organelles in the muscle fibres that contain a system of enzymes, coenzymes, and activators that carry on the oxidation of nutrients and release ATP for use in aerobic work. Oxidative phosphorylation consists of pathways that include the Krebs cycle (also known as the citric acid cycle) and the electron transport chain. The processes combine ADP and Pi through biochemical steps in the presence of oxygen to synthesize ATP. Both carbohydrates (glucose and glycogen) and fats (triglycerides and fatty acids) provide molecules that are used in oxidative phosphorylation. The system is highly efficient; the energy yield from the metabolism of glucose as the substrate is 36 ATP molecules in conditions of adequate oxygen supply (18 times the yield from the anaerobic system). Fats are an important energy source for athletic events that require large outputs of energy over a long period of time. For example, the oxidation of an 18-carbon fatty acid molecule produces 147 molecules of ATP. Water and carbon dioxide are given off as by-products of this reaction. Fats are an ideal molecule for storage of energy (each gram of lipid yeilds approximately 9.4 kilocalories of energy, more than twice the amount found in carbohydrates or proteins. A normal person has enough energy stored as fats to run hundreds of miles, but only enough stored carbohydrate to run about 20 miles! In
addition to the efficient provision of energy for muscular contraction, the aerobic system is used to re-establish cellular homeostasis in muscle tissue after intensive exercise bouts. More specifically, removal of lactic acid from muscle tissue is accomplished largely via conversion of lactate back to pyruvate and then subsequent processing of pyruvate in the Krebs cycle. The lactic acid, once produced in type II muscle fibres, is actively transported into the blood and into type I fibres where lactate can be metabolized back to pyruvic acid.

Endurance exercise is the method of training that is most effective for eliciting adaptations in the aerobic oxidative energy system. It consists of sustained low to moderate intensity activity (50–75% of maximum heart rate) of long duration, typically in excess of 20 minutes and as long as several hours. Aerobic endurance exercise stimulates positive adaptations throughout the entire cardiovascular system, making it an excellent intervention for improving health and performance and for preventing or even treating various diseases, particularly obesity and Type II diabetes. The major adaptations that occur in the human body with aerobic endurance training are summarized in Fig. 7.

Endurance training increases the maximal aerobic power of a sedentary individual by 15–25% regardless of age. Genetics plays a large role in determining the rate of adaptation, with some individuals adapting quickly and others more slowly. Endurance training has many effects on aerobic metabolism and related physiological functions:

1. Increased cardiac output. The increase in cardiac output may arise due to an increase in the size of the heart cavities (ventricles and atria) as well as an increase in the contractility of the walls of the heart.

2. Increased vascularization (number of blood vessels and capillaries) within skeletal muscle and heart muscle.

3. Increased capillarization is a benefit as it allows for a greater surface area and reduced distance between the blood and the surrounding tissues, thus increasing diffusion capacity of oxygen and carbon dioxide, as well as easing the transport of nutrients to cells.

4. Increased total blood volume and the number and total volume of red blood cells through stimulation of erythropoiesis (formation of new red blood cells) in the bone marrow.

5. Increased number and size of mitochondria within the muscle fibres.

6. Increased activity of aerobic enzymes such as AMP kinase and Krebs cycle enzymes which can be observed as an increased arterial-venous O₂ difference, and preferential use of fats over glycogen during exercise.

In summary, aerobic endurance training stimulates many positive adaptations in aerobic oxidative metabolism and the cardiovascular system as a whole. Optimal health and performance depend upon these adaptations. It is important that health professionals understand these adaptations in order to be able to impart this knowledge to the general population and to encourage individuals to adopt lifestyles that will improve their health and quality of life.

Summary of Energy Systems Physiology

The function of muscles is to convert chemical energy from food into mechanical energy, allowing individuals to perform muscular work. Fats, carbohydrates and proteins are the basic interrelated fuel sources that are available to muscles to perform this function.
High energy phosphates contribute anaerobic energy to the muscle system. Very high power outputs can be produced on demand, but these outputs can only be maintained for very short durations.

Small amounts of blood glucose and large amounts of muscle glycogen can also supply energy rapidly. High power outputs can be maintained in this fashion through anaerobic glycolysis accompanied by lactic acid production. Lower power outputs for sustained periods of time can be maintained by aerobic oxidation of glycogen with limited production of lactate. Fuel stored as fat is also available to the mitochondria for oxidation and is limited to slow production of ATP at low power outputs for sustained periods of time.

REFERENCES


