Cardiovascular Physiology

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The Heart

The single most important muscle in the body is the heart. By performing continuous synchronized contractions, the heart works as a pump to deliver oxygen-rich blood and nutrients to tissues in the body. The heart is divided into two distinct sides that actually perform different tasks. The right side of the heart pumps deoxygenated blood to the lungs, whereas the left side of the heart sends oxygenated blood to the rest of the body. It accomplishes both responsibilities by functioning with a dual pump action. To manage this, each side of the heart has two distinct chambers, a top chamber called the atrium and a bottom chamber called the ventricle. The blood flows through the chambers under the force of the contracting tissue.

During cellular respiration, oxygen is used by the cell to perform its normal activities. In the process, oxygen chemically attaches to carbon to form carbon dioxide. The carbon dioxide is shuttled into circulation as bicarbonate where it is transported to the heart. It is then pumped to the lungs to be diffused across the alveoli and expired into the air. The deoxygenated blood enters the upper portion of the heart, the right atrium, through a large blood vessel called the superior vena cava. Blood fills the right atrium and is prevented from entering the right ventricle by the closed tricuspid valve. When the upper portion of the heart contracts both the left and right atria are emptied into their respective ventricles. Upon contraction, the deoxygenated blood is pushed through the tricuspid valve into the right lower chamber, which fills while the ventricle tissue is in a relaxed state. The ventricle relaxation phase is referred to as diastole. When the lower portion of the heart contracts it pushes the blood back against the tricuspid valve, forcing it to close. At the same time, the pulmonary semilunar valve is pushed open, allowing the blood to pass into the pulmonary artery. The contraction phase of the ventricles is referred to as systole. This interaction between the chambers and their corresponding valves is important so that blood flow is maintained in only one direction. The familiar “lub-dub” sound of a heart beating is actually the sound that the valves make when they close. It is important to understand that while the atria are contracting, the ventricles are relaxed (diastole), allowing them to fill with blood. Conversely, when the ventricles contract (systole), the atrium is relaxed, allowing for them to refill with blood so that the cycle can repeat itself.

The pulmonary trunk transports the blood to the lungs where carbon dioxide is released while freshly inhaled oxygen is picked up. The oxygen diffuses through the lungs’ alveoli and attaches to hemoglobin located in the red blood cells. The blood turns red with oxygenation and is transferred back to the heart via the pulmonary vein. It re-enters the heart through the left atrium. In the same manner it was pumped out to the lungs, the now oxygen-rich blood is pushed through the bicuspid valve (mitral valve), which separates the left atrium from the left ventricle. Contraction of the left ventricle pushes the blood back against the bicuspid valve, closing it, while at the same time forcing the volume of blood through the aortic valve to the aorta. The aorta then distributes the blood to the rest of the body.
Oxygen depleted blood returning from the body enters the right atrium, which fills and contracts. This mobilizes the blood into the right ventricle. The right ventricle then contracts, pushing the blood into the pulmonary artery, which delivers it to the lungs where carbon dioxide is exchanged for oxygen. The oxygen diffuses into the blood across the lungs’ alveoli and binds to hemoglobin, a component of red blood cells that serves as oxygen’s transporter throughout circulation. Once oxygenated, the blood returns to the left side of the heart through the pulmonary vein and enters the left atrium, which contracts, pushing the blood into the left ventricle. Completing the heart flow cycle, the left ventricle contracts, driving the blood through the aorta out to the rest of the body where oxygen and nutrients are exchanged for carbon dioxide and metabolic waste, all of which is returned back to the right side of the heart, re-initiating this continuous ongoing loop. The left ventricle has to deliver blood to the entire body, so it is not surprising that it is the largest of all the chambers. Furthermore, the wave of depolarization smoothly moves blood through the respective chambers through simultaneous and synchronized contractions. The SA Node dictates pace to the right and left atrium, which contract, pushing the blood into the ventricles, which, in turn, are then stimulated to contract in a likewise synchronized fashion to effectively push blood out from the heart.
Cardiac Muscle Tissue

The heart muscle, also called the myocardium, is somewhat similar to skeletal muscle but is more specialized for its purpose of repeated, measured contractions. Cardiac muscle tissue, like skeletal muscle tissue, has a sarcoplasmic reticulum for calcium storage and T-tubules to manage action potentials. It also has organized sarcomeres, which contain actin and myosin contractile proteins. However, there are distinct differences between cardiac and skeletal muscle. These differences allow the heart to function in a constant non-stop manner, rather than serving the intermittent, voluntary actions common of skeletal muscle.

Cardiac tissue, like all tissue, relies on ATP for fuel. The heart needs a constant supply of energy and oxygen so it will not fatigue. If the heart were to fatigue under conditions of high stress, it could be lethal because oxygen would no longer reach vital organs, including the brain and the heart’s contractile tissue. Cardiac tissue relies heavily on ATP produced from lipids. In the last chapter, lipid metabolism was shown to produce large quantities of ATP at lower intensities. This makes it the ideal fuel for the heart, as the cardiac muscle runs almost exclusively using oxidative metabolism to satisfy its energy demands.

In an effort to maximize the efficiency of the aerobic system, cardiac muscle is densely packed with mitochondria and contains an extensive network of capillaries (one capillary per muscle fiber). This arrangement provides a constant flow of oxygen-rich blood to the mitochondria for the production of ATP. Consistent with skeletal muscle, cardiac muscle must utilize carbohydrates to fuel the higher force outputs required during heavy exercise (6). But unlike the skeletal muscle, the heart cannot allow hydrogen ions from lactic acid to build up, as they may inhibit enzyme activity and contractility. To ensure this does not occur, myocardial tissues possess greater capacity to utilize oxygen and blood to increase the rate of lactate conversion, effectively preventing fatigue. Cardiac muscle extracts approximately 75% of the available oxygen, whereas skeletal muscle extracts closer to 25% of the oxygen delivered to the tissue.

Another significant difference between cardiac and skeletal muscle is the conduction system used by the heart to manage an efficient pump mechanism. The sinoatrial (SA) node and the atrioventricular (AV) node are modified cardiac muscle cells that connect to a conducting bundle. The nodes send electrical impulses that run down the connecting bundle, which branches to the chambers of the heart. Respectively, the branches are identified as the left and right bundle branches.

The signals from the nodes dictate the contractile element of the heart. Essentially, the SA and AV nodes communicate to the atria and ventricles when to contract. This eloquent system of conduction allows the atria and ventricles to contract in synchronicity so that the forward flow of blood is maintained.

The initial contractile signal for the heart originates in the SA node. For this reason, the SA node is called the pacemaker, as its chief responsibility is to signal the contractile pace to the atria. It sends a slower signal through the atrial cardiac tissue to stimulate contraction of the right and left atrium and a faster messenger signal to the AV node through preferential pathways to relay the pace to the ventricles (17). The passage of the slower signals across the atrial portion of the heart represents the electrical impulse that drives the atrial contraction. After receiving the signal from the SA node, the AV node transfers these signals to the AV bundle. When the action potential reaches the left and

~Key Terms~

Myocardium- The muscular tissue of the heart.
Sinoatrial (SA) node- A small mass of specialized cardiac muscle fibers that controls the heartbeat.
Atrioventricular (AV) node- A small mass of specialized cardiac muscle fibers between the atria and the ventricles of the heart, which conducts the normal electrical impulse from the atria (SA node) to the ventricles.
Bundle branches- Part of the impulse-conducting network of the heart that rapidly transmit impulses from the atrioventricular node to the ventricles.
Wave of depolarization- Electrical activation of the myocardium. Occurs in the sinoatrial (SA) node; current travels through the tracts of the atria to the atrioventricular (AV) node then through the Bundle of His, which divides into right and left bundle branches.
right bundles, it speeds up to stimulate the contraction of the ventricles. This process of electrical transfer across the heart is called the **wave of depolarization**. The relatively slow transfer time allows the atrium to contract and then relax as the ventricles become stimulated. This conduction system maintains a steady flow of blood through the heart and out to the lungs and circulation.

**Conduction System of the Heart**

Cardiac Output

When the heart pumps blood from the left ventricle out to the body’s tissues, the volume of blood expelled per contraction is called the **stroke volume (SV)**. The volume expelled depends upon the strength of the cardiac muscular contraction, as well as the volume of the left ventricle. Individuals who engage in endurance training activities increase their capacity to pump blood out to the tissues through adaptations that make the ventricular contraction stronger and the volume of blood expelled out of the aorta larger (18). The rate at which the blood is pumped determines the amount of blood available to the tissue. **Heart rate** describes the number of beats that occur in the heart each minute. When the heart rate is multiplied by the amount of blood expelled per beat (stroke volume), the total volume of blood available per minute can be determined. This value is referred to as the heart’s **cardiac output**. Cardiac output is a major determinant of the body’s ability to sustain physical activity (12).

**CARDIAC OUTPUT = HR X SV**

Blood Pressure

Blood leaving the heart enters into peripheral circulation via the left ventricle. Blood from the right ventricle flows to the lungs to be re-oxygenated, while the blood from the left ventricle flows through the systemic vessels and is transported to the body tissues. When the blood reaches the tissue, it deposits oxygen and nutrients and removes the cellular waste. To ensure that the flow of blood to the tissues is maintained at appropriate levels, the circulatory system has regulatory mechanisms that control the pressure exerted on the blood. **Blood pressure** is managed by **baroreceptors** located in the aorta and the carotid arteries. When the body needs oxygen for working tissue, the pressure in the blood vessels is adjusted to meet the demand. Areas of the body which require more oxygenated blood experience expansion in the diameter of their respective vessels called **vasodilation**, while the areas requiring less oxygenated blood experience a narrowing of the vessels referred to as **vasoconstriction**. By changing the diameter of the vessels, blood pressure can be increased or decreased according to relative demands.

Blood pressure is determined by multiplying the cardiac output of the heart and the **peripheral resistance** applied by the vessels. When the body is at rest, the cardiac output is low, so the main determinant of blood pressure is peripheral resistance (20). Peripheral resistance reflects the difficulty with which the blood passes through the vessels. Constricted or compressed...
vessels or those that have plaque built up along the walls make it harder for the blood to pass because the space in the vessel is compromised. When the blood experiences difficulty passing through a vessel, it builds up pressure and becomes turbulent. This is common in individuals who smoke, are obese, or experience a build-up of fat along the vessel wall (16). In small vessels, the stress can lead to artery disease. On the contrary, large vessels and those that provide little resistance pass blood with much less effort and do not cause damaging fluid turbulence.

During exercise or high stress situations, the heart rate is increased, consequently increasing cardiac output. The increase in cardiac output forces blood to flow through the system at a faster rate. The high speed circulation of blood pushes out on the walls of the vessels, increasing the pressure. When this pressure is added to the peripheral resistance of the vessels, it equals the net blood pressure of the body. Due to elevations in heart rate during exercise, blood pressure is always higher than when the body is at rest. At rest, mean arterial pressure (MAP) in the large arteries is about 100 mm Hg. During aerobic exercise the MAP will jump to 115-120 mm Hg, while during heavy resistance training that number can increase to 200 mm Hg (4). When selecting or prescribing exercise modalities for clients, personal trainers should consider blood pressure response, to ensure the exercises reflect the individual’s current vascular health. Increasing blood pressure in hypertensive and elderly clients increases risk of vessel wall damage and may exacerbate tissue lesions and arteriosclerosis (2).

**Peripheral Circulatory System**

To get blood to all the working tissues of the body, an intricate network of vessels of varying sizes is needed. In the same way a tree branches into limbs that further divide into smaller branches, large vessels from the heart branch to smaller vessels that are far reaching throughout the body. Blood leaving the heart enters into large arteries, which branch repeatedly into smaller arteries. The main arteries direct blood to the major sections of the body. Leaving the heart, the ascending aorta branches into the large arteries that deliver blood to the brain, called the carotid arteries, and the brachiocephalic artery, which extends to arteries of the upper extremity, including the brachial artery. The descending aorta travels down the trunk to form the iliac artery, which eventually branches into the femoral arteries. These arteries are responsible for delivering blood to the lower limbs. Along the way, the aorta has branches that extend to the organs and tissues of the trunk.

The large arteries have elastic properties to manage the high pressure in the vessels. They maintain lower amounts of smooth muscle tissue when compared to smaller vessels in part due to their role in delivery and their respective proximity to the heart. Their primary function in the vascular system is to deliver large quantities of blood to the main body segments, which is why they are referred to as **conducting arteries**. Large arteries give way to medium size arteries, which turn...
into smaller branch arteries. As the artery diameter becomes narrower, the amount of elastic tissue is reduced and is replaced by larger amounts of smooth muscle. Medium size arteries are called distributors because they have a regulatory control over what area of the tissue gets the most blood flow through vasodilation and vasoconstrictive controls. During exercise, the medium arteries that supply blood to the gastrointestinal organs, such as the stomach and bowel vasoconstrict, decreasing the blood flow to these areas. Conversely, the medium arteries that distribute blood to muscles vasodilate, effectively shunting a larger amount of blood to the muscles, where more oxygen is required due to increased activity levels. The small arteries further control the flow of blood through a similar process.

Capillaries are the smallest blood vessels and supply the cells with oxygen and nutrients. Because these vessels do not have a muscle layer, the nutrients diffuse across the capillary walls into the interstitial spaces for cellular use. They connect to the arterial system via arterioles. The smallest of the arteries, arterioles have only a couple of layers of smooth muscle surrounding the endothelium, and they do not have an elastic layer like their larger counterparts. Like the other vessels surrounded by smooth muscle, arterioles can constrict or dilate depending upon need to assist in blood flow management.

After the oxygen diffuses into the cells and carbon dioxide is absorbed, the blood travels from the capillaries to venules which turn into small veins. Venules enable a level of nutrient transport across their walls, but as those walls thicken with smooth muscle cells, (as they turn into small veins) the exchange is

~Key Terms~

**Stroke volume**- The volume of blood pumped out of the left ventricle of the heart in a single beat.

**Heart rate**- The number of heart beats per unit of time, usually expressed as beats per minute.

**Cardiac output**- The volume of blood being pumped by the heart; it is equal to the heart rate multiplied by the stroke volume.

**Blood pressure**- The pressure exerted by the blood against the walls of the blood vessels, especially the arteries.

**Baroreceptors**- Detect the pressure of blood, and can send messages to the central nervous system to increase or decrease total peripheral resistance and cardiac output.

**Vasodilation**- Dilation or expansion in flow width of a blood vessel.

**Vasoconstriction**- Constriction or reduction in flow width of a blood vessel.

**Peripheral resistance**- Resistance of the blood vessels in the body.

**Plaque**- A fat deposit on the inside wall of a blood vessel.

**Conducting arteries**- Deliver large quantities of blood to different regions of the body.

**Capillaries**- Tiny blood vessels throughout the body that connect arteries and veins.

**Arterioles**- One of the small, thin-walled arteries that end in capillaries.

**Endothelium**- A thin layer of flat epithelial cells that lines blood vessels.

**Venules**- Small veins that join capillaries to larger veins.
How Oxygen Exchanges with Muscle Tissue

Oxygen rich blood leaves the heart via the arterial system.

After the oxygen is deposited and waste removed, the blood travels from capillaries to venules then veins and back to the heart.

Within the muscle, capillaries supply cells with oxygen and nutrients and remove cellular waste.

Blood travels via the arteries to arterioles to capillaries to the muscle tissue.

Distribution of Blood

- Veins 64%
- Arteries 15%
- Capillaries 5%
- Pulmonary vessels 9%
- Heart 7%
essentially blocked. The deoxygenated blood travels from small veins to medium-sized veins, like tributaries flowing into a river. The venous system is similar to the arterial system of vessels in size and distribution, but holds significantly more blood. The two circulatory passages run basically parallel to each other throughout the body, which is clearly illustrated by red and blue color distinction. The major difference between veins and arteries is the amount of oxygen in the blood contained within the respective vessels and the way the fluid is moved through circulation.

Arteries have a pulse because the blood that flows through them is pushed by the rhythmic contractions of the heart. The venous return does not have the pressure from cardiac output to drive the fluid back to the heart, and therefore, must use smooth muscle contractions and a system of one-way valves to prevent any back flow as the blood is mobilized to the right atrium and eventually to the lungs to be re-oxygenated. Veins that are larger than 2 mm contain valves that occlude the vessel when the blood attempts to reverse direction. The smooth muscle is stimulated to contract by nervous signals from the autonomic nervous system.

Assessing Pulse

Palpatating the area where large arteries are close to the skin, one will feel a rhythmical pulse, caused by the pressure exerted on the arteries when the heart contracts. There are a number of locations at the arms, legs, head and neck at which one can identify the heart’s pace. In the head and neck, the superficial temporal artery, facial artery, and common carotid artery can be palpated. The carotid arteries are often easily identified by a strong pulse as they ascend from the aorta. They can be palpated on either side of the larynx just below the jaw. In the arms, the radial pulse is probably the most recognized and is often palpated for exercise pulse rate. In the upper arm, both the axillary artery and brachial artery can be felt with moderately light finger pressure. Although not commonly used for pulse assessment, the leg’s femoral artery, popliteal artery, and dorsalis pedis all have a measurable pulse rate.

The tendency of the blood vessel to match pressure with volume is called compliance. The more the vessel will stretch when pressure increases, the better its compliance. As pressures increase against the endothelium, elastic vessels expand in compliance to accommodate an increase in blood flow, thereby reducing the pressure. Even small increases in pressure translate into large volume shifts by compliant tissues. The veins have significantly more compliance to variations in blood pressure than arteries. In fact, veins are almost 25 times more compliant than arteries, one of the primary reasons veins have a greater contribution to blood storage. Veins retain almost two-thirds of the blood supply at any given time. The ability of the venous system to hold blood is sometimes detrimental, as blood can build up in the tissues, referred to as blood pooling. Elevated levels of blood pooling result in reduced blood flow to the heart, lowering cardiac output.

Aging & Vessel Health

The aging effect plays a role in vessel decline. The elastic properties of the arteries suffer degenerative changes, causing them to lose pliability and compliance and begin to harden. Veins also experience decline in function through a reduced compliance to changes in blood pressure. This process is called hardening of the arteries or arteriosclerosis. Layers of the vessel thicken and experience chemical changes in elastic properties. Between the elastic and collagenous fibers, fat deposits...
build up, which begin to impede blood flow. The cholesterol-based materials eventually add calcium deposits and fibrous material further occluding the flow of blood. This process is called *atherosclerosis*. These mechanisms of vessel dysfunction can dramatically reduce and even stop the flow of blood to tissues, leading to cellular death. Obesity, smoking, high cholesterol, physical inactivity, and hypertension are all related to increased risk for arteriosclerosis.

Degenerative function of the vascular tissues reduces the capacity for the circulatory system to manage exercise. Personal trainers should be cautious when working with hypertensive clients and elderly populations due to their vascular systems’ reduced efficiency at regulating pressures. Rapid changes in body position, particularly from a supine to upright posture can cause *orthostatic hypotension* (19). Caution should also be applied when these exercisers perform activities with intense loads. Individuals with hypertension or reduced vascular compliance should not engage in heavy resistance training.

**Pulse Locations**

**Plaque Formation in Vessels**

**Varicose Vein**
If the veins get stretched, the integrity of the valve system may be compromised. When this occurs, the valves become progressively less capable of preventing backflow. Compromised valves cause the vein to become abnormally dilated in response to the back flow pressure, which causes them to swell. The outcome is a vascular bulge of the superficial vessels, most often observed in the legs. Hyperdilated superficial veins are known as varicose veins.

Most varicose veins do not present a serious medical problem but can sometimes lead to complications. When the flow of blood in the vessel becomes stagnant, clots can form. Unlike blood clots in deep veins, clots in superficial veins rarely travel to the heart or lungs, where they could cause serious blockages. Phlebitis or inflammation of the vein is more of a threat because it may lead to cellular ischemia and gangrenous tissue (13). Surgery may be needed to remove damaged vessels.

Exercisers with varicose veins should avoid heavy resistance training (11). Excessive pressure can increase back flow force, exacerbating the condition and causing pain. Aerobic or rhythmic physical activity is recommended because dynamic muscle contractions increase the propensity for blood to flow back to the heart.

The Role of Blood
During both rest and exercise, the dynamics of the circulatory system depend upon the physics of blood flow and the tissue anatomy of the vessels. Because they must satisfy the blood flow demands of all the tissues in the body, it makes sense that approximately 84% of the blood circulates systemically in the arteries and veins. The other 16% is in the process of oxygenation in the pulmonary vessels or in the heart itself. Blood flows quickly through large arteries and slowly through capillaries because pressure declines as the flow moves from large to small vessels. The pressure in the capillaries averages about 20 mmHg compared to the average aortic pressure of 100 mmHg. This lower pressure in the capillaries results in slower blood velocity, allowing the cellular nutrients and waste products to be exchanged between the arterial entrance and the venous exit.

Capillaries allow fluids containing oxygen and nutrients to diffuse across the vessel’s wall. This is possible because capillaries have less smooth muscle compared to veins and arteries. It is the combination of interstitial pressure and blood pressure that drives the exchange. The blood pressure pushes nutrients into surrounding tissues, while the interstitial pressure of the tissues drives metabolic waste from the tissue into the blood. Blood pressure at the beginning, or the arterial side, of the capillary is higher than the pressure at the venous side, which lends itself to the regulatory mechanisms of exchange. Essentially, cellular nutrients leave the vessel at the beginning of the capillary, and waste enters the vessel at the end. Because exercise increases the cellular demand for oxygen and nutrients, as well as the removal of metabolic waste, the body will add capillaries as an adaptive response. Increasing the number of capillaries or capillary density within muscle tissue, occurs mainly in response to repetitive endurance activities. This allows for increased oxygen and nutrient delivery to the muscle cells during exercise, consequently improving performance outcomes.

Function of Blood
- Transports nutrients and oxygen to the tissues
- Coagulates to prevent excess fluid loss
- Plays a role in temperature, fluid, electrolyte, and pH regulation
- Transports enzymes to certain tissues
- Carries CO₂ & waste products away from the tissues
- Carries hormones to target tissues
The blood’s ability to deliver nutrients and remove waste is a factor of its transport mechanisms and constitution. Blood is the connecting factor between tissues.

The human body generally maintains 4 to 5 liters of blood in total circulation. Some of the blood is comprised of cells and cell fragments called the formed element of blood. The rest is made up of a liquid plasma called the fluid matrix. Approximately 95% of the formed element is comprised of red blood cells. The remaining 5% is made up of the white blood cells and platelets. Males have nearly 14% more formed element than females, which makes up approximately 44-54% of the total blood volume in the body. The formed element of blood is referred to as hematocrit. The remaining plasma makes up the other 46-56%. Plasma is comprised of mostly water, interspersed with some dissolved or suspended molecules. Due to its high water volume, plasma is often extracted from the blood during periods of dehydration. This is one mechanism by which dehydration causes body dysfunction. During dehydration, the plasma volume, and thus blood volume, decreases. The heart then has to pump harder to maintain blood pressure so that oxygen delivery to tissue is maintained.

At any given time, numerous compounds are contained within the constituents of the blood. Each compound has a specific function and the measured concentration of each depends upon the internal and external environment the body is exposed to. During exercise, concentrations of dissolved components such as ions, enzymes, hormones, nutrients, and exercise by-products, increase in response to work demands. In addition to the changes in plasma concentrations, erythrocytes (red blood cells) increase in oxygen and carbon dioxide transport during physical activity. Oxygen bonds to hemoglobin contained within the erythrocytes. The erythrocytes also contain an enzyme that catalyzes the reaction between carbon dioxide and water to form carbonic acid, which ionizes to form hydrogen and bicarbonate ions. Bicarbonate ions diffuse into the blood plasma, which represents the primary method of carbon dioxide transport to the lungs. Recalling the buffering effect from sugar metabolism, bicarbonate is an important component to the maintenance of blood pH as well.

~Quick Insight~

Hemoglobin is a molecule made of proteins that require iron to carry oxygen in the body. Approximately 66% of the four grams of iron contained in humans is found attached to hemoglobin. Females lose iron through menstruation, requiring an increased ingestion of dietary iron above the requirements of males. Research indicates that iron absorption triples in the presence of ascorbic acid (Vitamin C). If iron availability is insufficient, blood hemoglobin levels decrease, leading to a condition known as iron-deficiency anemia. Consequently, the body experiences a reduced availability of oxygen in the blood. Additionally, cigarette smoking affects oxygen transport with hemoglobin. Cigarette smoke produces carbon monoxide, which bonds to hemoglobin, inhibiting the ability of oxygen to be transported in the blood. In its transport form with hemoglobin, carbon monoxide may represent 5-15% of blood and impede on physical capacity during work due to decreased oxygen delivery to working tissue.

Compliance- A measure of the ease with which a structure may be deformed or distended.

Blood pooling- An accumulation of blood in the venous system that can reduce blood return to the heart.

Arteriosclerosis- A chronic condition, characterized by thickening and hardening of the arteries and the build-up of plaque on the arterial walls.

Atherosclerosis- A stage of arteriosclerosis in which the arteries become clogged by the build-up of fatty substances, which eventually reduces the flow of blood to the tissues.

Orthostatic hypotension- A form of low blood pressure precipitated by moving from a lying or sitting position to standing up straight.

Plasma- The clear, fluid portion of blood in which cells are suspended.

Red blood cells- Cells in the blood that transport oxygen and carbon dioxide to and from the tissues.

White blood cells- A group of several cell types that occur in the bloodstream and are essential for a properly functioning immune system.

Platelets- A type of blood cell responsible for blood coagulation and for the repair of damaged blood vessels.

Hematocrit- The proportion, by volume, of the blood that consists of red blood cells.

Erythrocytes- Red blood cells.
Circulation During Activity

When the body engages in activities with increasing intensity, the circulatory system increases its capacity to deliver blood to the working tissue. At rest, only 20%-25% of the capillaries in skeletal muscle are open, and the rate of the heart is at its lowest working level. When the body is about to engage in activity, the circulatory system receives signals from the brain preparing it to manage oxygen demands. Heart rate increases before a person even picks up a weight or turns on the treadmill in anticipation of the activity. Concurrently, capillary beds open up to provide oxygen to the tissues they feed. During exercise, 100% of the capillaries in active skeletal muscle are open.

Three mechanisms regulate blood flow to the tissues:

1) Individual tissues can control flow based on metabolic need.

2) The nervous system manipulates blood flow by adjusting the mean blood pressure and shunting the blood from one area of the body to another.

3) Hormonal communications influence the mean blood pressure and the chemical release by tissues that affect blood flow characteristics.

Blood flow is generally proportionate to the metabolic needs of the tissue. Therefore, organs that are not needed during exercise, such as those of the digestive tract, have their blood redirected to active skeletal muscle tissue or metabolic organs. Blood flow to skeletal muscles increases by 15-20 fold. To accommodate the increase in blood needed by the cell, the blood vessels react to vasodilators released into circulation in response to exercise. Lactic acid, carbon dioxide, and potassium ions are key dilators, as their presence signals to the body that there is increased metabolic turnover and greater demand for oxygen in the active tissues. The nervous system interprets the metabolic messages and signals the less metabolically active tissues to vasoconstrict, resulting in shunting and redirection of blood flow. Initially, blood flow to the skin is reduced, but as the body heats up, nervous signals redirect blood flow back to the skin to release the heat created from metabolic activities.

The heart must work harder to accommodate the demand of blood by the tissues. Sympathetic nervous system stimulation of the heart increases the heart rate and stroke volume resulting in greater cardiac output and increased blood pressure by approximately 20-60 mmHg. At the same time, veins constrict to increase the flow of blood back to the heart for gaseous turnover in the lungs. Recall that the pressure response in the vessels is a factor of cardiac output and peripheral resistance; thus the harder the body works, the more the pressure in the vessels will increase. During activities of a rhythmic nature, such as running, swimming, or biking, the blood flow back to the heart is constant and consistent. Venous return is efficiently managed by vasoconstriction through coordinated smooth muscle action. Because the forces being produced are relatively low, and breathing rates are consistent with heart rate, diastolic pressure remains low. Mean systolic blood pressure, like ventilation rates, increases linearly with oxygen consumption due to increases in cardiac output. When assessing exercise blood pressure during aerobic steady-state work, personal trainers should expect to see a rise in systolic

~Quick Insight~

A natural tendency when lifting or exerting high force is to hold your breath. This action, referred to as the valsalva maneuver increases intra-abdominal pressure, allowing the diaphragm to forcefully contract against the viscera to support the spine. The process of holding your breath during resistance training dramatically increases blood pressure. Exercisers should be conscious to exhale during concentric contractions and inhale during eccentric contractions to reduce the blood pressure response during exercise.
blood pressure consistent with the work rate, but only a slight change in diastolic blood pressure compared to rest.

When activities require greater intra-abdominal pressure for spinal stability and the contracting muscles mechanically compress arteries, peripheral resistance increases. Both diastolic and systolic blood pressure will increase linearly with the intensity of the effort. The magnitude of the response is specific to the amount of muscle tissue employed and the resistive load. Blood pressure is further increased when internal compressive forces from muscle contractions, elevated cardiac output, and external compressive forces. Exercises such as the back squat and leg press have significant compressing forces from the external load, causing blood pressure to increase dramatically. For this reason, hypertensive clients should avoid heavy lifting exercises, particularly those which apply compression upon the body. Although factors that affect increased exercise blood pressure can work independently, they usually work together to cause an additive effect. Blood pressure factors in resistance training exercises include the valsalva maneuver, intra-abdominal pressure, compressive forces from muscle contractions, elevated cardiac output, and external compressive forces.

Exercise is very important for the circulatory system. Regular exercise improves blood pressure response at rest, both immediately post-exercise and as a chronic adaptation to routine aerobic training. It is presumed that alterations in the sympathetic nervous system reduce peripheral resistance, and increase renal secretion of sodium, accounting for the normal 8-11 mmHg decrease following aerobic endurance training (10). The chronic effects of resistance training do not yield the same results, but may provide slight improvement in resting measures. Measured resistance training blood pressure response has shown to decrease with regular participation.

The heightened action of the heart during physical activity, like any other muscle, increases its oxygen demand. However, the heart cannot pull oxygen from the blood in its atria or ventricles, as there are no circulatory channels from inside the chambers. The coronary blood supply leaves the aorta through the main coronary arteries and enters an extensive network of myocardial blood vessels called the coronary circulation. The myocardium is densely packed with capillaries and mitochondria, allowing for efficient extraction and utilization of oxygen. At rest, between 70-80% of oxygen is extracted from the 200-250 ml of coronary blood flow every minute. During activity, that value can jump 5-6 times if the activity is performed at a vigorous level (15). The demand of work must be met by proportionate increases in coronary blood flow to maintain cardiac output. As the myocardial tissue increases in metabolic function, the subsequent by-products produced stimulate vasodilation, consequently increasing the flow of blood to the tissue. To estimate the oxygen demand of the heart, systolic blood pressure is multiplied by the heart rate. The product, or myocardial oxygen demand, is called the rate pressure product.

The high demand for oxygen in the heart occurs because the tissue is not efficient at using anaerobic pathways. As previously stated, cardiac muscle tissue is mitochondria dense, deriving its energy almost exclusively from aerobic metabolism. Consequently, cardiac muscle is highly adapted for ATP production using lipid metabolism. The largest majority of the ATP used in the heart during rest, like skeletal tissue, comes from lipid metabolism. During exercise of increasing intensity, energy metabolism comes from glucose, fatty acids, and lactic acid freed from skeletal muscle metabolism. Heavy exercise is mainly fueled by aerobic metabolism of lactic acid due to the heightened availability and increased power response from carbohydrate breakdown when compared to fats. When the exercise is performed using a prolonged steady-
state pace, the heart tissue increases lipid metabolism to spare carbohydrates. Trained and untrained individuals are comparable in myocardial metabolic pathways when the work is hard and carbohydrates are used as fuel. When the work is moderate, trained individuals show a greater reliance on myocardial lipid metabolism when compared to their untrained counterparts. Again, the differences reflect carbohydrate sparing in trained individuals.

**Ventilation**

The increased myocardial vigor is met by increased ventilation rates needed to meet the oxygen demand during exercise. Heart rate alone does not regulate the ventilation response. If it did, breathing rates would noticeably increase when psychological nervousness was experienced or stimulants were present in the body. Physiological control of respiration is multifaceted, based upon chemical and neural mediation. At rest, pulmonary ventilation is largely controlled by factors that affect the chemical state of the blood, including temperature, arterial gas concentrations, and pH. During the onset of exercise or work, body movement stimulates the medulla of the brain through neurogenic means to rapidly increase respiration rates. This abrupt increase is then leveled and begins to more closely reflect the intensity of the exercise. Neurons in the brain and peripheral chemoreceptors in the vessels dictate ventilation rates to ensure adequate oxygen is available in the blood.

During exercise, ongoing ventilation will be controlled by chemoreceptor modulation based on concentrations of blood metabolites, temperature of the blood, and variations in gas exchange and pH. When the exercise is continuous and steady-state, the ventilation is linear to oxygen uptake. When the exercise is intense, the minute ventilation increases disproportionately to the oxygen uptake (5). A dramatic upswing in the rate of breathing corresponds with heightened lactate accumulation in the blood. When lactate threshold is exceeded, ventilation rates increase in an attempt to make more oxygen available to the tissue and to buffer the lactic acid produced by the muscle. Heavy resistance performed in short bouts causes dramatic increases in both heart and ventilation rates due to significant increases in blood lactate (8). This explains rapid post-lift respiration rates in exercises like the squat and deadlift.

Breathing adaptations do occur with training. In maximal measures, the ventilation rates correspond to increases in oxygen consumption, which makes sense due to the increase in oxygen required to meet the tissue demand. The increased turnover of oxygen to carbon dioxide triggers increased ventilation rate to remove the CO₂ and infuse O₂ back into the blood. During submaximal work, ventilation rates reduce at the same relative intensity in trained individuals compared to the untrained. This is due to a reduced demand on ventilatory musculature and the oxygen not used because of an improved efficiency of exercise breathing that can be used by other tissues.

Trained individuals expire about 3% less oxygen compared to untrained individuals at the same relative intensity. Therefore more oxygen is being used and less respiration is required in trained exercisers compared to the untrained. An improved rate of oxygen extraction from the blood by working tissues occurs in response to endurance adaptations, accounting for the differences between trained and untrained individuals.

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**Key Terms**

**Valsalva maneuver** - A strain against a closed airway combined with muscle tightening, such as when a person holds his or her breath and tries to move a heavy object.

**Coronary circulation** - Consists of the blood vessels that supply blood to, and remove blood from, the heart muscle itself.

**Rate pressure product** - The measure of myocardial oxygen consumption.
Chapter Six References


