13. EXERCISE PHYSIOLOGY

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1. What is skeletal muscle?

Whole skeletal muscle, such as the biceps, which is observable and palpable, is really several kinds of tissue. Each muscle comprises long, thin, cylindrical muscle fibers or cells that extend its entire length. As such, these cells can be very long. Each multinucleated muscle cell or fiber is surrounded by and connected to parallel muscle cells by a layer of connective tissue called the **endomysium**. These fibers are then grouped in bundles held together by another layer of connective tissue called the **perimysium**. This encased group or bundle of fibers is called a **fascicle**. Groups of fascicles, bundles of fibers each with associated blood vessels and nerve tissue, collectively are held in close approximation by another layer of connective tissue called the **epimysium**. The epimysium-surrounded fascicles, which run the entire length of skeletal muscle, are then completely surrounded by an important connective tissue called **fascia**. For greater detail, see Chapter 1, Cells, Nerves, and Muscles.

2. What is the role of fascia in skeletal muscle?

Fascia is a tough, dense, and strong connective tissue that covers the entire muscle and then extends beyond the muscle itself to become the fibrous tendon. The fascia is a fusion of all three internal connective tissue layers of skeletal muscle. Fascia separates muscles from one another, permits frictionless motion, and forms the tendon with which muscle is connected to bone. It is often an overlooked component of muscle physiology. Many believe that normal fascial movement is required for free, unrestricted movement of muscle and thus of joints.

3. How is skeletal muscle force measured?

Although terms such as *strength* and *power* are often used to describe force-generating capabilities of skeletal muscle, they are really incorrect. A contracting skeletal muscle produces a force that acts parallel to the muscle fibers; thus it is a linear force. Only an isolated skeletal muscle generates tension that is measurable as a force. In the body, muscles produce movement by rotation of a bone in a plane that is perpendicular to the joint's axis of rotation. The magnitude of the rotation is expressed as a torque. Appropriate measures of strength in the body then are torques with units of foot-pounds (ft-lb) or Newton-meters (N-m).

4. How does skeletal muscle contraction result in movement?

Repetitive cross-bridge cycling with sarcomere shortening pulls the ends of the muscle toward the middle. The strong connective fascial sheath, which unites skeletal muscle via the tendons to the bones, transmits the force to the bones. To produce movement, the muscle's linear force pulls on a bone and causes rotation in a perpendicular plane to the joint's axis. Because muscle typically crosses at least one joint, the segment that is most free will move, resulting in rotational movement at the joint.

5. How does skeletal muscle contract or shorten?

The ability of muscle to contract is a function of microstructural components—specifically, an interaction of the contractile proteins actin and myosin that occurs under the appropriate conditions (the presence of intracellular calcium ions and energy). The availability of energy for contraction comes from the hydrolysis of adenosine triphosphate (ATP), and calcium is released from the sarcoplasmic reticulum (SR) when stimulated by depolarization. The linkage of a neural impulse generated in the central nervous system with a distant skeletal muscle contraction is called **excitation-contraction coupling**.

6. How much does a muscle shorten during a single cross-bridge cycle or power stroke?

If all the cross-bridges in a single muscle were to go through one cycle simultaneously, a muscle would shorten by only 1% of its resting length. The fact that many muscles are capable of shortening up to 60% of their resting length demonstrates that cross-bridge cycling must occur repeatedly, each time with myosin grabbing a new actin site and pulling for extensive shortening and force to be generated.

7. Where does the energy for skeletal muscle contraction come from?

The breakdown of ATP is achieved by the enzyme myosin ATPase located on the globular head. When hydrolyzed, ATP releases the energy to the myosin head and adenosine diphosphate (ADP) + P_i is formed. The energized myosin head performs the power stroke. The reaction is as follows:

$$ATP \leftrightarrow ADP + P_i + \text{energy}$$

8. How much ATP does the body store?

Essentially, the body stores enough ATP for only a few seconds' worth of activity. After that, ATP must be resynthesized from ADP + P_i. ATP is a large, heavy molecule. If the body stored enough ATP for a single day's use, it is estimated that even a sedentary person would have to increase body weight by 75%.

9. Where does the ATP come from?

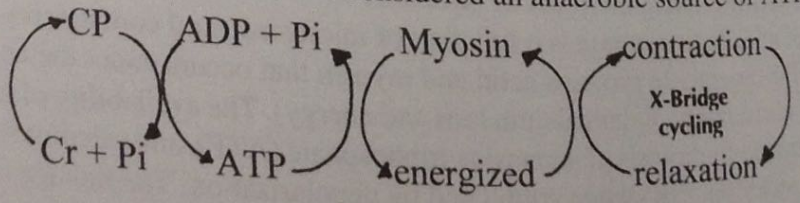
Muscle fibers contain three major pathways to resynthesize ATP: (1) creatine phosphate (CP) system, (2) glycolysis, and (3) aerobic oxidation of nutrients to produce carbon dioxide and water. Each system has different capacities, characteristics, and lag time to produce ATP. Therefore, they are used to meet different ATP demands.

10. Which food is used by which pathway?

Only carbohydrates can be used in glycolysis. Almost all digestible carbohydrates can be converted into glucose or stored as glycogen. Glycogen and glucose are metabolized by glycogenolysis and glycolysis. Any food source that is converted into acetyl-coenzyme A (CoA) is metabolized via the Krebs cycle and oxidative phosphorylation. Specifically, fat is broken down into glycerol, which, through a two-step process, becomes pyruvate and fatty acids. Fatty acids are oxidized through beta oxidation to acetyl-CoA. Beta oxidation occurs in the mitochondria. Proteins are broken down into amino acids and, after deamination (removal of NH_3), can be converted to pyruvate or acetyl-CoA or enter the Krebs cycle. None of the steps in the Krebs cycle or beta oxidation directly uses oxygen, but without the electron transport chain (ETC), a shortage of electron acceptors (nicotinamide adenine dinucleotide [NAD], reduced flavin adenine dinucleotide [FADH]) results, slowing and ultimately inhibiting the metabolism.

11. Which system produces ATP the fastest?

The **CP system** is the most rapid resynthesis system available in humans because it involves only a single enzymatic step. Basically, a high-energy phosphate is transferred from CP directly to rephosphorylate ADP to make ATP. However, there appears to be a finite level of CP stored in cells, and thus its ability to resynthesize ATP is limited. Because this system does not require the presence of oxygen to produce ATP, it is considered an anaerobic source of ATP.



Creatine phosphate–ATP production link in energizing the myosin head to permit cross-bridge cycling (contraction and relaxation).

12. What type of activities does CP and stored ATP fuel?

Collectively, the CP system combined with stored ATP is used for short-term, high-intensity bursts of activity lasting about 10–12 seconds. It is located right at the myosin heads, the site of use. The CP and ATP systems are used for rapid movements such as rapid lifting, high jumping, a 10-yard sprint, getting up from the couch quickly, moving quickly when in danger of being stung by a bee, or jumping out of the way of a moving truck when crossing a street.

13. Can the effectiveness of the CP system be increased?

The CP system responds to training, and recent studies have demonstrated that consuming creatine monohydrate, an ergogenic aid, appears to increase anaerobic performance. Studies are ongoing to determine how much creatine must be taken, for which activities it is beneficial, when it should be taken, and the side effects or toxicity, if any.

14. Where does the energy come from when physical activity lasts longer than 10–12 seconds or is of lesser intensity?

Glycolysis produces ATP anaerobically (without the use of oxygen). Glycolysis occurs within the cytoplasm of skeletal muscle and involves the breakdown of carbohydrate to pyruvate or lactate with the net energy yield of 2 ATP (3 ATP if started with glycogen). Glycolysis produces ATP quickly but is slower than the CP system. Glycolysis alone can support activity lasting several minutes in duration. For moderate-intensity, long-duration activities, carbohydrate and fat produce large quantities of ATP via complete oxidation (Krebs cycle), beta oxidation (fats), and ETC.

15. How are the energy-producing systems controlled?

Both glycolysis and the Krebs cycle are controlled by hormonal and local regulation of the rate-limiting step or by enzyme regulation. Similarly, the ETC also is regulated by the (ADP + P_i)/ATP ratio. Similar to most regulated enzymes, energy-producing systems are subjected to end-product inhibition. For example, increased concentrations of pyruvate inhibit the regulated step in glycolysis and the key enzyme **phosphofructokinase**. In general, increased concentrations of ADP and P_i stimulate metabolism, whereas high concentrations of ATP inhibit further production of ATP. Some of the key enzymes are regulated by hormones such as epinephrine, norepinephrine, glucagons, insulin, and cortisol.

16. Is the end-product of glycolysis pyruvate or lactate?

When glycolysis is slow and the acceptance of reduced NAD (NADH) by the mitochondria is adequate, **pyruvate** is the end product of glycolysis. Pyruvate is converted into acetyl-CoA (a step requiring NAD) and undergoes complete combustion via the Krebs cycle and ETC. When the mitochondria are unable to accept the pyruvate or provide regenerated electron acceptors (NAD or FADH), pyruvate is converted to **lactate**. The conversion of pyruvate to lactate decreases pyruvate concentration, prevents end-product inhibition, and permits glycolysis to continue.

17. When is lactate produced?

Lactate is produced when mitochondrial function is inadequate to accept pyruvate or produce sufficient electron acceptors. This happens when enzymatic activity in the mitochondria is low, when oxygen supply is insufficient, or when glycolysis is rapid. In general, lactate production is increased during hypoxia, ischemia, and hemorrhage; after carbohydrate ingestion; when muscle glycogen concentrations are high; and during exercise hyperthermia.

18. What else can happen to pyruvate?

During exercise or when caloric intake is insufficient, pyruvate can be converted into the nonessential amino acid **alanine**. Alanine is produced by skeletal muscle and can be converted by the liver into new glucose. This is commonly called the **alanine cycle**. In this case, pyruvate

is converted to lactate, and the lactate is transported in the blood to the liver and reconverted to pyruvate and then to alanine. The alanine is then converted to glucose for subsequent release.

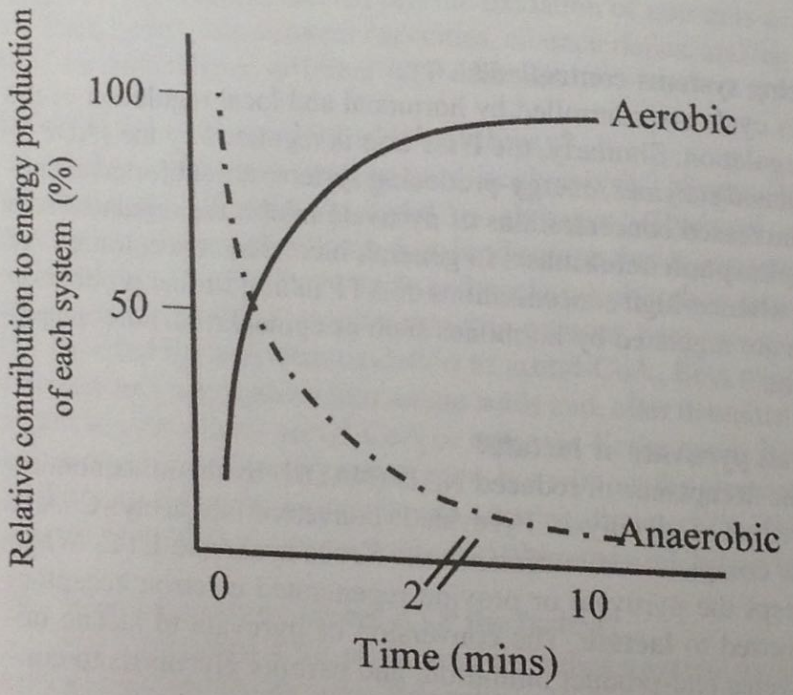
19. Compare and contrast the energy pathways in terms of their use in physical activity.

In reality, these pathways interact to provide the needed energy for all activity. However, the contribution of anaerobic sources predominates during high-intensity, short-duration activity, whereas aerobic sources dominate in activities lasting more than 5 minutes. This difference is summarized in the following table.

	ANAEROBIC METABOLISM	AEROBIC METABOLISM
Type of activity	Short, explosive	Longer time (>2 min)
Intensity of activity	High	Low to moderate
Example of event	Shot put, 100-m run	≥ 1500-m run
Major system	ATP-CP, glycolysis	Krebs, ETC
Stimulators	ADP, AMP, P_i	ADP, NAD, P_i
Inhibitors	ATP	ATP, NADH
Type of response	Rapid and immediate	Slower but prolonged

20. How do anaerobic and aerobic metabolism interact?

The intensity and duration of activity dictate the pathways for regeneration of ATP and the metabolic and systemic events contributing to fatigue.



Relative contribution of aerobic and anaerobic metabolism to total energy production as a function of exercise time. Increasing exercise time results in a dominance of aerobic metabolism.

21. Do all skeletal muscles use the same source of ATP and produce the same force?

No. Skeletal muscle comprises different types of muscle cells with different nerve morphology and physiology. This results in different conduction velocities, contractile velocities, force-generating capacity, and metabolic capacities. Basically, when categorized by contractile velocity, the two major subtypes of skeletal muscle are **slow-twitch or type I** and **fast-twitch or type II**. The fast-twitch category is further subdivided based on metabolic capacity. The fast-twitch subdivisions include the following:

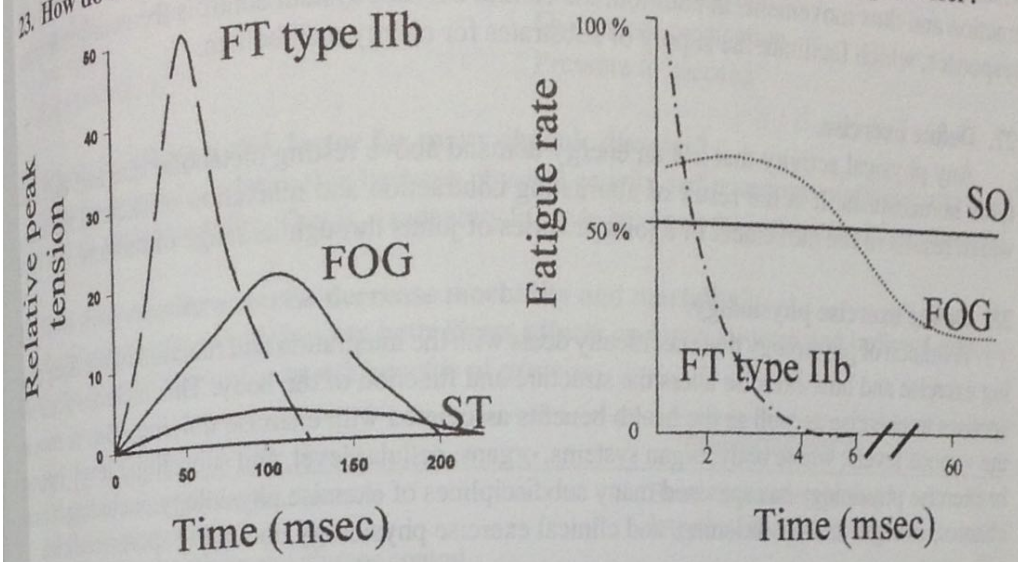
- Type IIa (fast-twitch fatigue-resistant) fibers have moderate capacities for both glycolytic and oxidative metabolism.
- Type IIb (fast-twitch fatigable) fibers are large-diameter fibers, produce more force, and have a high glycolytic capacity.

- Type IIab (fast-twitch intermediate) fibers

22. What are FOG, SO, and FG?

Histochemical profiles of skeletal muscle fibers that correspond to fast-twitch oxidative-glycolytic (FOG), slow-twitch oxidative (SO), and fast-twitch glycolytic (FG).

23. How do the response time and fatigue curves for the three main fiber types differ?



Schematic representation of relative peak tension and fatigue rate of fast-twitch (FT type IIb), fast-twitch oxidative-glycolytic (FOG), and slow-twitch (SO) fibers in human skeletal muscle.

24. Which fiber type is used when?

Slow-twitch fibers have a low threshold and are the first to be recruited during incremental exercise. They have a slow maximal shortening velocity. This is followed by a progressive increase in **FOG** and **FG** recruitment.

25. List the biochemical differences among fiber types.

	SLOW-TWITCH (TYPE I)	FAST-TWITCH (TYPE IIa)	FAST-TWITCH GLYCOLYTIC (TYPE IIb)
Glycogen content	Moderate	Moderate-high	Moderate-high
Capillary density	High	High	Low
Myoglobin content	High	High	Low
ATPase activity	Low	High	High
Mitochondrial density	High	High	Low
Oxidative capacity	High	Moderate high	Low
Color	Red	Intermediate	White
Predominant energy system	Aerobic	Combination	Anaerobic

26. How does skeletal muscle contraction result in physical activity or exercise?

The control of motor function is a complex integration of many parts of the central and peripheral nervous systems. Each plays an important role in the coordinated movement patterns of daily living and in high-skill activities such as sports. The major components of motor function include:

- Motor cortex (stores rough drafts of planned activities)
- Subcortical areas (prime drive for conscious movement)
- Cerebellum and basal ganglia (for precise temporal and spatial execution)
- Thalamus (relay center)

- Spinal neurons (conduction system)
- Skeletal muscle motor end plates (reception and signal conversion)
- Muscle receptors (signal reception and transmission)
- Proprioceptors (for error correction)

When all systems are functioning appropriately, the **motor cortex** with input and modification from **subcortical areas** and the **cerebellum** initiates and modifies (via **proprioception** and visual information) neural output in terms of frequency and intensity to selected muscles for contraction and thus movement. In addition, the central nervous system controls the neuroendocrine responses, which facilitate the supply of substrates for energy metabolism.

27. Define exercise.

Any physical activity that has an energy demand above resting metabolic rate and that disturbs homeostasis. It is the result of alternating contraction and relaxation of skeletal muscles, which results in the movement of a joint or series of joints through its range of motion.

28. Define exercise physiology.

A branch of physiology that specifically deals with the integration and function of the body during exercise and how exercise alters the structure and function of the body. This includes acute responses to exercise as well as the health benefits associated with exercise training. This is done at the various levels: whole body, organ systems, organs, cellular level, and subcellular level. Interest in exercise physiology has spawned many subdisciplines of exercise physiology, including biomechanics, strength and conditioning, and clinical exercise physiology, including sports medicine.

29. How does exercise differ from physical fitness?

Physical fitness is often defined as sufficient physical structure, function, and capacity to perform and respond favorably to whatever specific task an individual person requires. Exercise is any physical activity. Physical fitness is a term that has its origin in physical education. In the 1950s, the physical fitness movement gained momentum when endorsed by President Eisenhower. This endorsement was fueled by three pieces of information: (1) an alarming number of military draftees failed their induction exams, many with physical defects; (2) autopsies of young soldiers killed in the Korean war showed significant coronary artery disease; and (3) U.S. children performed poorly on a minimal muscular fitness test when compared with European children of similar ages. This information prompted President Eisenhower to create the President's Council on Youth Fitness. During President Kennedy's term, the name was changed to the President's Council on Physical Fitness in efforts to promote school fitness or physical education classes of all ages and to develop a "fit society." Today, we speak of physical fitness in terms of general health as well as the protection from many preventable diseases.

30. What is Healthy People 2020?

Healthy People 2020, previously called Healthy People 2000, is a U.S. Department of Health and Human Services' initiative that spells out specific health objectives. Initially, the target year was 2000, but, because the objectives were not met by that year, the name was changed to reflect the new target goal of 2020. The objectives are designed to improve the health and well-being of all Americans and deal with issues such as fitness, body composition, mental health, tobacco and alcohol use, and nutrition.

31. Name a specific goal of Healthy People 2020 in terms of physical fitness.

To increase the proportion of people 18 years old and older who engage in physical activity regularly, preferably daily for at least 30 or more minutes, to develop and maintain the cardiorespiratory system.

32. Why is physical fitness important from a public health standpoint?

The three leading causes of death in the United States are diseases of the heart and blood vessels, cancer, and chronic obstructive pulmonary disease. For each of these degenerative diseases

epidemiologists have identified major risk factors and separated them into three categories: inherited or biologic, environmental, and behavioral. Because nothing can be done currently in terms of modification of inherited risk factors (age, gender, race, and susceptibility), health care providers and researchers have focused on environmental and behavioral risk factors. A major behavioral risk factor for each of the three major diseases is inactivity or a lack of regular exercise.

33. What are the behavioral risk factors for degenerative disease?

Smoking
Inactivity
Poor nutrition
Alcohol consumption
Overuse of medication
Pressure to succeed

34. Why is inactivity a risk factor for many chronic diseases?

There is an inverse relationship between physical activity and premature cardiovascular mortality and all-cause mortality. That is, a sedentary lifestyle increases the incidence of these diseases.

35. How does regular exercise decrease morbidity and mortality?

Regular exercise or training has both **direct effects** on organ systems and **indirect effects,** all of which contribute to the health benefits of exercise.

DIRECT EFFECTS	INDIRECT EFFECTS
Stronger, more efficient heart muscle	Better stress management
Lower blood pressure	Improved immune system
Better insulin sensitivity and glucose control	
Improved body composition	
Lower-low-density lipoprotein concentration	
Higher high-density lipoprotein concentration	

In general, the higher the activity level or level of cardiorespiratory fitness, the lower the mortality and the longer the life span.

36. What is homeostasis?

The maintenance of a constant or **optimal** internal and cellular environment that is compatible with cell life in the face of external and internal influences. Homeostasis is achieved through the integration of multiple compensatory or regulatory systems making continual adjustments. Homeostasis is a dynamic constancy and not an absolute constancy. A dynamically constant internal environment is necessary for optimal cell function.

37. What are the components of a homeostatic control system?

- A **receptor,** which is excited by a stimulus
- An **integrating center,** which processes the information for comparison to its set-point and determines the appropriate response
- The **effector,** which, in response to a signal from the integrating center, responds to correct the disturbance
- The **evoked responses,** which return the internal environment back to normal

The restoration of the internal environment decreases the initiating stimulus and as such is called a **negative feedback control system**.

38. List examples of negative feedback homeostatic control systems involved in adapting to exercise.

Although numerous systems are involved in maintaining homeostasis during exercise, three major systems are vital to exercise:

1. Arterial blood pressure and blood volume regulation, including the baroreceptors
2. Regulation of blood glucose
3. Temperature regulation

39. Why is exercise described as a great challenge to homeostasis?

Physical activity or muscular exercise is the repetitive contraction of groups of skeletal muscle that permits movement about a joint or series of joints. Physical activity or contraction of skeletal muscles of any kind changes the internal environment at a variety of levels and, as such, is a broad homeostatic challenge. For example, during exercise:

- Glucose utilization can be increased twentyfold.
- Skeletal muscle pH drops dramatically.
- Six to 10 lb of water can be lost from the system as sweat.
- Temperature can increase to 106°F.
- Cardiac output can increase from 4.5 L/min to 25 L/min even in untrained adults.

These disturbances must be compensated for to promote cell survival.

40. Why are changes in skeletal muscle associated with whole-body responses to exercise?

Of the approximately 660 skeletal muscles in the human body, more than 400 are under voluntary control. Skeletal muscle constitutes greater than 40% of total body weight and is responsible for three major functions: force production for locomotion and breathing, force production for posture, and heat production during cold exposure. The relative mass of skeletal muscle is indicative of its ability to elicit large changes in homeostasis. The diverse needs of the skeletal muscle are met by multiple systems. For example, because of an increased demand for oxygen, cardiac output or blood flow must increase. Similarly, increases in ventilation and transport of oxygen to the red blood cells by the respiratory system must occur. The acids made by skeletal muscle result in extracellular acidity and are a serious challenge to acid–base homeostasis. Thus, the individual organ systems of the body serve as primary support systems that permit skeletal muscles to perform their functions. Therefore, the whole-body or physiologic responses to exercise function to support skeletal muscle and restore homeostasis.

41. What is ultimately the driving factor for the physiologic changes associated with exercise?

The majority of changes that occur in response to exercise are related to the increased demand for energy to fuel skeletal muscle contraction. For movement of any kind to occur, skeletal muscle must contract or shorten. Skeletal muscle shortening is powered by the hydrolysis of ATP. During exercise, energy utilization can increase from 1.2 kcal/min to 18–30 kcal/min, or a 25-fold increase. These bioenergetic demands dictate physiologic changes in a predictable fashion.

42. What is the difference among exercise, sporting activities, and the physical activities of daily living or work?

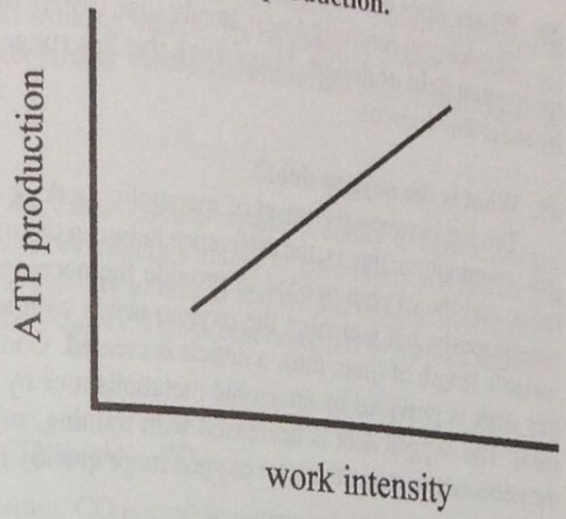
From a metabolic point of view, nothing. The ATP demands and whole-body response to sprinting to intercept a pass or sprinting to catch a bus differ only in their magnitude and skill level. Within a single step, the ATP needs of skeletal muscle have increased above rest. The energy or ATP utilization during heavy exercise can increase by 200 times above resting levels. The ability to sustain this or any type of activity is directly linked to the ability of skeletal muscle to produce an equivalent amount of ATP. That is, contractions continue as long as sufficient ATP is produced. If work intensity increases, the amount of ATP required to perform those contractions increases regardless of the motivation for the movement.

43. Does that mean that any activity, even kissing, burns calories?

From a purely metabolic point of view, yes. Kissing is physical activity, and the number of calories has been determined. In fact, the caloric requirements for nearly all activities have been determined and are published in table format in standard exercise physiology textbooks.

44. Graph the relationship between exercise (work) and ATP production.

Increases in work intensity can only be met by a concomitant increase in ATP production. If ATP production does not match work or ATP utilization, work or, in this case, skeletal muscle contraction will cease.



45. Can the ATP demands of exercise be measured?

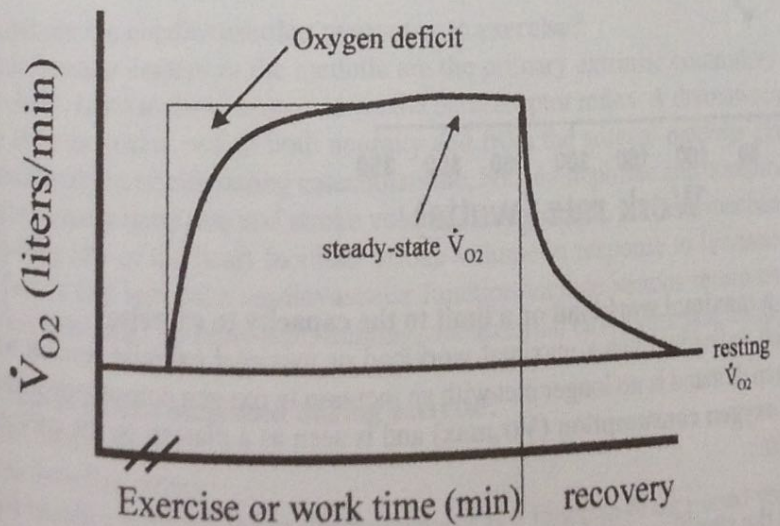
No. ATP is used at the subcellular level, and aerobic metabolism occurs within the mitochondria and cannot be measured directly. Measuring oxygen consumption at the mouth is a commonly used indirect method for assessing the ATP needs of metabolic work or exercise.

46. What does skeletal muscle require to produce ATP?

A constant supply of substrates (glucose, fatty acids, and oxygen) and an appropriate environment through the removal of waste products (carbon dioxide, acids, adenosine, heat, and potassium).

47. How is oxygen related to exercise?

Because the synthesis of ATP is most efficient under aerobic conditions, the amount of oxygen used or consumed is an indirect measure of ATP synthesis and thus of ATP utilization. Because ATP synthesis cannot be measured, oxygen consumption usually is measured to indicate ATP need. This is best demonstrated in the following figure. The time course of oxygen utilization indicates that oxygen consumption will increase until a new steady state is achieved where oxygen (ATP) demands are met by oxygen (ATP) delivery. *Note that the y-axis is labeled oxygen consumption in liters/min.*



Relationship between exercise or metabolic work and oxygen consumption (L/min). Oxygen consumption and thus ATP production increases until ATP production appropriately balances ATP consumption during work at which a steady state is achieved. Oxygen consumption (ATP production) will be maintained until intensity is changed in either direction.

48. Where does the ATP come from if it takes time for oxygen consumption to increase?

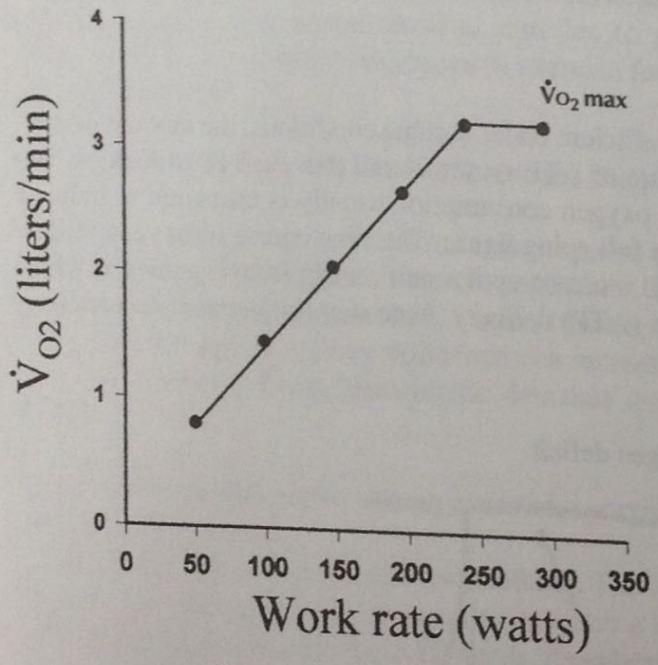
The delay in reaching a new steady state (where oxygen need is met by supply) is often called the **oxygen debt** or **deficit**. Many think that this suggests that the ATP for this work was supplied by anaerobic sources.

49. What is the oxygen debt?

The lag between the onset of metabolic work or exercise and reaching the increase in oxygen consumption; that is, the difference between the oxygen uptake in the first few minutes of exercise and the oxygen needed to provide the necessary ATP for work. ATP needs increase instantaneously, but matching the oxygen needs with an increase in oxygen consumption takes a variable length of time; thus, a deficit is created. Controversy exists about whether the ATP for this work is provided by anaerobic metabolism or by stored sources or is just a lag in measurement. The oxygen debt is decreased with training, suggesting an ability to induce more rapidly the necessary systems to move oxygen more quickly in response to exercise.

50. What is the relationship between oxygen consumption and work when the load is continuously increased?

A progressive increase in workload is called an **incremental workload**. This is like running up a hill and with each step the hill gets just a little steeper, so you run just a little bit faster. If workload is progressively increased, the need for ATP is increased; therefore, the oxygen need is similarly increased until a plateau is reached. The relationship between workload and oxygen consumption is shown in the figure. Oxygen consumption continues to increase so long as oxygen demands are increased to produce ATP to meet the energy needs of the increasing work.



Relationship between oxygen consumption (L/min) and incremental work or ATP needs. Oxygen consumption will increase to match work in a near linear fashion until a maximal level is obtained.

51. Is there a maximal workload or a limit to the capacity to exercise?

Yes. Each individual has a maximal workload or maximal exercise level at which the increased oxygen demand is no longer met with an increase in oxygen consumption. This is defined as **maximal oxygen consumption ($\dot{V}O_2$max)** and is seen as a plateau on the curve in the figure in question 50.

52. What is the significance of $\dot{V}O_2$ max?

Maximal oxygen consumption or $\dot{V}O_2$max represents the maximal capacity to transport and use oxygen during exercise. As such, many consider $\dot{V}O_2$max to be the best indicator of cardiovascular and respiratory fitness. $\dot{V}O_2$ increases in a linear fashion relative to workload or exercise

until $\dot{V}O_2$max is reached. This plateau can be thought of as the physiologic maximum or limit in the ability to transport and deliver oxygen to working muscle. As an index of fitness, $\dot{V}O_2$max increases with training and decreases with age. Higher values are associated with an increased capacity to perform physical activity or work.

53. What determines $\dot{V}O_2$max?

Oxygen consumption is a function of the cardiovascular system's ability to deliver oxygen specifically to the working muscle, the respiratory system's ability to get oxygen into and carbon dioxide out of the blood, and skeletal muscle's ability to take in and use the oxygen aerobically to produce ATP. Training and genetics influence $\dot{V}O_2$max. This is best described by the Fick equation.

54. What is the Fick equation?

$$\dot{V}O_2 = CO \times (aO_2 - \bar{v}O_2)$$

where $\dot{V}O_2$ is O_2 consumption in mL of O_2/min; CO is cardiac output in L/min; $aO_2 - \bar{v}O_2$ is the difference in arterial and mixed venous O_2 contents in mL of O_2/L.

This equation states that the ability to consume oxygen is a function of the ability of the cardiovascular and respiratory systems to deliver oxygen-enriched blood in combination with the ability of skeletal muscle to extract and utilize oxygen.

55. What is the role of the cardiovascular system during exercise?

According to Fick's equation, the cardiovascular system functions to deliver oxygen and substrates to the specific working muscle for use, to deliver hormones to their target site to facilitate substrate availability, and to remove metabolic wastes from the muscle, including heat. The circulatory system serves as the conduit for transport and exchange of oxygen and waste products, whereas the heart serves as the driving pump to meet such needs.

56. What are the cardiovascular responses to acute exercise?

Two major adjustments occur during exercise to meet oxygen demands.

1. Cardiac output must be increased. This increase is achieved by increasing heart rate and stroke volume

2. Blood flow must be redistributed specifically away from relatively inactive tissue to the working muscle while maintaining appropriate blood flow and pressure to critical organs such as the brain.

57. What controls the cardiovascular responses to exercise?

The cardiovascular centers in the medulla are the primary extrinsic controllers of heart rate and stroke volume. Input to these centers is via the baroreceptor reflex. A dramatic increase in the sympathetic nervous system output both neurally and from the adrenal medulla gland results in increased concentrations of circulating catecholamine, both epinephrine and norepinephrine, during exercise to increase heart rate and stroke volume. Furthermore, intrinsic mechanisms such as the Frank-Starling law of the heart facilitate stroke volume in response to increased venous return. Other factors that influence cardiovascular function include venous return and blood volume, which are influenced by body size, training, and external environmental temperatures.

58. How is venous return increased during exercise?

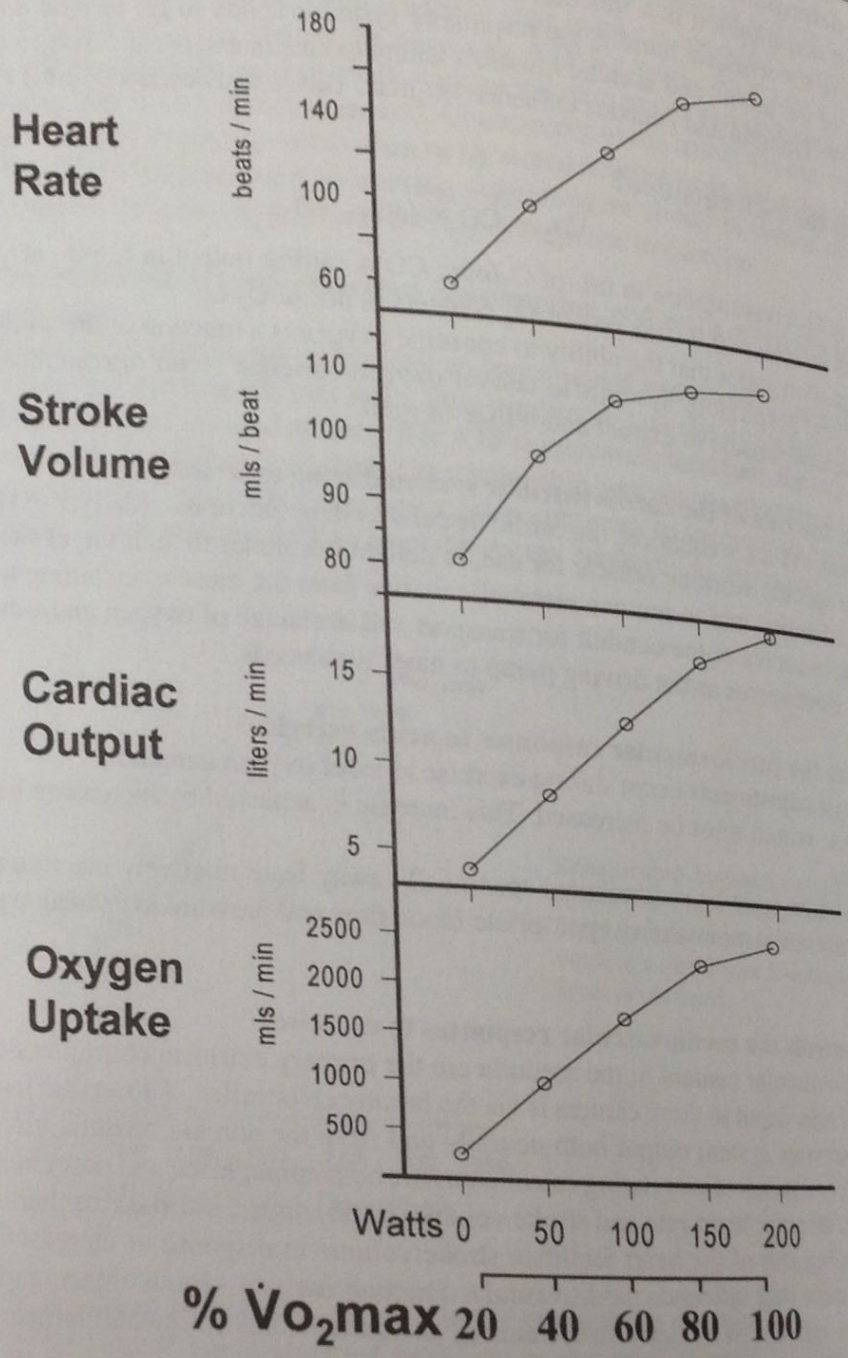
- Skeletal muscle pump
- Increased cardiac output
- Greater negative pressure in the thoracic cavity as a function of increased ventilation

59. How much can cardiac output increase during exercise?

Resting cardiac output is on average 5 L/min with an average heart rate of 72 bpm and stroke volume of approximately 70 mL per beat. In endurance-trained individuals, maximal cardiac out-

put measures exceed 34 L/min for men (70 kg) and exceed 23 L/min for women (50 kg). Consider that this is equal to seventeen 2-L bottles of soda or just over 9 gallons of blood being pumped through an organ the size of one's fist every minute.

60. What is the relationship among heart rate, stroke volume, mean arterial pressure, and cardiac output with oxygen consumption or workload?



Cardiovascular responses to incremental exercise or work.

61. What is the maximal heart rate?

Commonly, maximal heart rate is considered to be 220 bpm. At heart rates higher than 220 bpm, filling time is decreased, and stroke volume and thus cardiac output are compromised.

62. How are exercise heart rate maximums calculated for use in determining exercise intensity?

Generally, one of two formulas is used to calculate exercise heart rate maximum: the age formula or the Karvonen formula.

- The **age formula** is simply 220 minus your age. For example, a 46-year-old man's maximal heart rate is $220 - 46 = 174$ bpm.
- The **Karvonen formula** is explained in question 133.

Neither of these formulas puts a physiologic limit on heart rate, and heart rates can exceed calculated values. Heart rate maximums are used more for safety during exercise.

63. Is there a difference in cardiac output between men and women?

If you measure straight cardiac output in terms of liters per minute, men have a higher cardiac output. In general, men are larger, which means they have a bigger heart, a greater stroke volume, larger blood volume, and higher hematocrit and hemoglobin concentration. Each of these factors contributes to a greater stroke volume and thus cardiac output and oxygen consumption. When data are normalized per gram of lean body mass, the gender differences are significantly diminished. That is, women have a lower cardiac output, but they have less lean muscle mass and smaller body mass as well.

64. What is the role of the microcirculation of skeletal muscle during exercise?

The capillaries of skeletal muscle intertwine with the individual fibers and form an intricate tortuous network with extensive capillary-to-fiber (cell) contact. The tortuosity of the network enhances the transit time of the blood in the muscle. Collectively, this facilitates diffusion of oxygen and nutrients. The microcirculatory system is controlled by autoregulation and local controllers, and capillary density responds to training.

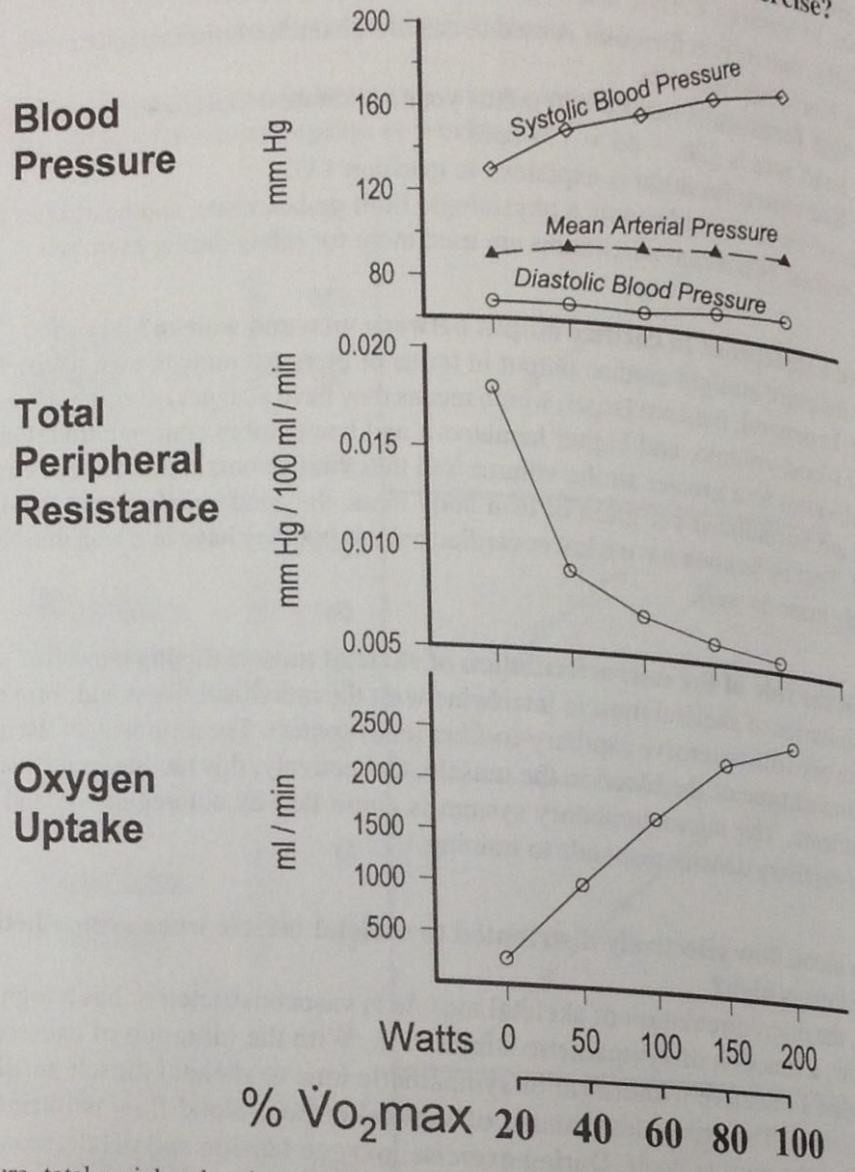
65. How is blood flow selectively distributed to skeletal muscle when sympathetic or vasoconstrictor tone is high?

At rest, the microcirculation of skeletal muscle is vasoconstricted or has a high resistance to blood flow, a function of sympathetic stimulation. With the initiation of exercise, it is hypothesized that a selective withdrawal of sympathetic tone to skeletal muscle results in a relative vasodilation. The prime determinant of skeletal muscle blood flow is intrinsic, that is, inherent within the muscle itself. During exercise, oxygen tension and pH decrease; the concentration of carbon dioxide, extracellular potassium, adenosine, and local temperature all increase, and each acts as a direct local vasodilator. These local factors are directly linked to contraction and metabolism; therefore, the greater the demand, the greater the vasodilation. Collectively, local factors vasodilate the microcirculatory system of skeletal muscle and result in a decrease in resistance and an increase in blood flow. The high sympathetic tone vasoconstricts nonmetabolically active tissue, which effectively facilitates the selective redistribution of blood flow to the area of least resistance (i.e., the dilated capillaries of active skeletal muscle).

66. How does blood flow to skeletal muscle change with exercise?

Because of the high tone in the microcirculation at **rest,** skeletal muscle gets only 15–20% of the total cardiac output at rest. Using the average cardiac output of 5 L/min, blood flow would be less than 1 L/min to all skeletal muscle. During heavy work or **exercise,** cardiac output can increase well above 20 L/min. If an average cardiac output of 25 L/min is coupled with vasodilation in skeletal muscle, 80–85% of the blood flow will be distributed to the muscle. This would be equivalent to more than 20 L of blood delivered to working skeletal muscle per minute.

67. What is the relationship between blood pressure and incremental exercise?



Blood pressure, total peripheral resistance, and oxygen uptake responses to incremental exercise or work. Note that mean arterial pressure changes very little despite large increases in work and decreases in total peripheral resistance.

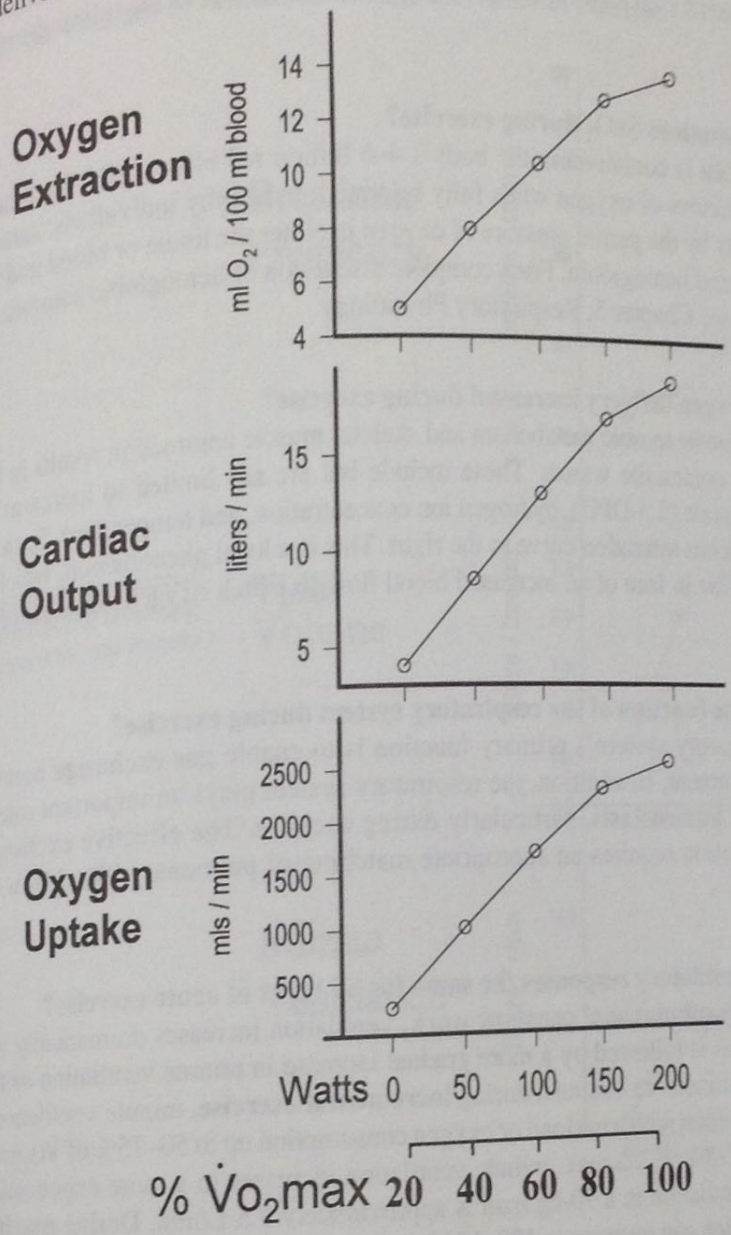
68. How does blood pressure change during aerobic exercise?

During exercise, systolic blood pressure increases as a function of pumping more blood through the system per minute. The degree of the response is related to the type and intensity of exercise. Diastolic blood pressure is an index of total peripheral resistance and is the sum of all of the resistance beds. During exercise, many of the microcirculatory beds are vasoconstricted. Skeletal muscle, which represents a large circulatory bed, vasodilates. As a result, diastolic blood pressure either decreases or stays the same during exercise. In fact, an increase in diastolic blood pressure is an abnormal response to exercise and a reason to terminate a graded exercise tolerance test.

69. Besides the redistribution of blood flow, what else facilitates oxygen delivery during exercise?

According to Fick's equation, $\dot{V}O_2$ is the product of oxygen delivery (cardiac output) and oxygen extraction ($aO_2 - \bar{v}O_2$). At rest, oxygen extraction of skeletal muscle is relatively low (ap-

proximately 5 mL of oxygen is removed per 100 mL of blood). During exercise, when oxygen need is significantly increased, oxygen extraction increases nearly linearly with work rate to a maximal value of approximately 160 mL O_2 per L of blood. This equates to an extraction of 85% of the oxygen delivered in the presence of an increase in blood flow. (See figure.)



Oxygen extraction by skeletal muscle, cardiac output, and oxygen uptake responses to incremental exercise or work.

70. List the direct influences on oxygen extraction.

- Skeletal muscle blood flow
- Mitochondrial density
- Capillary density
- Training
- Arterial oxygen content
- Muscle mass
- Fiber type
- Pulmonary function

71. What are additional, indirect influences on oxygen extraction?

Exercise conditions including barometric pressure (altitude) and air pollution can indirectly influence extraction by affecting pulmonary function and the partial pressure of oxygen in the inspired air.

72. What determines oxygen content of blood?

The oxygen-carrying capacity (CaO_2) is 20 mL of oxygen per 100 mL of blood. CaO_2 is a function of hemoglobin and the percent arterial saturation (SaO_2). In women, hemoglobin is generally lower, which contributes to the lower $\dot{V}O_2$max reported in women. Hemoglobin concentration is increased with endurance training, which contributes to the training-induced increases in $\dot{V}O_2$max.

73. What determines SaO_2 during exercise?

Hemoglobin is contained in the body's 4–6 billion red blood cells. Each hemoglobin can carry four molecules of oxygen when fully saturated. In healthy individuals, saturation is determined primarily by the partial pressure of oxygen in either the tissue or blood and the affinity between oxygen and hemoglobin. For a complete discussion of hemoglobin saturation and changes with exercise, see Chapter 5, Respiratory Physiology.

74. How is oxygen delivery increased during exercise?

The increase in aerobic metabolism and skeletal muscle contraction results in the increase of metabolic and contractile wastes. These include but are not limited to increases in P_{CO_2}, 2,3-diphosphoglycerate (2,3-DPG), hydrogen ion concentration, and temperature. Each of these shifts the oxyhemoglobin saturation curve to the right. This is a local phenomenon, which increases the oxygen extraction in face of an increased blood flow to match oxygen demands of the increased metabolism.

75. What is the function of the respiratory system during exercise?

The respiratory system's primary function is to enable **gas exchange** between the body and the environment. In addition, the respiratory system plays an important role in maintaining **acid–base homeostasis,** particularly during exercise. The effective exchange of oxygen into the circulation requires an appropriate matching of pulmonary blood flow with ventilation.

76. Are the ventilatory responses the same for all types of acute exercise?

No. During **submaximal constant work,** ventilation increases dramatically with the onset of exercise. This is followed by a more gradual increase in minute ventilation or the amount of air moved per minute. In contrast, during **incremental exercise,** minute ventilation increases in a near-linear fashion with workload or oxygen consumption up to 50–75% of $\dot{V}O_2$max. When $\dot{V}O_2$ is greater than 75% of $\dot{V}O_2$max, minute ventilation increases in a more exponential pattern. At rest, minute ventilation in a 70-kg man is approximately 7.5 L/min. During **maximal exercise,** minute ventilation can increase to 120–175 L/min.

77. How is minute ventilation changed during exercise?

Minute ventilation is the product of the amount of air moved per breath and the frequency of breathing. During exercise, respiratory rate can increase from resting values of 12–15 breaths per minute (bpm) to 40–50 bpm. Tidal volume, or the volume of air per breath, can increase from resting values of 0.5 L to greater than 3.0 L/min.

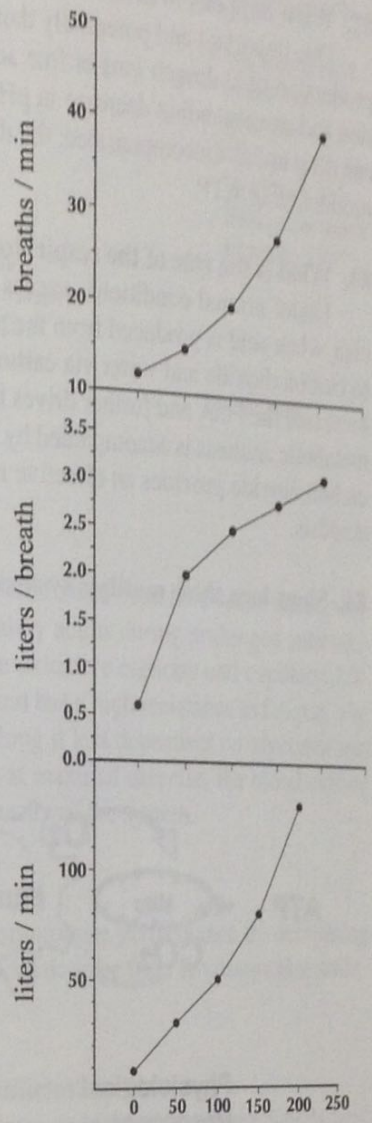
$$\text{Minute ventilation} = \text{tidal volume (L)} \times \text{bpm}$$

78. How are the ventilatory responses to exercise controlled?

Both the frequency (rate) and depth (tidal volume) of ventilation are controlled by motor neuron output from the respiratory control centers located in the medulla oblongata. The respiratory control center receives input from central and peripheral chemoreceptors, which are sensitive to changes in pH and arterial P_{O_2} and P_{CO_2}. Exercise-induced decreases in pH and P_{O_2} and increases

in PCO_2 each tend to increase minute ventilation. There is also some experimental evidence to suggest that afferent neural impulses originating in the motor cortex to drive skeletal muscle activity may spill over and assist in the drive of ventilation.

79. Summarize the changes in ventilation during incremental exercise



Respiratory responses to incremental work or exercise including breathing frequency, tidal volume, and minute ventilation.

80. What signals the respiratory control center to change ventilation?

In addition to chemoreceptor input, the respiratory control centers receive afferent information from peripheral receptors, including muscle spindles, Golgi tendon organs, and joint pressure receptors. Others have suggested that skeletal muscles have special chemoreceptors, which may respond to potassium and hydrogen ion concentrations with direct input to the respiratory centers. Finally, mechanoreceptors in the heart send afferent information relative to increases in cardiac output. These mechanoreceptors may also play an important role in providing afferent information to control respiration after the initiation of exercise.

81. Which dominates ventilatory control during exercise: chemoreceptors or neural input?

There is no clear agreement about which factors are the major regulators of breathing during exercise. Controversy also exists regarding the controllers during different types of exercise (submaximal versus heavy). There is evidence to suggest regulation only by neural input; there is evidence to suggest regulation only by humoral input; and, finally, there is some evidence to support regulation by a combination of humoral and neural controllers. It is likely that

ventilation is regulated by an interaction between these two types of information. Under this scenario, the primary drive to breathe during exercise would be mediated neurally, and precise adjustments to match ventilation would be provided by humoral input regarding the specific changes in P_{CO_2}.

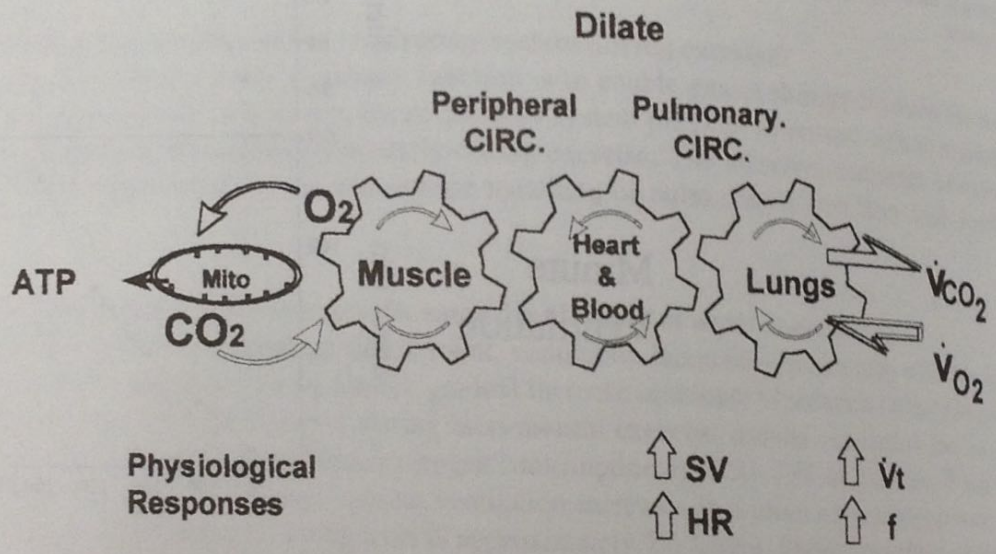
82. What happens to arterial blood pH during exercise?

One important and potentially dangerous by-product of exercise metabolism is an increased production of hydrogen ions or free acids from skeletal muscle. The increase in acid concentration and corresponding decrease in pH is a significant threat to homeostasis. Skeletal muscle pH can drop to 7.2. Uncompensated, the drop in pH threatens enzyme kinetics and compromises the production of ATP.

83. What is the role of the respiratory system in acid–base balance during exercise?

Under normal conditions, excess H^+ is buffered by the bicarbonate system. During exercise, when acid is produced from the production of lactate, the bicarbonate formed is converted to carbon dioxide and water via carbonic anhydrase. This excess production of carbon dioxide increases the P_{CO_2} and further drives the increase in minute ventilation. Thus, exercise-induced metabolic acidosis is accompanied by increases in P_{CO_2} and ventilation. Blowing off the excess carbon dioxide provides an effective method to compensate for the exercise-induced metabolic acidosis.

84. Show how these multiple systems are linked to support exercise.



Interdependency of the respiratory, cardiovascular, and microcirculatory systems to deliver oxygen and remove metabolic wastes to produce ATP by the mitochondria. Each system must function optimally to meet the needs of working skeletal muscle. The weakest system will always be the rate-limiting system.

85. What are the endocrine responses to acute exercise?

HORMONE	CHANGE DURING EXERCISE	ENERGY FUNCTION	GROWTH FUNCTION	OTHER EXERCISE FUNCTIONS
Growth hormone	Increase	FFA mobilization, gluconeogenesis, decreases glucose uptake	Stimulates protein synthesis	
Epinephrine	Increase	Glycogenolysis, FFA mobilization		Increases heart rate, stroke volume, and TPR

(Table continued on following page.)

HORMONE	CHANGE DURING EXERCISE	ENERGY FUNCTION	GROWTH FUNCTION	OTHER EXERCISE FUNCTIONS
Thyroxine tri-iodothyronine	Increase	Mobilizes fuels	Stimulates growth	
Cortisol	Increase with heavy	Mobilizes fuel substrates (FHA, protein), increases gluconeogenesis		Breaks down skeletal muscle
Aldosterone	Increase			Saves sodium and aids in fluid homeostasis
Vasopressin	Increase when ≥50% $\dot{V}O_2$max			Decreases water loss by kidney, aids fluid homeostasis, increases TRP
Insulin	Decrease	Uptake of glucose, amino acids, and FHA into tissues		
Glucagon	Increase	Glucose and FFA mobilization and gluconeogenesis		
Endorphins	Increase when ≥20% $\dot{V}O_2$-max			Blocks pain

FFA = free fatty acid; TPR = total peripheral resistance.

86. Does respiration limit exercise performance?

Although the pulmonary system can limit physical performance in some disease states, ventilation generally is not considered a limiting factor in healthy adults during prolonged submaximal exercise. The diaphragm has two to three times more oxidative capacity and capillary density than other skeletal muscle, uses glycogen sparingly, and has a high resistance to fatigue. The diaphragm favors oxidation of fat over carbohydrate, making it less dependent on glycogen and carbohydrate supply. In normal healthy individuals, even at maximal exercise, the blood exiting the lungs remains nearly saturated, demonstrating the capacity of the system.

87. Can the pulmonary system ever limit exercise?

Yes. Any pathology in the pulmonary system can compromise performance by decreasing SaO_2 or increasing the work of breathing. Pathology includes damage from environmental pollutants, asthma, or other respiratory diseases.

88. Can the pulmonary system limit exercise in elite athletes?

Pulmonary ventilation may be limiting for elite athletes or highly trained individuals performing prolonged heavy work, such as a marathon. At these levels, the competition between respiratory and skeletal muscles for blood flow and oxygen may be a factor.

89. Does the cardiovascular system limit exercise?

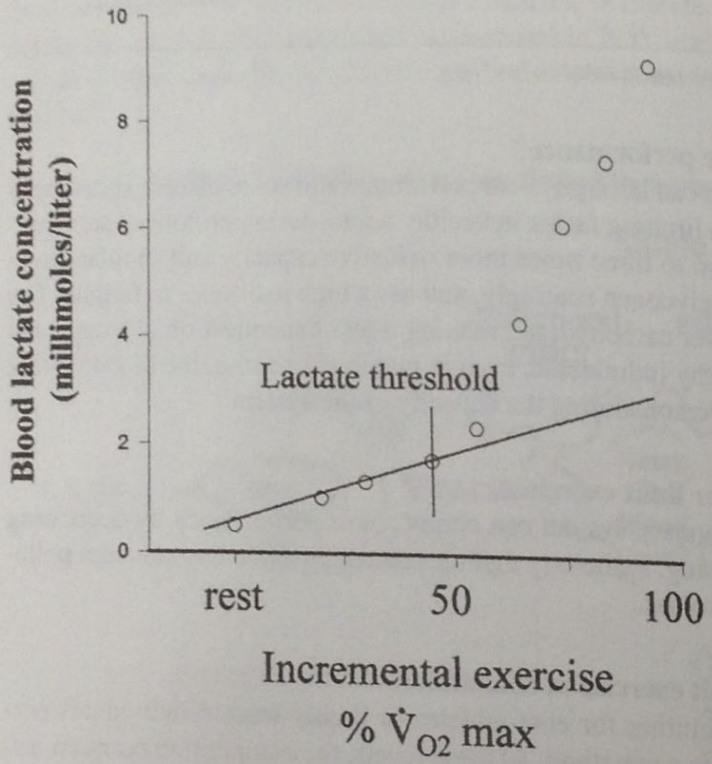
One theory about what limits exercise capacity is known as the **central theory.** It holds that exercise is limited when sufficient oxygen cannot be delivered to skeletal muscle, which is a function of the cardiovascular system. Fick's equation demonstrates the important role of the cardiovascular system in maintaining oxygen consumption. A cardiovascular limitation is hypothesized because once stroke volume maximum is reached, increases in cardiac output can occur only with higher heart rates. At heart rates over 200 bpm, the filling time is compromised, so stroke volume actually decreases. Thus, there is a difficult balance between high enough heart rates and sufficient filling time. Because minute ventilation and respiratory rates can be increased even at $\dot{V}O_2$max when heart rate maximum has been reached, the cardiovascular system is generally considered the limiting factor. In addition, as core temperature increases secondary to heat production by skeletal muscle, the need to deliver blood to the cutaneous circulatory bed to facilitate sweating and heat loss comes into direct competition for blood flow to skeletal muscle.

90. What is the anaerobic threshold?

The term **anaerobic threshold** was first used in the mid-1960s to describe the sudden increase in blood lactate that occurs at high workloads. This was interpreted as an increased lactate production most likely due to local hypoxia (low blood oxygen partial pressures) or ischemia (low blood flows). When oxygen is lacking, pyruvate is converted into lactate. As a result, the production of lactate was interpreted as evidence that there was a lack of oxygen in contracting skeletal muscle. This is controversial. Today, most prefer the term **lactate threshold** to describe the time during which lactate appearance in the blood in no longer linearly related to the workload.

91. What is the lactate threshold?

In the figure below, there is an interesting relationship among the onset of lactate in the blood, the drop in arterial pH, and the change in minute ventilation during exercise. The exercise intensity at which a systematic increase in blood lactate levels occurs is called the **lactate threshold**. Although still being investigated, most would agree that skeletal muscle continually produces lactate during exercise. However, as seen in the figure, blood lactate concentration does not increase until much higher exercise intensities are reached.



Blood lactate concentration as a function of incremental exercise. Lactate is continually being produced and released into the systemic circulation. Lactate threshold represents the workload where blood lactate concentration begins to increase in a nonlinear fashion.

92. What causes the sudden increase in blood lactate?

There are several theories:

- Decreased removal of lactate from the circulation
- Increased recruitment of fast-twitch glycolytic fibers, which produce more lactate
- Imbalance between glycolysis and mitochondrial respiration
- Tissue hypoxia or ischemia
- Altered ratio of $NADH/NAD^+$

93. Does muscle become hypoxic during exercise?

Although technically impossible to measure directly, to date, there is no experimental evidence to demonstrate hypoxia within skeletal muscle during incremental exercise. Estimates of the $NADH/NAD^+$ ratio even at high workloads suggest that sufficient oxygen is available to permit the ETC regeneration of electron acceptors. Thus, there is no evidence that skeletal muscle is hypoxic, so it is unlikely that hypoxia contributes to the lactate threshold.

94. Why is the lactate threshold important?

The lactate threshold for any given individual is relatively reproducible for a given exercise. Research indicates that the exercise intensity at lactate threshold is the maximal intensity of exercise that can be maintained at a steady state. This means that the higher the lactate threshold, the higher the intensity that can be sustained during endurance exercise. Simply put, given the same $\dot{V}O_2$max, you could run at 70% of your maximal effort instead of being able to run at only 50% of your maximal effort.

95. How is lactate threshold determined?

Typically, an incremental exercise test is performed in which an arterial catheter is inserted for serial blood sampling. The workload is increased incrementally until maximal capacity is reached. Lactate levels are measured from small samples of blood taken every couple of minutes. Blood lactate concentrations are plotted against workload, and the break point from linearity is determined.

96. Can lactate threshold be determined without an arterial catheter?

No. However, there is often a close association between the lactate threshold and a breakpoint in minute ventilation. This close association has been extensively studied. Some believe the lactate threshold can be estimated from gas exchange data collected during indirect gas colorimetry. In this case, at the lactate threshold and change in arterial pH, there very often is a ventilatory breakpoint or a disproportionate increase in ventilation relative to the change in workload. This breakpoint is called the **ventilatory threshold**. Ventilatory threshold is a crude (at best), noninvasive estimate of lactate threshold.

97. Is lactate production detrimental?

No. Many people used to think lactate production was responsible for muscle fatigue and delayed-onset muscle soreness; this is now known to be incorrect. Lactate is an important substrate for cardiac muscle energy production and is an important intermediate step in gluconeogenesis. In addition, the production of lactate from pyruvate regenerates NAD^+ and permits glycolysis to continue during high demands for ATP. Furthermore, the conversion of pyruvate to lactate when pyruvate production exceeds entry into the mitochondria for metabolism eliminates end-product inhibition of the key glycolytic enzymes. This facilitates energy metabolism. Lactate also can be converted by the liver back to pyruvate and as part of the Cori cycle synthesis of new glucose.

98. What is the ventilatory threshold?

The exercise intensity at which there is a deviation in linearity in minute ventilation simultaneously with an increase in ventilatory equivalents for oxygen ($\dot{V}_E/\dot{V}O_2$). This nonlinear point has traditionally been thought to occur secondary to the metabolic (lactate) acidosis (drop in pH and increase in PCO_2) occurring in relationship to the lactate threshold. Both pH and PCO_2 drive the increase in ventilation.

99. Are the ventilatory threshold and lactate threshold the same?

No. Although some have suggested that ventilatory threshold and lactate threshold are the same and can be used interchangeably, several studies suggest this is incorrect. Differences between lactate threshold and ventilatory threshold as large as 8% of $\dot{V}O_2$max have been reported.

100. Can ventilatory threshold and lactate threshold change?

Yes. Both lactate threshold and ventilatory threshold respond to training (i.e., shift to the right). The thresholds have practical implications both in sport performance and in designing exercise training programs for endurance athletes. Because fatigue is associated with high levels of lactate, exercising just below lactate threshold is important. With training, the shift in threshold permits working at a higher percentage of maximum without lactate build-up in the circulation.

101. What is fatigue?

The inability to continue exercise at a desired or given intensity. Often, **fatigue** and **performance limitation** are incorrectly used interchangeably. Fatigue is really a process and should be defined by the failing system for a specific type of exercise. For example, muscular fatigue during resistance-type exercise is characterized by the inability to sustain a generated force, despite an appropriate effort. Performance limitation is generally considered to focus on what limits $\dot{V}O_2max$.

102. Describe the two major theories regarding sites of fatigue.

1. **Central fatigue.** The central nervous system is primarily responsible for fatigue by either a reduction in the number of motor units firing or a decrease in the frequency of motor unit firing. There is limited evidence in support of this theory.

2. **Peripheral fatigue.** Peripheral fatigue occurs as the result of neural, mechanical, or energetic system failures. The peripheral theory supports the conclusion that fatigue is the result of failure at the cellular level to provide ATP secondary to disrupted homeostasis.

103. List the potential mediators of skeletal muscle fatigue during prolonged exercise.

- Metabolic acidosis
- Decreases in glycogen
- Electrolyte imbalances
- Dehydration
- Hypoglycemia
- Damage to skeletal muscle
- Changes in muscle membrane excitability
- Inability to supply ATP adequately
- Mechanical failure owing to high H^+ concentration
- Failure of temperature regulatory systems resulting in hyperthermia

104. Define DOMS.

Delayed-**o**nset **m**uscle **s**oreness (DOMS) is a common overuse injury that appears 24–48 hours after strenuous exercise (delayed). Although originally thought to be due to lactate, this is clearly not the case. Current evidence for the mechanisms for DOMS indicates that excessive mechanical force results in skeletal muscle and connective tissue damage or injury. Associated with the cell damage or injury is a classic inflammatory response, including an increase in cell mediators such as histamine, kinins, and likely prostaglandins; increased macrophage, mast cell, and lysosomal activities; edema formation; and an increase in local temperature. Each of these stimulates sensory nerve endings and results in pain.

105. What limits $\dot{V}O_2max$?

Currently there are two theories to explain $\dot{V}O_2max$ limitations:

1. The **central limitation theory** focuses on the central nervous system and the systemic circulation as limiters. This includes changes in blood volume, arousal, cardiac function, and oxygen transport. Central theory proponents believe that sufficient oxygen-enriched blood cannot be transported to the skeletal muscle without compromising systemic blood pressure and blood flow to essential organ systems, particularly the brain or temperature regulatory beds such as cutaneous microcirculation.

2. In contrast, the **peripheral limitation theory** has focused on factors occurring in the skeletal muscle itself. These factors include structural and functional elements, such as capillary density, mitochondrial density, oxygen extraction capabilities, and oxygen utilization capability of the mitochondria.

106. List the functional limitations for different types of exercise.

EXERCISE	FUNCTIONAL LIMITATION AND MECHANISM
Intense <30 s	Energy depletion (CrP and ATP)
Intense 0.5–10 min	Energy depletion (CrP and ATP), acidosis, accumulation of waste products, electrochemical disturbance
Low intensity <90 min	Hyperthermia, muscle damage
Low intensity >90 min	Low muscle glycogen, hypoglycemia, muscle damage, low liver glycogen, dehydration, hyperthermia, electrochemical disturbance, central nervous system and cardiovascular disturbance

CrP = creatinine phosphate.

107. What limits all-out anaerobic performance?

During high-intensity exercise lasting less than 180 seconds, contractions are dominated by a very high percentage of type IIb fibers (> 70%). Type IIb fibers have a high glycolytic capacity, which means ATP needs are met primarily by anaerobic glycolysis and the creatine phosphate system. The primary result is a large production of lactate with resulting muscle acidosis and spillover to systemic acidosis. The elevated H^+ concentration interferes with metabolism or the mechanics of contraction by interfering with troponin's ability to bind calcium. Collectively, these limit the exercise time.

108. Describe the skeletal muscle adaptations to endurance exercise training.

Skeletal muscle responds to endurance training with characteristic adaptations designed to increase the tolerance to the metabolic challenge. Although the change in cross-sectional area is minimal, muscle fibers change their biochemical or metabolic features to facilitate this type of activity. Changes in skeletal muscle include:

- Hypertrophy of slow-twitch fibers
- Increased myoglobin content
- Increase in mitochondrial density and size
- Increase in glut 4 transporters
- Increase in oxidative enzyme content
- Increase in capillary density, which increases the autoregulatory capacity of the muscle itself

These changes not only result in an increased capillary-to-fiber ratio, which promotes oxygen delivery, but also permit a more rapid redistribution of blood to working muscle after endurance training. Collectively, these changes facilitate the delivery, extraction, and utilization of oxygen and thus increase ATP production for skeletal muscle contraction and delay the onset of metabolic acidosis.

109. Does endurance training burn more fat?

Yes, with aerobic conditioning, the activities of the enzymes involved in beta oxidation and those involved in liberating free fatty acids into the circulation are increased. This permits a greater utilization of fat as a fuel or substrate (burn more fat) and spares carbohydrate (glycogen) stores. Therefore, a greater percentage of fat is burned at intensities below the lactate threshold.

110. What are the cardiovascular adaptations to aerobic training?

In addition to the skeletal muscle changes noted above, aerobic training induces adaptations in the cardiovascular and respiratory systems. Specifically, $\dot{V}O_2max$ is increased because more oxygen can be delivered and consumed. The cardiovascular adaptations include:

- Cardiac hypertrophy
- Increased stroke volume at rest and during submaximal and maximal workloads
- Greater ejection fraction
- Greater end-diastolic volume
- Lower heart rate
- Faster heart rate recovery
- Increase in cardiac output
- Increases in blood volume and plasma volume
- Slight increase in red blood cell numbers

111. Why does aerobic training decrease the incidence of heart attacks?

Although the long-term benefits of aerobic training are multifactorial, a major factor in lowering the risk of myocardial ischemia is exercise-induced bradycardia. Myocardial oxygen consumption is best estimated by the **double product,** which is heart rate × systolic blood pressure. Because heart rate is lower at rest and during all levels of exercise or physical activity, the heart is less likely to exceed its oxygen delivery capacity. Thus, endurance exercise training results in a lower oxygen demand of the heart for a given cardiac output, avoiding the damaging effects of ischemia.

112. What are the respiratory adaptations to aerobic training?

Without appropriate adaptations in the respiratory system, adaptations in the cardiovascular system would be meaningless. The specific adaptations are designed to maximize the efficiency of oxygen delivery. Specific adaptations include:

- Slight increase in maximal tidal volume
- Decreases in respiratory rate at rest and during submaximal exercise and an increase at maximal levels
- Increase in maximal minute ventilation
- Increase in oxygen diffusion in the alveoli during maximal exercise (unchanged at rest and during submaximal exercise)
- Improved ventilation/perfusion ratio, permitting optimal O_2 uptake from the alveoli into the pulmonary capillaries

113. Does oxygen extraction change with aerobic training?

Although the content of arterial oxygen does not change with training, the venous content is lower. That is, the skeletal muscle extracts more, so the $aO_2 - \bar{v}O_2$ is increased with training. This is a function of the skeletal muscle changes from endurance training, including increases in capillary density and myoglobin content. The net effect is to extract more of the delivered oxygen into the skeletal muscle for use by mitochondria for ATP production.

114. What happens to the lactate threshold with aerobic training?

The lactate threshold shifts to the right, so it will occur at a higher workload. Thus, the **onset** of lactate will occur at a higher percentage of a greater $\dot{V}O_2max$. This appears to be the result of an enhanced clearance of lactate by muscle and a shift toward fatty acid metabolism (produce less lactate). In addition, there is not only a delayed onset, but also an increased tolerance to the acidosis that occurs with training.

115. Describe the mechanisms of skeletal muscle adaptations to resistance training.

Skeletal muscle adaptations to resistance training are partially mediated by adaptations within skeletal muscle and partially associated with changes in the neural motor system. The initial or rapid increases in strength are primarily a function of the neural motor system and learning—that is, a greater ability to recruit motor units. The skeletal muscle adaptations require protein synthesis via transduction, translation, and synthesis, all of which require more time.

116. What are the neural adaptations to resistance training?

- Increase in integrated electromyographic activity, which increases force generation
- Increase in motor unit firing rate, which increases force production and duration of contraction
- Greater ease of motor unit recruitment, so that more motor units are fired simultaneously for greater force production
- Improved motor unit synchronization or coordination, which increases force production and permits a more efficient application of the generated force
- Coordination of antagonists, timing, and inhibition of Golgi tendon organs

117. List the skeletal muscle adaptations to resistance training.

Neural and Skeletal Muscle Tissue Adaptations to Strength Training

ADAPTATIONS	SIGNIFICANCE
↑ Muscle mass	↑ Muscle strength
↑ Cross-sectional area	↑ Contractile capacity
↑ Type I and II fiber area	↑ Strength
↑ Intracellular glycogen content	↑ Glycolytic capacity
↑ Intramuscular high-energy phosphate pool	↑ Phosphagen metabolism

(Table continued on following page.)

Neural and Skeletal Muscle Tissue Adaptations to Strength Training (cont.)

	ADAPTATIONS		SIGNIFICANCE
↑	Intramuscular ATP utilization rate	↑	Capacity for maximum contraction
↑	Androgen receptors	↑	Androgen-induced hypertrophy
↑	Glycolytic enzymes	⇔	Adequate
⇔	Capillary density (weightlifters); ↑ in bodybuilders	↓ or ↑	Diffusion capacity
↑	Rate of motor unit activation	↑	Rate of force development
↑	Integrated electromyographic activity	↑	Force production
↑	Coordination of antagonist and muscle groups	↑	Effectiveness of force application
↑	Motor unit synchronization	↑	Force; ↑ efficiency in application of force
↑	Time high-threshold motor units can be activated	↑	Length of time maximal force can be maintained
↑	Inhibition of Golgi tendon organs	↓	Inhibition of maximal muscle contraction

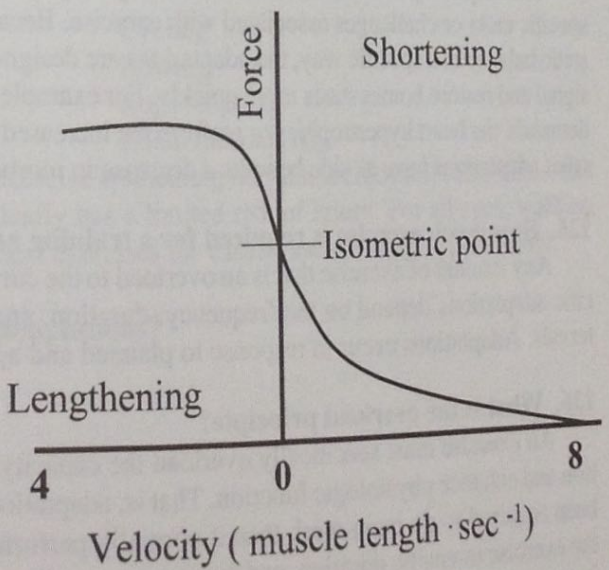
↑ = increased, ↓ = decreased, ⇔ = no change.

118. How is muscle size related to force production?

Force production is directly proportional to the cross-sectional area of the muscle. In response to training, particularly resistance training, skeletal muscle hypertrophies, resulting in an increased cross-sectional area and a concomitant increase in force production.

119. What is the force–velocity relationship?

A **force–velocity curve** is created when the rate of shortening (velocity) is plotted against the force developed. During an isotonic contraction, the muscle changes length. Muscle is capable of shortening at different velocities depending on the load and intrinsic properties. During a shortening or **concentric** contraction, increasing the load results in a decrease in the shortening velocity. That is, when the load is light, the velocity of shortening is fast. When the load is maximal, velocity is zero, and the load does not move. In terms of eccentric or lengthening contraction, note that the force for any given eccentric contraction is greater than the maximal concentric force by 50–100%. That is, skeletal muscle can generate more eccentric force at any velocity than concentric force. These high eccentric forces are the primary reason for exercise-induced muscle injury, which is prevalent after exercise with an eccentric bias.



Relationship between velocity or shortening and force-generating capacity of human skeletal muscle.

120. What is the length–tension relationship?

The amount of tension that a muscle is capable of generating for a given threshold stimulus is critically dependent on its initial resting length relative to its optimal length. Optimal length is defined as the fiber length at which maximal force is generated and where optimal actin–myosin

overlap exists. It is an inverted U-shaped curve. Because the optimal length is the site of optimal force-generating capabilities and is at the peak of the U, changes in fiber length in either direction compromise force.

121. Does fiber type influence performance?

No one knows for sure. Descriptive studies of elite athletes suggest that muscle fiber composition differs for different sports. For example, elite sprinters have 55–75% fast-twitch fibers, whereas elite distance runners have 60–90% slow-twitch fibers. Although this difference suggests that fiber type may be important in sport performance, the studies report a large variability within athletes of a given sport. Clearly, fiber composition is just one component to performance, and one cannot eliminate the complex physiologic interactions of the other systems or ignore the role of training, personality, and psychological components.

122. How does skeletal muscle mass increase?

No one knows for certain. No receptors, signal transducers, or integrating centers have been identified that are responsible for skeletal muscle size. Skeletal muscle is approximately 20% protein and 60–70% water. In humans, skeletal muscle **hypertrophy,** an increase in fiber size, is thought to be the dominant response to training versus an increase in fiber numbers (**hyperplasia**). The increase in fiber size is the result of an increase in protein synthesis. All protein synthesis is regulated by gene expression and is influenced by the cellular environment. Both recruitment and load are known to stimulate muscle DNA translation and thus protein synthesis. Exercise training, nutrition, humoral factors, overall health, and gender are all capable of modifying the protein synthesis in response to the same signal. These factors can either facilitate or inhibit protein synthesis.

123. Other than exercise, what else causes skeletal muscle hypertrophy?

Any work that is an overload stimulates protein synthesis. Furthermore, growth hormone and androgens (endogenous and synthetic) stimulate protein synthesis, as does appropriate nutrition. Research is currently under way to investigate ergogenic aids for their hypertrophic potential. This is not only important in terms of sports and exercise, but also clinically relevant in terms of aging and many patient populations that experience muscle wasting secondary to disease.

124. Why do training adaptations occur?

The major objective of the cellular and organ system adaptations is to facilitate the response to specific tasks or challenges associated with exercise. Because each type of exercise disturbs homeostatic balance in a specific way, the adaptations are designed to respond more quickly to that specific signal and restore homeostasis more quickly. For example, as a result of the increased cardiac output demands, the heart hypertrophies to perform the increased work but at a lower oxygen cost. This and other adaptations have as side benefits a decrease in morbidity and mortality from all causes.

125. How much exercise is required for a training adaptation to occur?

Any amount of exercise that is an overload to the current system will induce adaptations. Specific adaptations depend on the frequency, duration, and intensity of exercise as well as rest intervals. Adaptations occur in response to planned and appropriate overload.

126. What is the overload principle?

An exercise must specifically overload the capacity of the target to evoke a training adaptation and enhance physiologic function. That is, adaptations occur only when a specific system has been required to do more work than it normally performs. If the overload principle is followed, the exercise intensity, duration, and frequency must be manipulated continually to continue to induce adaptations. Adaptations are appropriate to the specific stimulus.

127. What is the principle of task specificity?

Training adaptations respond to the specific initiating stimuli. If one trains the arms, then the arms respond, and the legs show no training adaptations. Similarly, training to shoot free throws

is done by shooting free throws, not by swimming. By definition, the principle of **task specificity** means that specific exercise elicits specific adaptations creating specific training effects or changes in performance. Those systems not stimulated show minimal if any adaptations; this includes the biochemical, neural, and mechanical aspects of exercise. Furthermore, the adaptations are specific to the intensity of the stimuli. Walking for 30 minutes per day results in adaptations to walking with many associated health benefits, but it will not make you a good sprinter or able to complete a marathon.

128. What is the reversibility principle?

Simply stated, **use it or lose it**. Detraining occurs rapidly. If a sufficient stimulus is not provided, the training improvements are rapidly lost. Significant losses can be measured within 1–2 weeks, and bed rest can decrease $\dot{V}O_2$max by 25%, increase resting heart rate, and reduce maximal cardiac output in just 20 days. The central point is that the training benefits are only transient and rapidly reversible unless sufficient stimuli (exercise) are provided to prevent it. Research suggests that training benefits show signs of reversal within 3 days. Therefore, to sustain the adaptations or prevent their loss, exercise should be performed every 48–72 hours. In support of this, studies have demonstrated the effectiveness of 3 days per week frequency vs. 1–2 days per week in terms of retaining cardiovascular training effects.

129. How much exercise is needed to get a beneficial effect in terms of cardiovascular disease?

Healthy People 2020 recommends 30–45 minutes of aerobic exercise 3–5 times per week. Originally, it was thought that this exercise needed to be continuous and of an intensity over 65% of $\dot{V}O_2$max. However, it is now recognized that a cumulative total of 30–45 minutes, that is, the total minutes throughout the day, is sufficient to reap important health benefits, including decreases in cardiovascular mortality. Furthermore, studies have reported the effectiveness of low-risk exercises (low injury rate) such as walking in improving health.

130. What type of exercise or machine is best for cardiovascular disease prevention?

According to the American College of Sports Medicine, in selecting the mode of exercise, any exercise that involves the use of large muscle groups over prolonged periods and is rhythmic and aerobic in nature results in the greatest improvements in $\dot{V}O_2$max and reduction in cardiovascular disease risk. Examples include:

Walking	Cycling
Cross-country skiing	Rowing
Machine-based stair climbing	Rope skipping
Swimming	Endurance activity

Key in the selection of the mode of exercise is selecting one that is enjoyable, affordable, and readily available for participation and ideally has a limited risk of injury. For all ages, **walking** has continually proved to be one of the best exercises for cardiovascular disease prevention.

131. What factors influence training adaptations?

Initial level of fitness
Intensity of training
Frequency of training
Duration of training
Genetics

132. How is training intensity determined?

- Calories per minute
- Absolute workload (watts)
- Relative workload (% of $\dot{V}O_2$max)
- Workload relative to lactate threshold
- Workload at a particular heart rate or a percentage of maximal heart rate
- Multiples of METs
- Rating of perceived exertion

Percentages of **heart rate maximums** and **ratings of perceived exertion** are the most common techniques used for fitness and include a percentage of age-adjusted heart rate maximum (HR_{max} = 220 – age), the Karvonen formula, or the Borg scale of perceived effort.

133. What is the Karvonen formula?

This formula determines exercise intensity based on age-adjusted heart rate maximum but takes into consideration resting heart rate (an index of initial fitness level). To calculate: Subtract standing heart rate (HR) from age-adjusted heart rate maximum (HR_{max}) to obtain heart rate reserve. Calculate intensity range by multiplying high and low ranges by heart rate reserve. To each range value, add back the resting heart rate to obtain target training heart rates.

To calculate the target heart rate for exercise in the range of 50–85% maximum:

$$\text{Target HR range} = [(HR_{max} - HR_{rest}) \times 0.50] + HR_{rest} \text{ and}$$

$$[(HR_{max} - HR_{rest}) \times 0.85] + HR_{rest}$$

134. What is resting metabolic rate?

The amount of oxygen consumed to provide ATP for the metabolic processes occurring at rest. For men it is 3.7 ml O_2/body weight in kg/min. For women it is 3.2 ml O_2/body weight in kg/min. Resting metabolic rate (RMR) differs from basal metabolic rate (BMR). The requirements for measuring RMR are much less stringent and often include the thermic effect of food, whereas BMR can be measured only following a minimum of a 12-hour fast and refraining from performing any physical activity for several hours prior to the test. Typically, BMR is measured after an overnight stay in a special facility. RMR is a good estimate of BMR and can be measured 3 hours after a light meal or exercise. Lean body mass has the greatest effect on increasing either RMR or BMR.

135. Are METs a baseball team?

No, a MET is a unit of metabolic work. MET stands for **metabolic equivalent**. Average resting metabolic rate for men and women is 3.5 mL of oxygen uptake per kilogram of body weight per minute, which means that 3.5 mL O_2/kg body weight/min are burned or metabolized to make ATP while just resting. This is equal to approximately 1.2 kcal/min.

136. How are METs used to quantify work?

By knowing the energy cost of different types of activity and converting them to their requirement for oxygen, one can use multiples of METs to define intensity. Thus, 1 MET is resting activity, 2 METs is work above rest, and 10 METs requires 10 times more oxygen than at rest and is thus harder. METs have been worked out for many activities. METs are commonly used to express exercise intensity and for exercise prescriptions because they are easy to understand and remember for many people. Low intensity is 3–4 METs, moderate is 6–8 METs, and vigorous exercise increases metabolic rate above 10 METs.

137. Define calorie.

The quantity of heat required to raise the temperature of 1 kg of water 1°C. It is most appropriately called a kilogram calorie or a **kilocalorie (kcal)**. As such, a quantity of food containing 250 kcal contains sufficient energy to increase the temperature of 250 kg of water 1°C. Thus, kilocalorie is a unit of expressing energy. Humans are inefficient in converting kilocalories to ATP, and they lose 40–60% of the energy as heat. Energy consumption may be measured by measuring heat loss or, more conveniently, by measuring oxygen uptake. This is because oxygen is required in the combustion of food. Measuring oxygen consumption allows us to calculate the energy cost (kilocalories) of different activities.

138. How can you determine the calories burned by measuring oxygen consumption?

Oxygen is consumed in the combustion of food to release energy for activity. The more oxygen consumed, the more energy used. Each liter of oxygen burned is 5 kcal. Therefore, if resting oxygen is 3.5 mL of oxygen/kg/min for a 70-kg man, then at rest he burns the following:

$$3.5 \text{ mL} \times 70 \text{ kg} = 245 \text{ mL } O_2/1000 = 0.245 \text{ L } O_2$$

$$0.245 \text{ L } O_2 \times 5 \text{ kcal/L} = 1.225 \text{ kcal/min at rest}$$

This equals 74 kcal/hr (1.225 × 60 min/hr) or 1764 kcal in a single day just for resting metabolism.

138. How many calories do you burn when you exercise?

It depends on the type of exercise, the intensity, and, in some instances, the body weight. For example, if a 70-kg man performs 30 minutes of aerobic exercise at an intensity level of 8 METs, he is burning the following:

$$3.5 \times 8 \times 70 = 1960/1000 = 1.9 \text{ L } O_2 \times 5 \text{ kcal/L} = 9.8 \text{ kcal/min} \times 30 = \text{total of } 294 \text{ kcal}$$

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