Cardiovascular System Physiology

The cardiovascular system maintains the flow of oxygenated blood to the tissues by adjusting pressure throughout the system. In this section we will investigate how the cardiovascular system produces and maintains blood pressure in a variety of circumstances.

Cardiac Muscle

We covered some characteristics of cardiac muscle in the tissue chapter. You may recall that cardiac muscle is very similar to skeletal muscle. It consists of long red cells containing densely packed actin and myosin protein filaments which give it a striated appearance. Cardiac muscle cells only contain one nucleus while their muscle counterparts are multinucleated. Cardiac muscle also contains a specialized cell junction called an intercalated disc. Intercalated discs help to transmit action potentials from cell to cell in order to produce a more ordered contraction of large areas of muscle tissue.

Cardiac muscle contraction physiology is also very similar to skeletal muscle. Depolarization of cardiac muscle cells causes the release of calcium. Calcium in turn binds to troponin surrounding actin causing it to move and expose myosin binding sites. Myosin and actin connect and slide past each other powered by ATP.

Cardiac muscle has a resting membrane potential of about -90mV. The threshold for a typical ventricular muscle cell is about -75mV. An action potential that reaches the threshold causes rapid depolarization and movement of sodium inside the cell. This changes the membrane potential to +30mV at which the sodium channels close. The sodium channels are known as fast channels because of their quick reaction to stimuli. Once the membrane reaches +30mV slow calcium channels open in order to maintain the transmembrane potential at about 0mV. The slow calcium channels react slowly to stimuli and remain open for longer periods of time (about 175 milliseconds). At the end of their cycle the calcium channels close and slow potassium channels open allowing the diffusion of potassium ions out of the cell. The cells then repolarizes back to the resting membrane potential.

Cardiac muscle cells also exhibit relative and absolute refractory periods much like skeletal muscle cells. During the absolute refractory period the membrane cannot respond to stimuli. This is due to the sodium channels being open. The absolute refractory period in ventricular muscle cells is about 200 milliseconds. This is followed by a relative refractory period in which a strong stimulus can produce an action potential. The relative refractory period is characterized by closed sodium channels that can open. The relative refractive period lasts for about 30 ms.

Cardiac muscle contraction like skeletal muscle relies on the influx of calcium. In cardiac muscle there are two sources of calcium. These include the influx of calcium from slow calcium channels as mentioned above and the calcium stored in the sarcoplasmic reticulum. The long action potential in cardiac muscle also allows it to continue contraction until relaxation occurs. There is no summation in cardiac muscle. This prevents cardiac muscle cells from undergoing tetanic contractions.
Cardiac muscle tissue is capable of contracting on its own without stimulation from the nervous or endocrine systems. This phenomenon is known as automaticity. Automaticity occurs because of specialized cells that produce action potentials.

The impulse from the SA node is transferred by an intermodal pathway consisting of conducting cells to the atroventricular (AV) node located in the floor of the right atrium. The impulse is delayed about 100 ms as it passes through the AV node. This allows for the completion of atrial contraction before the beginning of ventricular contraction. The AV node is also capable of producing action potential on its
own at a rate of 40-60 bpm. If for some reason the SA node becomes damaged the AV node will cause the heart to contract at 40-60 bpm. The AV node can conduct impulses at a maximum rate of 230 bpm. The heart begins to decrease its pumping efficiency at about 180 bpm. The heart cannot produce rates greater than 230 bpm unless it is damaged. The maximal rate of ventricular contraction is about 300-400 bpm. However contractions at these rates are very inefficient.

The impulse from the AV node travels to the atrioventricular (AV) bundle or Bundle of His. These cells are also capable of producing action potentials at a rate of 20-40 bpm. The AV bundle connects the atria and ventricles. The AV bundle sends impulses to the right and left bundle branches. The branches extend to the apex of the heart and distribute impulses to the ventricles via Purkinje fibers and to the papillary muscles via moderator bands. This distribution of impulses allows for contraction of the papillary muscles before the ventricles. This allows for tensioning of the chordae tendinae of the atrioventricular valves to help prevent backflow of blood to the atria. Purkinje fibers are fast conducting cells and allow for even emptying of the ventricles.

Damage to the heart can manifest in what is known as an ectopic pacemaker. This is an area of tissue that generates abnormal impulses that bypass the normal conducting system. Ectopic pacemakers can disrupt normal ventricular contraction and produce dangerous arrhythmias.
The Electrocardiogram

The heart generates significant electrical impulses that can be measured. Devices that measure the heart’s electrical impulses produce a recording called an electrocardiogram or ECG (sometimes called an EKG). The information from an ECG can be used to determine problems with conduction, nodes, or contraction of the heart. There are a variety of locations of electrodes that produce different views of the impulses. We will examine a standard ECG view.

The electrical impulses in an ECG produce waves which are a summation of electrical impulses in a given time frame. The P wave is the first wave seen in an ECG and represents atrial depolarization. Atrial depolarization occurs just before atrial contraction (atria contract about 25 ms after the beginning of the P wave.)
The P wave is followed by the QRS complex. The QRS complex represents ventricular depolarization. Atrial repolarization is also occurring during this time but is overshadowed by the powerful ventricular signal. The T wave follows the QRS complex and results from ventricular repolarization.

Some common measurements include the P-R interval and the Q-T interval. The P-R interval extends from the beginning of the P wave to the beginning of the QRS complex. A prolonged P-R interval can indicate a conduction problem. The Q-T interval extends from the end of the P-R interval to the end of the T wave. The Q-T interval represents ventricular systole. A prolonged Q-T interval can indicate heart damage or electrolyte problems.

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Created by Agateller (Anthony Atkielski), converted to svg by atom.
Sinus bradycardia. Note the long interval between beats.
http://commons.wikimedia.org/wiki/File:Lead_II_rhythm_generated_sinus_bradycardia.JPG

Ventricular tachycardia.
http://commons.wikimedia.org/wiki/File:12_lead_generated_ventricular_tachycardia.JPG
Ventricular fibrillation. There is no organized contraction with this arrhythmia.

http://commons.wikimedia.org/wiki/File:Lead_II_rhythm_generated_ventricular_fibrillation_VF.JPG

Asystole represents no contraction.

http://commons.wikimedia.org/wiki/File:Lead_II_rhythm_generated_asystole.JPG
Cardiac Output

The primary goal of the cardiovascular system is to maintain the flow of oxygenated blood to the tissues. In order to accomplish this task the heart must maintain what is known as a good cardiac output.

Cardiac output is the amount of blood pumped by each ventricle in one minute. It is a measure of ventricular efficiency. Cardiac output can be described by this equation:

\[ CO = SV \times HR \]

\[ CO = \text{Cardiac output} \]
\[ SV = \text{Stroke volume} \]
\[ HR = \text{Heart rate} \]

Stroke volume is the amount of blood ejected by a ventricle in one contraction. Heart rate is in beats per minute. Thus cardiac output is the amount of blood ejected by a ventricle in one minute. Generally SV is about 70-80ml. For example if HR is 70 bpm and SV is 80 ml then cardiac output is 5600 ml per minute or 5.6 L per minute.

Factors that influence SV and HR then will affect cardiac output. SV is affected by end diastolic volume (EDV) or the amount of blood in the ventricle just before contraction as well as end systolic volume (ESV) which is the amount of blood remaining in the ventricle after contraction (systole). SV can be calculated from EDV and ESV by the following:

\[ SV = EDV - ESV \]

The following is an example to illustrate how cardiac output works to maintain blood flow. Let’s say we have two patients. One is a highly trained endurance athlete; the other suffers from congestive heart failure. The athlete enters our office and you begin your cardiac assessment by taking her pulse. You record the resting pulse as 55 bpm. Your next patient enters the room and you also take his pulse and record it at 100 bpm. How is cardiac output responsible for the difference in the two pulses?

In both circumstances the heart is working to provide adequate amounts of oxygenated blood to the tissues. In other words the heart is working to maintain a good cardiac output. The athlete’s stroke volume is high because of her athletic conditioning. Therefore the heart rate will be low in order to maintain good cardiac output. The CHF patient’s stroke volume is much lower than the athlete’s. Heart rate must then be higher in order to maintain cardiac output.

Starling’s law of the heart relates stretch of the ventricular walls to stroke volume. The degree of stretch of the ventricular walls is called preload. An increase in preload results in an increase in stroke volume which in turn increases cardiac output. Stroke volume then is affected by venous return which can vary from 2L/min to about 24 L/min.

Other factors that affect cardiac output include neural and hormonal control mechanisms. We will explore these next.
Nervous System Connections

We have examined how the heart beats on its own accord by generating impulses in the nodes. However heart rate must sometimes vary in order to meet the varying demands of the body. This control of heart rate comes from the nervous and endocrine systems. In fact the autonomic nervous system is constantly adjusting heart rate in order to maintain good blood pressure and flow of blood to the tissues.

The autonomic nervous system connects to the heart by means of the cardiac plexus. The cardiac plexus sends postganglionic sympathetic neurons to the SA and AV nodes and the atrial muscle cells. The postganglionic neurons are referred to as cardiac accelerator nerves and they originate in the cervical and upper thoracic paravertebral ganglia. The parasympathetic nervous system sends postganglionic neurons to the cardiac plexus via the Vagus nerve (CN X).

The autonomic nervous system impulses originate in the cardiac control centers in the medulla oblongata. There is a cardioacceleratory center and a cardioinhibitory center. The cardioacceleratory center controls the sympathetic pathway and increases heart rate while the cardioinhibitory center controls the parasympathetic pathway and decreases heart rate. The centers have input from higher cortical regions of the brain as well as the hypothalamus.

Sensory information about the cardiovascular system originates in baroreceptors and chemoreceptors. These receptors are innervated by the glossopharyngeal nerve (CN IX). The baroreceptors monitor changes in pressure while chemoreceptors monitor changes in blood levels of oxygen, carbon dioxide, and pH. An increase in carbon dioxide or decrease in blood pH will stimulate the sympathetic nervous system which will result in an increase in heart rate and force of contraction. Chemoreceptors in the carotid sinus and aortic body sense changes in oxygen concentration. A drop in oxygen levels causes vasoconstriction and a decrease in heart rate. This allows for movement of blood without an increase in oxygen use of the heart.

For example, when a subject rises from a supine to a sitting position there is a temporary drop in blood pressure in the head. This is sensed by baroreceptors in the carotid sinus. The sensory information travels via the glossopharyngeal nerve to the cardiac control centers to produce a subsequent increase in heart rate via the sympathetic pathway.

The sympathetic neurotransmitter released by the postganglionic neurons is norepinephrine (NE). NE binds to beta adrenergic receptors causing sodium and calcium channels to open. The resulting influx of sodium decreases the period of depolarization causing the threshold to be reached more quickly. This results in an increase in heart rate. Likewise the parasympathetic postganglionic neurons secrete acetylcholine (Ach) that causes potassium gates to open resulting in a longer time period for depolarization. This produces a slower heart rate.

The Bainbridge reflex (atrial reflex) occurs with an increase in stretch of the atrial walls. The reflex results in an increase in sympathetic activity and subsequent increase in heart rate.

NE and ACh have both neurotransmitter and hormonal action. NE and epinephrine are both secreted by the adrenal medulla. These hormones are secreted in response to stress and exercise. Thyroid hormone also has a similar action to NE and increases heart rate.
Ischemic Response

The ischemic response or central nervous system ischemic response occurs with a decreased in blood flow to the medulla oblongata. The ischemic response occurs when blood pressure decreases to about 50 mm Hg. It produces systemic vasoconstriction in an effort to support blood flow. If ischemia continues then the vasomotor center will cease to function resulting in vasodilation and death.

Blood Pressure Control

Blood pressure is a measure of the force on blood vessel walls. There are two numbers associated with blood pressure. The systolic pressure is the higher number and results from ventricular contraction. The diastolic pressure represents the pressure in the system during ventricular diastole.

Blood pressure can be measured with a stethoscope and a device called a sphygmomanometer. Typically the pressure in the brachial artery is measured. The examiner listens to (ascultates) the artery at the elbow while the cuff is squeezed above the elbow until the brachial artery collapses. The examiner then slowly releases the cuff and listens for Korotkoff sounds which are produced by turbulent blood flow. The first sound heard represents the systolic pressure. The cuff is loosened until turbulent flow ceases. The pressure at which the sounds disappear represents the diastolic blood pressure. The normal systolic pressure is around 120 mm of mercury. The normal diastolic pressure is around 80 mm Hg.

The difference between the systolic and diastolic pressures is called the pulse pressure. With a normal blood pressure of 120/80 the pulse pressure is 40 mm Hg. Stroke volume and vascular compliance both affect pulse pressure. When stroke volume decreases then so does pulse pressure. Likewise when vascular compliance decreases then pulse pressure increases. This occurs with aging and atherosclerotic plaquing.

Mean arterial pressure is a measure of pressure in the arteries and is somewhere between the average systolic and diastolic pressures. Mean arterial pressure (MAP) can be determined by the following:

$$\text{MAP} = \text{SV} \times \text{HR} \times \text{PR}$$

$\text{SV} =$ stroke volume
$\text{HR} =$ heart rate
$\text{PR} =$ peripheral resistance (resistance in vascular system)

This means that anything affecting stroke volume, peripheral resistance, or heart rate will also affect blood pressure. The mechanisms that control these variables will also work to control blood pressure.

Blood pressure is directly related to cardiac output. Therefore the previously discussed factors that affect cardiac output also affect blood pressure. For example we know that an increase in cardiac output results in an increase in blood pressure. We also know that an increase in heart rate increases cardiac output given no changes in stroke volume. If sympathetic activity increases say, due to periods of stress, then we know that heart rate will increase because of stimulation from the medulla’s cardiac control center activating the sympathetic pathway to the SA node. The increase in heart rate increases cardiac
output which in turn increases blood pressure. In essence long periods of stress can cause an increase in blood pressure.

The same process occurs with pain. Pain will activate the sympathetic pathway and increase heart rate and cardiac output. Blood pressure will also increase with pain.

**Fluid Volume and Blood Pressure**

Overall fluid volume is directly related to blood volume. An increase or decrease in overall fluid volume subsequently increases or decreases blood volume. Likewise blood volume is directly related to blood pressure. Mechanisms that control fluid volume also have an effect on blood pressure. We will examine three mechanisms in this section. They include the renin-angiotensin system, atrial natriuretic hormone and antidiuretic hormone.

**Renin-Angiotensin System**

The renin-angiotensin system (renin-angiotensin-aldosterone system) begins with the secretion of renin by the kidneys in response to a decrease in blood pressure (we will explore this system in more detail in the urinary system chapter). Renin activates a plasma protein called angiotensinogen by causing it to cleave a portion known as angiotensin I (one). Angiotensin I travels through the bloodstream to the lungs where it encounters an enzyme known as angiotensin converting enzyme (ACE). The angiotensin converting enzyme again cleaves angiotensin I producing angiotensin II. Angiotensin II causes systemic vasoconstriction as well as stimulates the release of aldosterone, an adrenal cortex hormone. Aldosterone targets the kidneys to conserve sodium and secrete potassium. The conservation of sodium causes an increase in fluid volume by way of osmosis. The increase in fluid volume causes a subsequent increase in blood volume and blood pressure.

**Atrial Natriuretic Hormone (ANH)**

Atrial natriuretic hormone (sometimes called a peptide) is secreted by the walls of the atria in response to atrial stretch. If blood volume increases so does venous return causing increased atrial stretch. The subsequent release of ANH targets the kidneys to eliminate sodium. Water follows sodium by osmosis causing a decrease in fluid volume, blood volume and blood pressure.

**Antidiuretic Hormone (ADH)**

ADH (vasopressin) is a hormone secreted by the posterior portion of the pituitary gland in response to increases in blood solute concentration. The hypothalamus contains neurons that sense changes in blood solute concentration. Like angiotensin II, ADH causes vasoconstriction although it is not as powerful as angiotensin II. ADH targets the kidneys to conserve fluid. Less urine is produced when ADH is secreted as fluid volume is conserved.
Peripheral Resistance

Fluid moves by virtue of a pressure gradient. In other word fluid moves from areas of higher to lower pressure. The left ventricle must produce a pressure that is greater than the fluid pressure in the arterial side of the vascular system in order to move blood through the system. The pressure that is resident in the vascular system that the heart must overcome in order to move blood is called afterload. The resistance to blood flow in the vascular system is also known as peripheral resistance.

Peripheral resistance is directly proportional to blood pressure.

Pressure in the vascular system is greatest in the aorta and decreases as blood moves from the arteries to arterioles, capillaries and the venous system. The pressure can be as low as 0 mm Hg at the right atrium. The pressure in each part of the arterial system is directly proportional to the resistance to blood flow. The larger structures such as the larger arteries have little resistance while the smaller structures such as the capillaries have a much larger resistance to blood flow. Pressure in the arterioles is about 85 mm Hg and in the capillaries about 30 mm Hg.

Pressure is controlled in part in the vascular system by changing the diameter of the vessels. Arteries and arterioles have a larger smooth muscle layer than veins and are capable of constricting or dilating according to the body’s needs for oxygenated blood.

The vessels receive input from the sympathetic nervous system. An increase in sympathetic stimulation will cause vasoconstriction while a decrease causes vasodilation. There is continuous stimulation from the sympathetic nervous system that produces a continuous partial vasoconstriction in order to maintain pressure. This is known as vasomotor tone.

When the arteries are fully stimulated by the sympathetic nervous system they are about one half of their normal diameter. Increases in vasoconstriction produce subsequent increases in peripheral resistance and blood pressure. Likewise a decrease in sympathetic stimulation results in vasodilation that in turn decreases peripheral resistance and blood pressure.

Peripheral resistance also increases with the disease process known as atherosclerosis. Atherosclerosis is a thickening of the tunic media of arteries along with damage to the endothelium. This disease has been linked to high levels of small particle low density lipoproteins. These lipids deposit on blood vessel walls and undergo phagocytosis by white blood vessels. The result is the deposition of what is known as plaque. Plaque narrows the lumen of the arteries and increases peripheral resistance and blood pressure.
The Renin-angiotensin-aldosterone system (RAS).

http://commons.wikimedia.org/wiki/File:Renin-angiotensin-aldosterone_system.png

Author: A. Rad Date: April 2nd, 2006
Atherosclerosis

http://commons.wikimedia.org/wiki/File:Endo_dysfunction_Athero.PNG

Original uploader was Grahams Child at en.wikipedia. Later versions were uploaded by Jrockley at en.wikipedia.
Shock

Shock results when there is inadequate supply of oxygenated blood to the tissues. Circulatory shock can be described in three stages; compensated, progressive and irreversible.

Compensated shock is characterized by a moderate decrease in blood pressure. Compensated shock stimulates all of the mechanisms for maintaining blood pressure. Blood pressure is gradually restored to normal levels in compensated shock.

If blood pressure control mechanisms are not adequate to restore blood pressure then progressive shock results. Blood flow decreases to levels that produce ischemia in heart tissue resulting in damage if not restored quickly.

Without successful intervention the body progresses into irreversible shock. Irreversible shock is fatal and does not respond to medical treatment.

Types of shock include the following:

Hypovolemic shock results from a loss of fluid volume. This can result from severe dehydration, urination, diarrhea, vomiting, hormonal problems, and diaphoresis (profuse sweating).

Hemorrhagic shock results from loss of blood volume. This can result from severe bleeding either externally or internally.

Neurogenic shock results from damage to vasomotor centers in the central nervous system. This causes profuse vasodilation and decrease in blood pressure.

Emotional shock results from fainting. This is also known as vasovagal syncope. An emotional response can increase parasympathetic input to the heart causing vasodilation in skeletal muscles and a decrease in cardiac output.

Anaphylactic shock results from an allergic reaction that produces an overabundance of certain antibodies that produce vasodilation and capillary permeability.

Septic shock results from toxic substances in the blood. The substances can come from infections and food. The toxic substances produce vasodilation and increased capillary permeability.

Cardiogenic shock results from heart damage. The heart is unable to maintain an adequate cardiac output.

Exchange of Substances between Capillaries and the Interstitium

Cells require a constant supply of substances from capillaries. Thus substances must be delivered at a constant rate. A variety of mechanisms help to move substances between capillaries and the interstitium. Of these mechanisms diffusion is the most prevalent.
Substances moving by diffusion move from an area of higher to lower concentration. Substances moving out of capillaries and into the interstitium include oxygen and glucose. Likewise substances moving from the interstitium to the capillaries also move by diffusion. These include carbon dioxide and various waste products.

Fluid also moves from the capillaries to the interstitium at the arterial end and returns back to the capillaries at the venous end. However not all of the fluid is returned to circulation. There is a net loss of fluid from the capillaries. This fluid returns to circulation via the lymphatic system.

Fluid flow between the capillaries and interstitium is controlled by forces. These forces include fluid pressure and osmotic pressure. The pressure moving fluid out of the capillaries is known as net hydrostatic pressure. This pressure must overcome another pressure that works to pull fluid back into capillaries. This pressure is known as net osmotic pressure.

We can calculate the total pressure by subtracting net osmotic pressure from net hydrostatic pressure.

Net Filtration Pressure = Net Hydrostatic Pressure – Net Osmotic Pressure

Our calculation gives us Net Filtration Pressure which accounts for all of the pressures moving fluids.

Net hydrostatic pressure actually consists of two pressures. These include capillary hydrostatic pressure (CHP) which is the blood pressure at the arterial end of the capillary and interstitial fluid pressure (IFP). Interstitial fluid pressure is the pressure in the interstitium that opposes movement of fluid from capillary to interstitium. This pressure is a negative pressure because of the action of lymphatic vessels. The lymphatic vessels create a suction effect that pulls fluid from the capillaries.

For example, CHP is usually around 30 mm Hg and IFP is usually around -3 mm Hg. We can calculate net hydrostatic pressure (NHP) as follows:

\[ NHP = CHP - IFP \]

\[ NHP = 30 \text{ mm Hg} - (-3 \text{ mm Hg}) \]

\[ NHP = 33 \text{ mm Hg} \]

This represents the pressure pushing fluid out of the capillaries.

The pressure pulling fluid back into the capillaries is the net osmotic pressure (NOP). NOP represents the difference in osmotic pressures between the capillaries and the interstitium. There are two pressures that make up NOP. These include blood colloid osmotic pressure and interstitial osmotic pressure.

Blood colloid osmotic pressure (BCOP) represents the pulling force resulting from the presence of plasma proteins in the blood. In osmosis fluid moves toward an area of higher concentration of solute and the plasma proteins act like a solute. BCOP then works to move fluid from the interstitium to the capillaries.

Interstitial colloid osmotic pressure (ICOP) results from the presence of proteins in the interstitium. The BCOP is much larger than ICOP because proteins are large molecules that do not pass through capillary walls and thus stay in the blood.

We can calculate the net osmotic pressure by subtracting the ICOP from the BCOP. For example the BCOP is usually around 28 mm Hg and the ICOP is usually around 8 mm Hg.
Net osmotic pressure (NOP) = Blood colloid osmotic pressure (BCOP) – interstitial colloid osmotic pressure (ICOP).

NOP = 28 mm Hg – 8 mm Hg
NOP = 20 mm Hg

Now we can calculate the net filtration pressure (NFP) by the following.

NFP = NHP – NOP
NFP = 33 mm Hg – 20 mm Hg
NFP = 13 mm Hg

This represents the arterial end of the capillary. Thus there is a net loss of fluid from this end of the capillary bed.

The venous end of the capillary is a bit different. Fluid pressure decreases between the arterial and venous ends of capillaries. The capillary hydrostatic pressure at the venous end decreases to about 10 mm Hg.

The net hydrostatic pressure at the venous end is:

NHP = CHP – IFP
NHP = 10 mm Hg – (-3 mm Hg)
NHP = 13 mm Hg

The colloid osmotic pressures do not change because the movement of proteins from capillary to interstitium does not change.

To calculate net filtration pressure at the venous end:

NFP = NHP – NOP
NFP = 13 mm Hg – 20 mm Hg
NFP = -7 mm Hg

The negative pressure at the venous end of capillaries causes fluid to move into the capillaries. The various movements of fluid between the capillaries and interstitium maintain a balance. Disrupting this balance can result in edema.
Movement of fluid in capillary.

http://commons.wikimedia.org/wiki/File:Illu_capillary_microcirculation.jpg
There is a loss of fluid from the capillaries at the arterial end. The net filtration pressure is 13 mm Hg.
Fluid flows back into capillaries at the venous end. The net filtration pressure is -7 mm Hg.