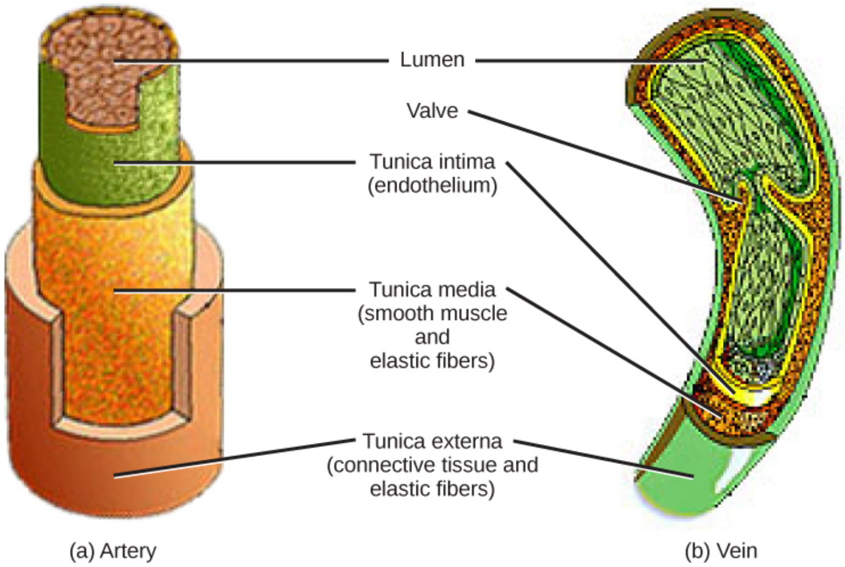

Figure 40.16 Arteries and veins consist of three layers: an outer tunica externa, a middle tunica media, and an inner tunica intima. Capillaries consist of a single layer of epithelial cells, the tunica intima. (credit: modification of work by NCI, NIH)

40.4 Blood Flow and Blood Pressure Regulation

By the end of this section, you will be able to do the following:

- Describe the system of blood flow through the body
- Describe how blood pressure is regulated

Blood pressure (BP) is the pressure exerted by blood on the walls of a blood vessel that helps to push blood through the body. Systolic blood pressure measures the amount of pressure that blood exerts on vessels while the heart is beating. The optimal systolic blood pressure is 120 mmHg. Diastolic blood pressure measures the pressure in the vessels between heartbeats. The optimal diastolic blood pressure is 80 mmHg. Many factors can affect blood pressure, such as hormones, stress, exercise, eating, sitting, and standing. Blood flow through the body is regulated by the size of blood vessels, by the action of smooth muscle, by one-way valves, and by the fluid pressure of the blood itself.

How Blood Flows Through the Body

Blood is pushed through the body by the action of the pumping heart. With each rhythmic pump, blood is pushed under high pressure and velocity away from the heart, initially along the main artery, the aorta. In the aorta, the blood travels at 30 cm/sec. As blood moves into the arteries, arterioles, and ultimately to the capillary beds, the rate of movement slows dramatically to about 0.026 cm/sec, one-thousand times slower than the rate of movement in the aorta. While the diameter of each individual arteriole and capillary is far narrower than the diameter of the aorta, and according to the law of continuity, fluid should travel faster through a narrower diameter tube, the rate is actually slower due to the overall diameter of all the combined capillaries being far greater than the diameter of the individual aorta.

The slow rate of travel through the capillary beds, which reach almost every cell in the body, assists with gas and nutrient exchange and also promotes the diffusion of fluid into the interstitial space. After the blood has passed through the capillary beds to the venules, veins, and finally to the main venae cavae, the rate of flow increases again but is still much slower than the initial rate in the aorta. Blood primarily moves in the veins by the rhythmic movement of smooth muscle in the vessel wall and by the action of the skeletal muscle as the body moves. Because most veins must move blood against the pull of gravity, blood is prevented from flowing backward in the veins by one-way valves. Because skeletal muscle contraction aids in venous blood flow, it is important to get up and move frequently after long periods of sitting so that blood will not pool in the extremities.

Blood flow through the capillary beds is regulated depending on the body's needs and is directed by nerve and hormone signals. For example, after a large meal, most of the blood is diverted to the stomach by vasodilation of vessels of the digestive system and vasoconstriction of other vessels. During exercise, blood is diverted to the skeletal muscles through vasodilation while blood to the digestive system would be lessened through vasoconstriction. The blood entering some capillary beds is controlled by small muscles, called precapillary sphincters, illustrated in Figure 40.17. If the sphincters are open, the blood will flow into the associated branches of the capillary blood. If all of the sphincters are closed, then the blood will flow directly from the arteriole to the venule through the thoroughfare channel (see Figure 40.17). These muscles allow the body to precisely control when capillary beds receive blood flow. At any given moment only about 5–10% of our capillary beds actually have blood flowing through them.

VISUAL CONNECTION

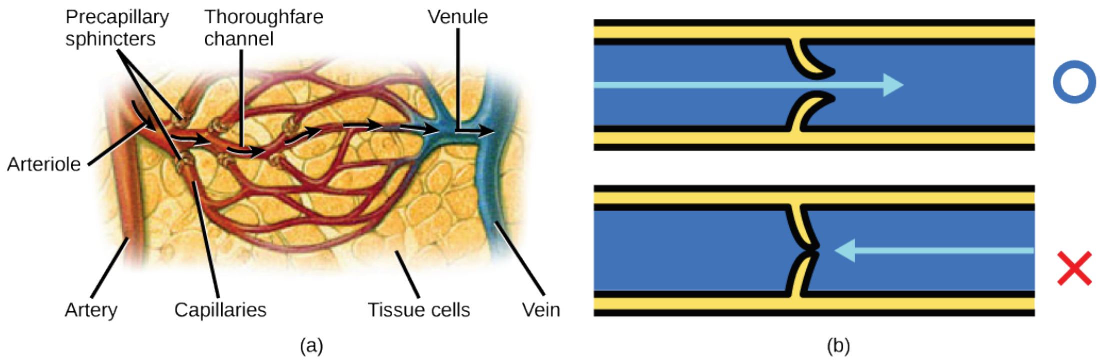

Figure 40.17 (a) Precapillary sphincters are rings of smooth muscle that regulate the flow of blood through capillaries; they help control the location of blood flow to where it is needed. (b) Valves in the veins prevent blood from moving backward. (credit a: modification of work by NCI)

Varicose veins are veins that become enlarged because the valves no longer close properly, allowing blood to flow backward. Varicose veins are often most prominent on the legs. Why do you think this is the case?

LINK TO LEARNING

See the circulatory system's blood flow.

Click to view content (https://www.openstax.org/l/circulation)

Proteins and other large solutes cannot leave the capillaries. The loss of the watery plasma creates a hyperosmotic solution within the capillaries, especially near the venules. This causes about 85% of the plasma that leaves the capillaries to eventually diffuse back into the capillaries near the venules. The remaining 15% of blood plasma drains out from the interstitial fluid into nearby lymphatic vessels (Figure 40.18). The fluid in the lymph is similar in composition to the interstitial fluid. The lymph fluid passes through lymph nodes before it returns to the heart via the vena cava. **Lymph nodes** are specialized organs that filter the lymph by percolation through a maze of connective tissue filled with white blood cells. The white blood cells remove infectious agents, such as bacteria and viruses, to clean the lymph before it returns to the bloodstream. After it is cleaned, the lymph returns to the heart by the action of smooth muscle pumping, skeletal muscle action, and one-way valves joining the returning blood near the junction of the venae cavae entering the right atrium of the heart.

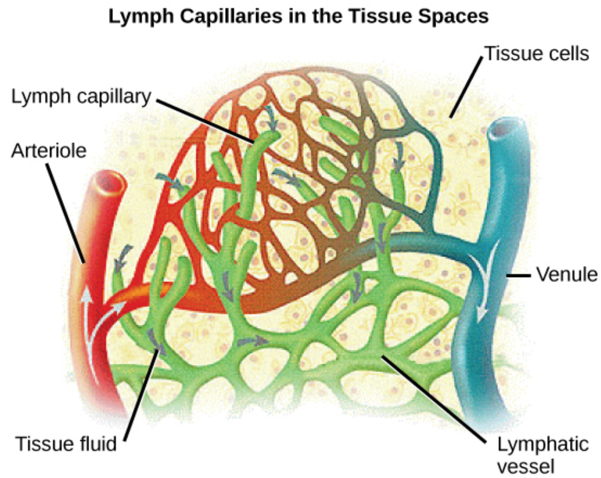

Figure 40.18 Fluid from the capillaries moves into the interstitial space and lymph capillaries by diffusion down a pressure gradient and also by osmosis. Out of 7,200 liters of fluid pumped by the average heart in a day, over 1,500 liters is filtered. (credit: modification of work by NCI, NIH)

EVOLUTION CONNECTION

Vertebrate Diversity in Blood Circulation

Blood circulation has evolved differently in vertebrates and may show variation in different animals for the required amount of pressure, organ and vessel location, and organ size. Animals with longs necks and those that live in cold environments have distinct blood pressure adaptations.

Long necked animals, such as giraffes, need to pump blood upward from the heart against gravity. The blood pressure required from the pumping of the left ventricle would be equivalent to 250 mm Hg (mm Hg = millimeters of mercury, a unit of pressure) to reach the height of a giraffe's head, which is 2.5 meters higher than the heart. However, if checks and balances were not in place, this blood pressure would damage the giraffe's brain, particularly if it was bending down to drink. These checks and balances include valves and feedback mechanisms that reduce the rate of cardiac output. Long-necked dinosaurs such as the sauropods had to pump blood even higher, up to ten meters above the heart. This would have required a blood pressure of more than 600 mm Hg, which could only have been achieved by an enormous heart. Evidence for such an enormous heart does not exist and mechanisms to reduce the blood pressure required include the slowing of metabolism as these animals grew larger. It is likely that they did not routinely feed on tree tops but grazed on the ground.

Living in cold water, whales need to maintain the temperature in their blood. This is achieved by the veins and arteries being close together so that heat exchange can occur. This mechanism is called a countercurrent heat exchanger. The blood vessels and the whole body are also protected by thick layers of blubber to prevent heat loss. In land animals that live in cold environments, thick fur and hibernation are used to retain heat and slow metabolism.

Blood Pressure

The pressure of the blood flow in the body is produced by the hydrostatic pressure of the fluid (blood) against the walls of the blood vessels. Fluid will move from areas of high to low hydrostatic pressures. In the arteries, the hydrostatic pressure near the heart is very high and blood flows to the arterioles where the rate of flow is slowed by the narrow openings of the arterioles. During systole, when new blood is entering the arteries, the artery walls stretch to accommodate the increase of pressure of the extra blood; during diastole, the walls return to normal because of their elastic properties. The blood pressure of the systole phase and the diastole phase, graphed in Figure 40.19, gives the two pressure readings for blood pressure. For example, 120/80 indicates a reading of 120 mm Hg during the systole and 80 mm Hg during diastole. Throughout the cardiac cycle, the blood continues to empty into the arterioles at a relatively even rate. This resistance to blood flow is called **peripheral resistance**.

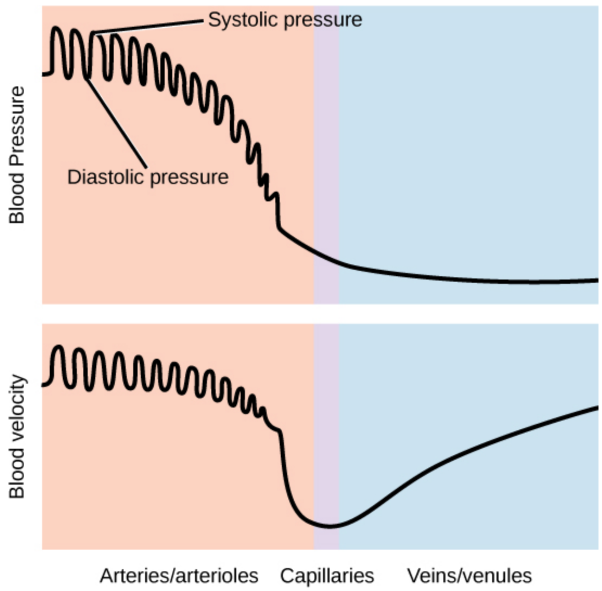

Figure 40.19 Blood pressure is related to the blood velocity in the arteries and arterioles. In the capillaries and veins, the blood pressure continues to decrease but velocity increases.

Blood Pressure Regulation

Cardiac output is the volume of blood pumped by the heart in one minute. It is calculated by multiplying the number of heart contractions that occur per minute (heart rate) times the **stroke volume** (the volume of blood pumped into the aorta per contraction of the left ventricle). Therefore, cardiac output can be increased by increasing heart rate, as when exercising. However, cardiac output can also be increased by increasing stroke volume, such as if the heart contracts with greater strength. Stroke volume can also be increased by speeding blood circulation through the body so that more blood enters the heart between contractions. During heavy exertion, the blood vessels relax and increase in diameter, offsetting the increased heart rate and ensuring adequate oxygenated blood gets to the muscles. Stress triggers a decrease in the diameter of the blood vessels, consequently increasing blood pressure. These changes can also be caused by nerve signals or hormones, and even standing up or lying down can have a great effect on blood pressure.

KEY TERMS

angina pain caused by partial blockage of the coronary arteries by the buildup of plaque and lack of oxygen to the heart muscle

aorta major artery of the body that takes blood away from the heart

arteriole small vessel that connects an artery to a capillary bed

artery blood vessel that takes blood away from the heart

atherosclerosis buildup of fatty plaques in the coronary arteries in the heart

atrioventricular valve one-way membranous flap of connective tissue between the atrium and the ventricle in the right side of the heart; also known as tricuspid valve

atrium (plural: atria) chamber of the heart that receives blood from the veins and sends blood to the ventricles

bicuspid valve (also, mitral valve; left atrioventricular valve) one-way membranous flap between the atrium and the ventricle in the left side of the heart

blood pressure (BP) pressure of blood in the arteries that helps to push blood through the body

capillary smallest blood vessel that allows the passage of individual blood cells and the site of diffusion of oxygen and nutrient exchange

capillary bed large number of capillaries that converge to take blood to a particular organ or tissue

cardiac cycle filling and emptying the heart of blood by electrical signals that cause the heart muscles to contract and relax

cardiac output the volume of blood pumped by the heart in one minute as a product of heart rate multiplied by stroke volume

cardiomyocyte specialized heart muscle cell that is striated but contracts involuntarily like smooth muscle

closed circulatory system system in which the blood is separated from the bodily interstitial fluid and contained in blood vessels

coronary artery vessel that supplies the heart tissue with blood

coronary vein vessel that takes blood away from the heart tissue back to the chambers in the heart

diastole relaxation phase of the cardiac cycle when the heart is relaxed and the ventricles are filling with blood

double circulation flow of blood in two circuits: the pulmonary circuit through the lungs and the systemic circuit through the organs and body

electrocardiogram (ECG) recording of the electrical impulses of the cardiac muscle

endocardium innermost layer of tissue in the heart

epicardium outermost tissue layer of the heart

gill circulation circulatory system that is specific to animals with gills for gas exchange; the blood flows through the gills for oxygenation

hemocoel cavity into which blood is pumped in an open circulatory system

hemolymph mixture of blood and interstitial fluid that is found in insects and other arthropods as well as most mollusks

inferior vena cava drains blood from the veins that come from the lower organs and the legs

interstitial fluid fluid between cells

lymph node specialized organ that contains a large number of macrophages that clean the lymph before the fluid is returned to the heart

myocardial infarction (also, heart attack) complete blockage of the coronary arteries and death of the cardiac muscle tissue

myocardium heart muscle cells that make up the middle layer and the bulk of the heart wall

open circulatory system system in which the blood is mixed with interstitial fluid and directly covers the organs

ostium (plural: ostia) holes between blood vessels that allow the movement of hemolymph through the body of insects, arthropods, and mollusks with open circulatory systems

pericardium membrane layer protecting the heart; also part of the epicardium

peripheral resistance resistance of the artery and blood vessel walls to the pressure placed on them by the force of the heart pumping

plasma liquid component of blood that is left after the cells are removed

platelet (also, thrombocyte) small cellular fragment that collects at wounds, cross-reacts with clotting factors, and forms a plug to prevent blood loss

precapillary sphincter small muscle that controls blood circulation in the capillary beds

pulmocutaneous circulation circulatory system in amphibians; the flow of blood to the lungs and the moist skin for gas exchange

pulmonary circulation flow of blood away from the heart through the lungs where oxygenation occurs and then returns to the heart again

red blood cell small (7–8 μm) biconcave cell without mitochondria (and in mammals without nuclei) that is packed with hemoglobin, giving the cell its red color; transports oxygen through the body

semilunar valve membranous flap of connective tissue between the aorta and a ventricle of the heart (the aortic or pulmonary semilunar valves)

serum plasma without the coagulation factors

sinoatrial (SA) node the heart's internal pacemaker; located near the wall of the right atrium

stroke volume the volume of blood pumped into the aorta per contraction of the left ventricle

superior vena cava drains blood from the jugular vein that comes from the brain and from the veins that come from the arms

systemic circulation flow of blood away from the heart to the brain, liver, kidneys, stomach, and other organs, the limbs, and the muscles of the body, and then the return of this blood to the heart

systole contraction phase of cardiac cycle when the ventricles are pumping blood into the arteries

tricuspid valve one-way membranous flap of connective tissue between the atrium and the ventricle in the right side of the heart; also known as atrioventricular valve

unidirectional circulation flow of blood in a single circuit; occurs in fish where the blood flows through the gills, then past the organs and the rest of the body, before returning to the heart

vasoconstriction narrowing of a blood vessel

vasodilation widening of a blood vessel

vein blood vessel that brings blood back to the heart

vena cava major vein of the body returning blood from the upper and lower parts of the body; see the superior vena cava and inferior vena cava

ventricle (heart) large inferior chamber of the heart that pumps blood into arteries

venule blood vessel that connects a capillary bed to a vein

white blood cell large (30 µm) cell with nuclei of which there are many types with different roles including the protection of the body from viruses and bacteria, and cleaning up dead cells and other waste

CHAPTER SUMMARY

40.1 Overview of the Circulatory System

In most animals, the circulatory system is used to transport blood through the body. Some primitive animals use diffusion for the exchange of water, nutrients, and gases. However, complex organisms use the circulatory system to carry gases, nutrients, and waste through the body. Circulatory systems may be open (mixed with the interstitial fluid) or closed (separated from the interstitial fluid). Closed circulatory systems are a characteristic of vertebrates; however, there are significant differences in the structure of the heart and the circulation of blood between the different vertebrate groups due to adaptions during evolution and associated differences in anatomy. Fish have a two-chambered heart with unidirectional circulation. Amphibians have a three-chambered heart, which has some mixing of the blood, and they have double circulation. Most non-avian reptiles have a three-chambered heart, but have little mixing of the blood; they have double circulation. Mammals and birds have a four-chambered heart with no mixing of the blood and double circulation.

40.2 Components of the Blood

Specific components of the blood include red blood cells, white blood cells, platelets, and the plasma, which contains coagulation factors and serum. Blood is important for regulation of the body's pH, temperature, osmotic pressure, the circulation of nutrients and removal of waste, the distribution of hormones from endocrine glands, and the elimination of excess heat; it also contains components for blood clotting. Red blood cells are specialized cells that contain hemoglobin and circulate through the body delivering oxygen to cells. White blood cells are involved in the immune response to identify and target invading bacteria, viruses, and other foreign organisms; they also recycle waste components, such as old red blood cells. Platelets and blood clotting factors cause the change of the soluble protein fibrinogen to the insoluble protein fibrin at a wound site forming a plug. Plasma consists of 90 percent water along with various substances, such as coagulation factors and antibodies. The serum is the plasma component of the blood without the coagulation factors.

40.3 Mammalian Heart and Blood Vessels

The heart muscle pumps blood through three divisions of the circulatory system: coronary, pulmonary, and systemic. There is one atrium and one ventricle on the right side and one atrium and one ventricle on the left side. The pumping of the heart is a function of cardiomyocytes, distinctive muscle cells that are striated like skeletal muscle but pump rhythmically and involuntarily like smooth muscle. The internal pacemaker starts at the sinoatrial node, which is located near the wall of the right atrium. Electrical charges pulse from the SA node causing the two atria to contract in unison; then the pulse reaches the atrioventricular node between the right atrium and right ventricle. A pause in the electric signal allows the atria to empty completely into the ventricles before the ventricles pump out the blood. The blood from the heart is carried through the body by a complex network of blood vessels; arteries take blood away from the heart, and veins bring blood back to the heart.

40.4 Blood Flow and Blood Pressure Regulation

Blood primarily moves through the body by the rhythmic movement of smooth muscle in the vessel wall and by the action of the skeletal muscle as the body moves. Blood is prevented from flowing backward in the veins by one-way valves. Blood flow through the capillary beds is controlled by precapillary sphincters to increase and decrease flow depending on the body's needs and is directed by nerve and hormone signals. Lymph vessels take fluid that has leaked out of the blood to the lymph nodes where it is cleaned before returning to the heart. During systole, blood enters the arteries, and the artery walls stretch to accommodate the extra blood. During diastole, the artery walls return to normal. The blood pressure of the systole phase and the diastole phase gives the two pressure readings for blood pressure.

VISUAL CONNECTION QUESTIONS

1. Figure 40.10 Which of the following statements about the circulatory system is false?
   a. Blood in the pulmonary vein is deoxygenated.
   b. Blood in the inferior vena cava is deoxygenated.
   c. Blood in the pulmonary artery is deoxygenated.
   d. Blood in the aorta is oxygenated.

2. Figure 40.11 Which of the following statements about the heart is false?
   a. The mitral valve separates the left ventricle from the left atrium.
   b. Blood travels through the bicuspid valve to the left atrium.
   c. Both the aortic and the pulmonary valves are semilunar valves.
   d. The mitral valve is an atrioventricular valve.

3. Figure 40.17 Varicose veins are veins that become enlarged because the valves no longer close properly, allowing blood to flow backward. Varicose veins are often most prominent on the legs. Why do you think this is the case?

REVIEW QUESTIONS

4. Why are open circulatory systems advantageous to some animals?
   a. They use less metabolic energy.
   b. They help the animal move faster.
   c. They do not need a heart.
   d. They help large insects develop.

5. Some animals use diffusion instead of a circulatory system. Examples include:
   a. birds and jellyfish
   b. flatworms and arthropods
   c. mollusks and jellyfish
   d. none of the above

6. Blood flow that is directed through the lungs and back to the heart is called ________.
   a. unidirectional circulation
   b. gill circulation
   c. pulmonary circulation
   d. pulmocutaneous circulation

7. White blood cells:
   a. can be classified as granulocytes or agranulocytes
   b. defend the body against bacteria and viruses
   c. are also called leucocytes
   d. all of the above

8. Platelet plug formation occurs at which point?
   a. when large megakaryocytes break up into thousands of smaller fragments
   b. when platelets are dispersed through the bloodstream
   c. when platelets are attracted to a site of blood vessel damage
   d. none of the above

9. In humans, the plasma comprises what percentage of the blood?
   a. 45 percent
   b. 55 percent
   c. 25 percent
   d. 90 percent

10. The red blood cells of birds differ from mammalian red blood cells because:
   a. they are white and have nuclei
   b. they do not have nuclei
   c. they have nuclei
   d. they fight disease

11. The heart's internal pacemaker beats by:
    a. an internal implant that sends an electrical impulse through the heart
    b. the excitation of cardiac muscle cells at the sinoatrial node followed by the atrioventricular node
    c. the excitation of cardiac muscle cells at the atrioventricular node followed by the sinoatrial node
    d. the action of the sinus

12. During the systolic phase of the cardiac cycle, the heart is ________.
    a. contracting
    b. relaxing
    c. contracting and relaxing
    d. filling with blood

13. Cardiomyocytes are similar to skeletal muscle because:
    a. they beat involuntarily
    b. they are used for weight lifting
    c. they pulse rhythmically
    d. they are striated

14. How do arteries differ from veins?
    a. Arteries have thicker smooth muscle layers to accommodate the changes in pressure from the heart.
    b. Arteries carry blood.
    c. Arteries have thinner smooth muscle layers and valves and move blood by the action of skeletal muscle.
    d. Arteries are thin walled and are used for gas exchange.

15. High blood pressure would be a result of ________.
    a. a high cardiac output and high peripheral resistance
    b. a high cardiac output and low peripheral resistance
    c. a low cardiac output and high peripheral resistance
    d. a low cardiac output and low peripheral resistance

CRITICAL THINKING QUESTIONS

16. Describe a closed circulatory system.
17. Describe systemic circulation.
18. Describe the cause of different blood type groups.
19. List some of the functions of blood in the body.
20. How does the lymphatic system work with blood flow?
21. Describe the cardiac cycle.
22. What happens in capillaries?
23. How does blood pressure change during heavy exercise?