Cardiovascular Training Program
Program Content and Organization

Introduction: The Cardiovascular System

The graphic associated with this menu shows the Cardiovascular system and Man with extended arms. This section of the program is divided into three main categories.

SUBMENU OF THE CARDIOVASCULAR SYSTEM

F1 Anatomy and Physiology

F2 Circulatory Control Mechanisms

F3 Primary Components

F4 Disease

Anatomy and Physiology

General Text

The functions of the cardiovascular system is to carry oxygen, nutrients, and hormones to the cells in the body tissues, and to carry waste products away from them.

The cardiovascular system consists of six parts, each of which will be considered in depth in this program: the heart, the vascular system, the cardiac conduction system, the renin-angiotensin-aldosterone system, the autonomic nervous system, and the adrenergic receptors.

Detailed Text

The heart is an efficient muscular pump; it propels blood through the intricate, branching network of large and small vessels comprising the vascular system.

The cardiac conduction system is composed of specialized cardiac muscle fibers and the function of those fibers is to coordinate the heartbeat. The renin-angiotensin-aldosterone system regulates blood pressure through hormonal control.

The autonomic nervous system releases messenger molecules that control the heart rate and also the contractility of the heart muscle itself; this, in turn, affects the amount of blood delivered to the heart in a given time (cardiac stroke volume)**.** These messenger molecules exert their control by binding to adrenergic receptors on cardiac muscle cells.

Circulatory Control Mechanisms

General Text

Detailed Text

Role of venous return:

At any level of contractile state, the performance of the myocardium is influenced profoundly by ventricular end-diastolic volume and therefore by myocardial fiber and sarcomere length. The stroke volume is controlled on the one hand by an interaction between the pumping capabilities of the heart and on the other by the capacity of the peripheral circulation to return blood to the heart. Hypovolemia or obstruction of the venae cavae reduce cardiac output by lowering venous return, even when the heart and vascular bed are normal. Most changes in cardiac output can be accounted for largely by changes in the ability of the peripheral vascular bed to return blood to the heart, which thereby alters the preload.

Large changes in output occur during maneuvers that radically alter the venous return, e.g., lower body negative pressure, positive pressure respiration, sudden assumption of the head-up or head-down positions, and the rapid infusion or withdrawal of blood. The following factors have a considerable influence over venous return:

[1] **Body position.** Since gravitational forces pool blood in the dependent portions of the body, assumption of the upright posture increases extrathoracic blood volume at the expense of intrathoracic and ventricular end-diastolic volumes and thereby reduces ventricular work and cardiac output. The effects of negative pressure (suction) applied to the lower limbs and torso with the subject supine mimic those of assumption of the upright posture, while inflation of a lower-body positive-pressure suit or the absence of gravitational force during space flight increased intrathoracic blood volume.

[2] **Intrathoracic pressure.** Normally, negative intrathoracic pressure increases thoracic blood volume, improves cardiac filling and augments cardiac performance. The pressure becomes more negative during inspiration and approximates atmospheric pressure during expiration. Elevation of mean intrathoracic pressure, as occurs with positive-pressure respiration, with pneumothrorax, or with opening of the chest, all tend to impede total venous return to the heart, to diminish intrathoracic blood volume, and ultimately to reduce ventricular performance.

[3] **Intrapericardial pressure.** When pericardial pressure is elevated, as in pericardial effusion, there is interference with cardiac filling, and the resultant reduction in ventricular diastolic volume reduces ventricular performance. Marked elevations of intra-pericardial pressure may lead to cardiac tamponade, which is characterized by lowering of stroke volume and arterial pressure with circulatory collapse. Chronic constrictive pericarditis also impedes ventricular filling and thereby lowers stroke volume.

[4] **Venous tone.** The smooth muscle in venous walls responds to a variety of neural and humoral stimuli; venoconstriction occurs during muscular exercise, anxiety, deep respiration or marked hypotension, any of which tend to diminish extrathoracic and to augment intrathoracic blood volume. Extravascular compression of the veins by skeletal muscle has an important role in augmenting venous return by exercising skeletal muscle.

[5] **Atrial contribution to ventricular filling.** A vigorous, appropriately timed, atrial contraction augments ventricular filling and end-diastolic volume. The atrial contribution to ventricular filling is of particular importance in the presence of ventricular hypertrophy and other states of reduced ventricular compliance with impedance of ventricular filling. Under these circumstances the loss of atrial systole, as occurs in atrial fibrillation, reduces ventricular end-diastolic pressure and volume, ultimately impairing myocardial performance.

Role of afterload:

The stroke volume is ultimately a function of the extent of ventricular fiber shortening during systole, which, at any given level of diastolic fiber length and contractility, varies inversely with afterload. Afterload is determined principally by the aortic impedance, which in turn is influenced largely by the peripheral vascular resistance, the physical characteristics of the arterial tree, and the volume of blood that it contains at the onset of ejection. An elevation of afterload often results

in a compensatory rise in ventricular preload, i.e., an elevation of end-diastolic volume and an increase in left ventricular diameter.

Arterial pressure is related to the product of cardiac output and systemic vascular resistance, while afterload is a function of left ventricular size and arterial pressure. An increase in arterial pressure induced by vasoconstriction, for example, augments afterload, which through a negative feedback tends to depress myocardial fiber shortening, stroke volume, and cardiac output. When left ventricular function is impaired, afterload becomes an increasingly important determinant of cardiac performance.

Role of contractility:

The factors that govern the intensity of the active state of the myocardium may be considered to operate by modifying the myocardial force-velocity length relations and the level of ventricular performance at any given ventricular end-diastolic volume.

[1] **Sympathetic nerve activity**: The quantity of norepinephrine released by sympathetic nerve endings in the heart is probably the most important mechanism that regulates myocardial contractility under physiological conditions. Rapid changes in contractility are effected by variations in the impulse traffic in the cardiac adrenergic nerves.

[2] **Circulating catecholamines**: When properly stimulated by nerve impulses, the adrenal medulla and other adrenergic ganglia outside the heart release catecholamines, which are carried by the bloodstream to the myocardium, where they augment the contractile state. This mechanism is slower than the response to norepinephrine release by cardiac nerves but is of physiological importance in conditions such as hypovolemia and a variety of chronic stresses, including congestive heart failure.

[3] **Heart rate**: Myocardial contractility may be profoundly influenced by the rate and rhythm of cardiac contraction. A simple increase in heart rate in the physiological range also augments cardiac contractility, but this effect is more prominent in hearts with depressed function than it is in the normal heart.

[4] **Exogenous inotropic agents**: The cardiac glycosides, sympathomimetic agents acting on beta-adrenergic receptors, calcium, caffeine, theophylline, glucagon, and their derivatives all improve the myocardial force-velocity relation.

[5] **Physiological and pharmacological depressants**: Anoxia, ischemia, acidemia, quinidine, procaine amide and other local anesthetics, barbiturates, and most general anesthetics depress myocardial contractility.

[6] **Loss of contractile mass**: When a portion of ventricle becomes nonfunctional, as occurs in ischemic heart disease, the overall performance of the ventricle at any given end-diastolic volume is depressed, even though the contractility of the remaining myocardium may be normal.

Long-term regulation

Other mechanisms, tend to provide circulatory homeostasis over longer periods. For example, reflexes originating primarily in atrial stretch receptors aid in the regulation of blood volume through control of antidiuretic hormone and renal vascular resistance. Mechanisms that act over much more extended periods, not yet clearly defined, involve the long-term control of arterial pressure, blood volume, and sodium balance. Arterial pressure and sodium balance are interdependent; e.g., a depression of arterial pressure tends to reduce renal perfusion. This is accompanied by sodium retention resulting from the reduction of glomerular filtration as well as through the activation of the renin-angiotensin-aldosterone system. Thus, arterial pressure is sensitive to marked changes in blood volume, which tends to rise in many conditions, including primary aldosteronism, low renin hypertension, and renal failure.

The renal excretion of sodium and water is a function of arterial pressure; marked elevations of pressure increase sodium excretion, and marked depressions of arterial pressure reduce it. Long-term circulatory control mechanisms are particularly interesting in patients with various forms of hypertension. For example, in patients with any of the varieties of inappropriate mineralocorticoid activity there is a tendency to volume expansion, and the resultant small increase in preload produces a small but sustained increase in cardiac output. In an attempt to return tissue perfusion to normal levels, peripheral resistance rises and adrenergic nervous activity declines, both to the heart and to the peripheral vascular bed.

On the other hand, in patients in whom there is a high plasma renin activity, such as those with renovascular or malignant hypertension, the plasma volume may be reduced as a consequence of renal sodium excretion. The renin-angiotensin-aldosterone system tends to defend both blood volume and arterial pressure in a variety of physiological and pathological conditions. A chronic low-sodium intake, a net sodium loss, mild-to-moderate hemorrhage, or reduced renal perfusion secondary to thoracic vena cava constriction all tend to stimulate the renin-angiotensin-aldosterone axis and thereby prevent further reduction of renal perfusion and natriuresis. Ultimately, blood volume and therefore preload and cardiac output are protected.

Primary Components

Cardiovascular Training Program
Program Content and Organization

The cardiovascular system is divided into six modules. The content for each module is detailed in the following sections of this document.

Section 1: The heart

Section 2: The vascular system

Section 3: The cardiac conduction system

Section 4: The renin-angiotensin-aldosterone system

Section 5: The autonomic nervous system

Section 6: The adrenergic receptors

Cardiovascular Training Program
Program Content and Organization

Section 1: The Heart

The graphic associated with the heart module menu shows the heart in longitudinal section, pumping blood through both the pulmonary and systemic circulations in the entire cardiac cycle. The heart module is broken down into three main categories.

SUBMENU OF THE HEART

F1	**Anatomy and Physiology**
F2	**Primary components**
F3	**Relationship to other systems and organs**

Anatomy and Physiology

General text

Since the heart is a pump, it consists largely of contractile muscle tissue, which does the pumping, and chambers, which hold the blood. Blood is brought to the heart by large veins and carried away from it by a single large artery, which branches into many tributaries.

Detailed text

Circulation within the heart

The heart has two anterior chambers, the atria, which receive incoming blood, and two posterior chambers, the ventricles, which pump blood out of the heart. The circulation of blood to, from, and within the heart can be considered as a dynamic process consisting of the following steps:

[1] The right atrium receives deoxygenated blood from the body tissues via two large veins, the superior and inferior vena cava, and transfers the blood into the right ventricle.

[2] The right ventricle then pumps the blood into the pulmonary artery, which takes it to the lungs where it picks up oxygen.

[3] The oxygenated blood returns to the pulmonary veins and passes into the left ventricle.

[4] The left ventricle then pumps a volume of blood (the cardiac stroke volume) into the body's largest artery, the aorta, for distribution to the body tissues via the systemic circulation.

The system of blood vessels that carries blood to the lungs and back is called the pulmonary circulation; all other blood vessels in the body are collectively known as the systemic circulation.

Preload

The capacity of the intact ventricle to vary its force of contraction on a beat-to-beat basis as a function of its end-diastolic size is one of the major determinants of cardiac function and is generally referred to as the Frank-Starling phenomenon. Changes in end-diastolic pressure and volume of the ventricle are useful in assessing acute directional changes in preload under chronic conditions and in disease states. During acute volume loading sarcomere length increases, whereas chronic volume loading leads to cardiac dilatation accompanied by only small additional changes in sarcomere length. The chronically dilated left ventricle is characterized by normal performance of each unit of an enlarged circumference, allowing delivery of a larger stroke volume without an apparent change in contractility. When properly timed, atrial contraction serves to augment ventricular filling and preload.

Afterload

Afterload may be defined as the tension, force, or stress (force per unit cross-sectional area) in the ventricular wall during ventricular contraction and to influences the quantity of blood ejected by the ventricles. The impedance of the arterial system is determined by the physical properties of the vascular bed and blood; the reflected pressure and flow waves generated distally may be used to provide a rigorous way of describing the conditions that contribute to myocardial stress. Afterload is inversely related to stroke volume, to the extent of wall shortening, and to the velocity of shortening. Ventricular end-systolic volume is determined by and varies directly with afterload; it is largely independent of preload and varies inversely with the inotropic state.

Contractility

Contractility reflects the intensity of the active state of the cardiac muscle; the active state, in turn, may be considered to be a mechanical measure of the chemical processes in the contractile element of the muscle that generate both force and shortening. A change in contractility may be

defined as an alteration in cardiac performance that is independent of alterations in preload or afterload. Adrenergic impulses and drugs such as the sympathomimetic amines, cardiac glycosides, anesthetics, antiarrhythmic agents, and thyroid hormone can alter contractility.

Heart Rate

At rest, venous return to the heart is reflexly and metabolically stabilized so that artificially varying the heart rate between about 60 and 160 beats per minute has little effect on the cardiac output, despite altered cardiac contractility. However, if the diastolic volume of the heart is maintained by increasing venous return as heart rate is increased, cardiac output will rise. Tachycardia augments the total fraction of each cardiac cycle occupied by systole, and the corresponding reduction in the duration of diastole interferes with ventricular filling. This effect is partially counteracted by an augmentation in contractility, which tends to reduce the duration of each individual contraction.

The heart's primary components

The graphic associated with this section will show the internal and external heart structures.

Additional information on the heart is presented in the following sections.

SUBMENU OF PRIMARY COMPONENTS

F1 Chambers and Walls

F2 Pulmonary Circulation

F3 Systemic Circulation

F4 Valves

F5 Coronary Arteries

Chambers and Walls

The graphic associated with this section shows the heart in longitudinal section with chambers and walls exposed. An animation shows the walls contracting and the chambers filling with blood.

General text

The heart's two anterior chambers, the atria, are contractile and serve as reservoirs for blood; its two posterior chambers, the ventricles serve as powerful pumps to force blood out of the heart and into the circulation.

Detailed text

The walls of the heart are constructed in three layers:

[1] The *endocardium* is the innermost layer; it lines the interior of the chambers and is composed of a single layer of flattened cells fitted together.

[2] The dominant layer of the heart wall is the middle layer or *myocardium.* "Myo" means muscle and the myocardium is composed largely of cardiac muscle cells The left ventricular myocardium is extremely thick because the left ventricle must generate enough pressure to pump blood through the systemic circulation to the tissues of the entire body. By contrast, the atria have thin walls because they function primarily as reservoirs, not as pumps.

[3] The *epicardium* is the outermost layer of the heart. It consists of a single layer of cells, beneath which lies a layer of connective tissue which functions as a support.

At this level, the user may view additional information on the three layers of the heart chamber walls

The *endocardium* is the innermost layer; it lines the interior of the chambers and consists of a single layer of cells.

The *myocardium* is the middle layer; it is composed mainly of cardiac muscle cells.

The *epicardium* is the outermost layer of the heart wall. It consists of a single cell layer covered by a layer of supporting connective tissue.

Pulmonary Circulation

The graphic in this section shows an animation of blood moving through the pulmonary circulation.

General text

The blood vessels leading to and from the lungs constitute the pulmonary circulation. They conduct blood from the heart to the lungs where it is oxygenated and then back to the heart where it is sent out to the body tissues.

Detailed text

The pulmonary artery emerges from the right ventricle and divides into right and left branches on leaving the heart. These arteries conduct blood from the right ventricle to the lungs where it is oxygenated when the hemoglobin in its red cells is exposed to the higher oxygen level present in the pulmonary capillaries. The pulmonary arteries are the only arteries in the body to carry deoxygenated blood.

There are four pulmonary veins, two for each lung. They return oxygenated blood to the left atrium and are the only veins in the body to transport oxygenated blood.

Systemic Circulation

The graphic in this section shows the systemic circulation an animation of blood moving through the systemic circulation.

General text

All blood vessels other than those leading to and from the lungs constitute the systemic circulation. The systemic circulation carries oxygen, nutrients and hormones to body tissues and removes carbon dioxide and other wastes from these tissues.

Detailed text

The main artery of the systemic circulation is called the aorta. It carries oxygenated blood from the heart to the body tissues. All systemic arteries branch from the aorta; each section of the

aorta gives off arteries that branch into distributing arteries leading to organs and finally into the very small vessels (arterioles and capillaries) that supply the tissues.

Blood is returned to the heart through the systemic veins. All the veins of the systemic circulation lead into either the superior or inferior vena cava which return blood from the body tissues to the heart; they empty into the right atrium.

At this level, the user may view additional information on arteries and veins which are composed of three layers.

The innermost *tunica intima* consists of a single layer of flattened endothelial cells. The middle layer, or *tunica media,* consists of elastic tissue, smooth muscle, or both. The outermost *tunica adventitia,* consists of connective tissue which functions as a support.

Valves

The graphic in this section shows an animation of the valves functioning.

General text

The heart has four valves to prevent backflow of blood. The atrioventricular valves prevent the backflow of blood during ventricular contraction.(systole); they are normally open during ventricular relaxation (diastole).The aortic and pulmonary valves open during systole, then close during diastole to prevent the backflow of blood after it has been pumped into the arteries.

Detailed text

There are two atrioventricular valves: the tricuspid valve lies between the right atrium and ventricle and the mitral valve lies between the left atrium and ventricle. The other two valves are the pulmonary valve, which lies between the right ventricle and the pulmonary artery, and the aortic valve which lies between the left ventricle and the aorta All the valves consist of three individual leaflets except for the mitral valve which has only two. The leaflets of the tricuspid and mitral valves are anchored to the inside of the right and left ventricles by fibrous cords (the *chordae tendinae)* and projections of myocardium called papillary muscles. These muscles

prevent the valves from being pushed up into the atria when the ventricles contract to pump blood out into the great arteries.

At this level, the user may view additional information on valves.

The atrioventricular valves are reduplications of *endocardium* (the layer of single cells forming the innermost layer of the heart wall) together with a core of dense connective tissue. The endocardium is thicker on the atrial than on the ventricular surface and contains more elastic tissue. The pulmonary and aortic valves are similar in structure to the atrioventricular valves.

The Coronary Arteries

The graphic in this section shows the coronary arteries providing blood to the heart.

General text

The heart receives oxygenated blood from the coronary arteries. These arteries originate at the base of the aorta and course down over the surface of the heart, sending their smallest branches deep within its muscular walls.

Detailed text

The right main coronary artery delivers blood primarily to the right ventricle, while the left descending and circumflex arteries serve the left ventricle.

Blood flow through the coronary arteries is unique; most arteries become filled with blood during cardiac contraction (systole) but the coronary arteries are filled during cardiac relaxation (diastole). This is because the tension developed in the walls of the heart during contraction compresses these arteries so that blood cannot flow into them. When the heart then relaxes, blood rushes from the aorta into the coronary arteries.

Relationship to other systems and organs

The heart is physically connected to the cardiac conduction system and the vascular system, both of which are vital to its functioning. The cardiac conduction system, which is contained within the heart itself, controls the rate at which the heart beats. It consists of cardiac muscle cells specialized to conduct an electric current. The vascular system is the network of large and small blood vessels through which blood is pumped by the heart.

The autonomic nervous system and the kidneys both affect the function of the heart. The rate and strength of the heartbeat are regulated by the autonomic nervous system (ANS) through secretion of neurotransmitters such as norepinephrine. The kidneys influence the functioning of the heart through the secretion and regulation of angiotensin II, the most powerful vasoconstrictor in the human body.

Section 2: The Vascular System

The graphic associated with the vascular system module shows a diagram of an arteriole leading into a capillary bed leading into a venule; the diagram becomes animated showing circulation through the capillary bed. The vascular system module is broken down into three main categories.

SUBMENU OF THE VASCULAR SYSTEM

F1 Anatomy and Physiology

F2 Primary components of the vascular system

F3 Relationship to other systems and organs

Anatomy and Physiology

General text

The vascular system is a closed network of vessels that carries blood in a continuous circuit throughout the body, thereby supplying essential nutrients, oxygen, and hormones to the tissues.

Detailed text

The basic layout of the vascular system is as follows: Upon leaving the heart, arteries divide into successively smaller branches-the smallest of which are called arterioles-that deliver blood into the capillary beds of individual tissues.

Capillaries are the smallest vessels in the vascular system; they consist of a single layer of endothelial cells fitted together to form a continuous tube. They are the only vessels in the cardiovascular system that permit the exchange of substances (eg, water, oxygen, carbon dioxide, glucose) between the bloodstream and the surrounding tissues. They form extensive networks (beds) of vessels between arterioles and venules, which are the smallest veins.

Capillaries converge to form venules, and these in turn converge to form successively larger veins that transport blood back to the heart to complete the vascular circuit.

Primary components of the vascular system

SUBMENU OF PRIMARY COMPONENTS

F1 Arteries

F2 Veins

F3 Arterioles

F4 Venules

F5 Capillaries

Arteries

The graphics associated with this menu shows a diagram structure of a large artery (in cross-section showing the three layers). It is animated to show the elasticity of arteries.

General text

Arteries transport blood away from the heart under high pressure to body tissues. Their structure adapts them for both high pressure and changes in pressure.

Detailed text

The main artery of the heart is the aorta, which originates from the left ventricle of the heart and then gives rise to branches that course upward and downward to supply all body tissues with oxygen and nutrients.

The structure of arteries permits them to expand and contract. This is due to the presence of elastic fibers that enable the arteries to stretch outward with each pulse of blood pumped by the heart and then recoil back to their original shape when tension is released. Like all blood vessels, arteries have an inner layer, the *tunica intima,* which is composed of a single layer of flattened

endothelial cells fitted together to form a smooth, continuous tube. In large arteries, this inner layer is interspersed with elastic fibers and surrounded by a thick band of elastic fibers. The middle layer or *tunica media* of large arteries is very thick and consists largely of smooth muscle and elastic fibers. In very large arteries, the outer layer or *tunica adventitia* also contains some elastic fibers in addition to connective tissue.

Veins

The graphic associated with this menu shows a diagram of a veins wall layers. Animated to show venous valves in operation.

General text

Veins transport blood under low pressure toward the heart and also act as a reservoir of variable capacity to maintain a steady return of blood to the heart. The veins of the systemic circulation lead into the body's largest veins, the superior and inferior vena cavae, which empty into the right atrium of the heart.

Detailed text

Veins differ from arteries in three ways: their walls are thinner and contain little elastic fiber, and their internal diameter is greater. These structural properties make them able to stretch outward with ease and thereby adapt them to their function as a reservoir for blood. Since veins contain blood under low pressure, some structural modification is needed to prevent the downward pull of gravity from leading to the accumulation of blood in the legs and feet. The veins in the lower body therefore contain special one-way valves that prevent this from occurring. When the muscles in the extremities are active (eg, during exercise), their alternating relaxations and contractions squeeze the veins in such a way that blood is forced upward toward the heart. (It has been observed that soldiers kept standing at rigid attention for more than about 15 minutes may faint. This is because without the "muscle pump" working on the veins, insufficient blood returns to the heart and blood flow to the brain is reduced.)

The tunica media of arteries is thick and heavily reinforced with elastic fibers and smooth muscle; the tunica media of veins is thinner and contains less elastic fiber and smooth muscle. Arteries are thus well adapted to their function of carrying blood under pressure and veins to their function of serving as a reservoir to maintain a steady return of blood to the heart.

Arterioles

The graphic associated with this menu shows an arteriole animated to show its smooth muscle contracting and expanding to change the diameter.

General text

In addition to their function of distributing blood, arterioles also act as pressure-reducing valves between the arteries and capillaries; they also play an important role in determining blood pressure.

Detailed text

Of all the blood vessels, arterioles have the greatest proportion of smooth muscle in their walls. This makes the muscular tension in their walls such that they do not stretch under pressure. Instead, they act as pressure-reducing valves between the arteries and capillaries, buffering the delicate capillaries from the high pressure of blood in the arterial system. The degree of muscular

tension in the walls of the arterioles dictates their internal diameter, and this in turn dictates the resistance to blood flow through the arterioles. The arterioles exert a profound effect on blood pressure because they account for a large component of the peripheral resistance to blood flow; blood pressure is a product of total peripheral resistance and cardiac output.

Venules

The graphic associated with this menu shows a diagram of a venule.

General text

The function of venules is to drain blood from the capillary beds into the venous section.

Capillaries

The graphic associated with this menu is an animation which shows a capillary bed with blood going in through an arteriole and coming out through a venule.

General text

Capillaries are functionally unique. They are the only blood vessels in the cardiovascular system that have the all-important function of permitting the exchange of substances (eg, water, oxygen, carbon dioxide, glucose) between the bloodstream and the surrounding tissues.

Detailed text

Capillaries are composed of a single layer of flattened endothelial cells fitted together to form a continuous tube. This structure adapts them to their function of permitting the exchange of substances between the bloodstream and the surrounding tissues. It is at the level of the capillaries that cells take in oxygen and give out carbon dioxide and that they take in nutrients and give out waste products of cellular metabolism. Branching of the capillaries is extensive; although they are very small, there are so many of them (approximately 10 billion) that their total cross-sectional area is more than six times that of all the other blood vessels combined. The net effect is that no cell in the body is ever very far away from a capillary and its life-sustaining contents.

Relationship to other systems and organs

The vascular system stands in a unique relation to the heart; these two components have the same function: To provide oxygen, nutrients, and hormones to the cells of all body tissues. It is, in a way, more accurate to think of the heart and the vascular system as one unit rather than two, because each is equipped to carry out half of that function.

The vascular system is also closely related to the adrenergic receptors and the autonomic nervous system, which together control important aspects of its function. The smooth muscle cells in the arteries, veins, arterioles, and venules bear on their surfaces alpha-adrenergic receptors; the receptors bind molecules released by cells of the autonomic nervous system and respond by contracting. These molecular messengers are called norepinephrine and epinephrine.

The contraction of the smooth muscle cells results in constriction of arterioles, which in turn causes (1) an increase in arteriolar resistance (and therefore an increase in blood pressure) and (2) an increase in return of venous blood to the heart. Another class of adrenergic receptors, called beta-2, causes dilation of blood vessels when stimulated by epinephrine.

The graphic associated with the cardiac conduction system module shows a diagram of an electrocardiogram. The cardiac conduction system module is broken down into three main categories.

Section 3: The Cardiac Conduction System

SUBMENU OF THE CARDIAC CONDUCTION SYSTEM

F1	**Anatomy and Physiology**
F2	**Primary components**
F3	**Relationship to other systems and organs**

Anatomy and Physiology

General Text

Contraction of the heart's chambers result from electrical activity in the heart, and is controlled and coordinated by the cardiac conduction system. The cardiac conduction system is composed of cardiac cells specialized for transmitting electrical signals called action potentials.

Detailed text

Myocardial (muscle) cells are characterized by two important properties: they can contract when stimulated and they can transmit stimulating electrical impulses to adjoining muscle cells. Myocardial cells can also contract spontaneously, ie, without an external stimulating impulse. In the cardiac conduction system, the tissue with the fastest rate of contraction functions as a pacemaker. That pacemaker tissue initiates contraction in the slower muscle fibers before they have a chance to contract spontaneously.

The primary components of the cardiac conduction system are the sinoatrial (SA) node, the atrioventricular (AV) node, the bundle of His, with its right and left bundle branches, and the Purkinje fibers. Each normal heartbeat is a combination of coordinated electrical and mechanical events organized into a sequence of events called the cardiac cycle. In this cycle, the SA node generates an electrical current that is conducted down through the atria and then to the ventricles via the AV node and the His-Purkinje system. The heart muscle contracts as the electrical current passes through it. The wave of electrical energy that passes down through the heart is called a wave of depolarization; this term refers to a change in the electrical properties of the muscle. The electrical changes taking place in the heart during the cardiac cycle create electromagnetic fields that can be detected by electrodes placed on the surface of the body. A characteristic set of electrical waves is produced during each cardiac cycle and the waves are known to correlate with specific events in the cycle. When this display of waves is recorded, it generates an electrocardiogram.

The *P-wave* correlates with atrial depolarization and contraction (systole).

The *QRS complex* correlates with ventricular depolarization and contraction (systole).

The *T-wave* correlates with ventricular repolarization and relaxation (diastole). Atrial repolarization is masked by the electrical field generated simultaneously during ventricular depolarization.

Primary components

SUBMENU OF PRIMARY COMPONENTS

F1	**The sinoatrial (SA) node**
F2	**The atrioventricular (AV) node and the bundle of His**
F3	**The Purkinje fibers**
F4	**Cardiac electrophysiology**
F5	**Mechanism of muscle contraction**
F6	**Calcium channel blockers**
F7	**Threshold potential and refractoriness**
F8	**Automaticity**

The Sinoatrial Node

General text

Each heart beat normally originates in a cluster of specialized myocardial tissue called the sinoatrial (SA) node. This bundle of cells is located in the right atrium.

Detailed text

The SA node has the fastest rate of spontaneous discharge of all myocardial tissue; it generates action potentials at a rate of about 70 to 80 per minute. Therefore, the SA node is the pacemaker and the whole heart beats at this rate. Electrical discharge from the SA node stimulates the atria and makes them contract.

The atrioventricular node and the bundle of His

General text

A special conduction system is required to stimulate ventricular contraction. This is because the atrial and ventricular myocardia are separated by a fibrous base that does not conduct electricity. This special system, located at the base of the right atrium, is a bundle of conduction fibers called the atrioventricular (AV) node and the bundle of His.

Detailed text

This bundle pierces the fibrous base of the heart and sends two branches down through the muscular septum between the right and left ventricles. These left and right bundle branches terminate in the Purkinje fibers.

The Purkinje fibers

The graphic associated with this menu shows the cardiac conduction system, animated to show waves of depolarization spreading through the cardiac conduction system

General text

The Purkinje fibers penetrate deep into the ventricular myocardium and transmit electrical impulses to it.

Detailed text

The Purkinje fibers are located just beneath the endocardium on the internal surface of the heart. Actual contraction of the ventricles is stimulated by the Purkinje fibers, which emerge from the bundle branches and pass into the cells of the myocardium.

In summary, the cardiac cycle responsible for each normal heartbeat consists of the following sequence of events:

1. The SA node depolarizes spontaneously (ie, transmits a wave of depolarization).
2. The atrial myocardium depolarizes and contracts.
3. The AV node transmits this wave of depolarization to the bundle of His.
4. The left and right bundle branches transmit the wave to the Purkinje fibers.
5. The Purkinje fibers stimulate the ventricular myocardium.
6. The ventricular myocardium depolarizes and contracts.

Cardiac electrophysiology

The graphic associated with this menu shows muscle cells with outside + and inside -. An animation shows a wave of depolarization passing through the myocardium so that outside is - and inside is +.

General text

Every living cell in the human body is characterized by a high intracellular concentration of potassium (K^+) ions and a low concentration of sodium (Na^+) ions. The relative concentrations of these two ions are just the opposite in the extracellular fluid. An energy-requiring transport process maintains this unequal distribution of sodium and potassium ions by pumping potassium ions into the cell and pumping sodium ions out.

Detailed text

The interior of a resting myocardial cell contains many negatively charged ions that cannot cross the cell membrane. In such a cell, therefore, the inner surface of the membrane is negatively charged and the outer surface is positively charged. The cell membrane is said to be polarized when it is in this state.

A polarized cell membrane can be compared to a simple battery, which has positive and negative poles. If we connect a light bulb between the two terminals (ie, poles), it lights up because electric current is flowing from the negative terminal to the positive terminal. The current is a result of the electric *potential* (energy) that is released when the connection is made. The electric potential across the membrane of a resting myocardial cell is called the resting transmembrane potential. Just as the potential energy of a battery can be released in the form of an electric current, the transmembrane potential of a myocardial cell can be released in the form of an *action potential*. The cell's transmembrane potential is measured in millivolts (one millivolt = one thousandth of a volt). Transmembrane potentials varies from -90 mV to -80 mV, depending on the specific cell type. The critical electrical event in myocardial function is called *depolarization*; it consists of a reversal in membrane potential caused by the rapid movement of positively charged sodium ions into the cell. Depolarization stimulates the cell to contract by triggering the release of calcium ions from a membranous structure called the sarcoplasmic reticulum.

Mechanism of muscle contraction

The graphic associated with this menu shows thick and thin filaments). An animation shows thick and thin myofilaments sliding past each other.

General text

The contraction of a muscle results from the shortening of individual muscle cells. This occurs because muscle cells contain two sets of interdigitating filaments that slide past each other during contraction, telescoping in such a way that the total length of the filament array is shortened. This is called the sliding filament mechanism of contraction.

Detailed text

The myofilaments of a muscle cell do not extend the full length of the cell, but are stacked in compartments called sarcomeres. Each sarcomere contains an array of thick filaments of a protein called myosin and thin filaments of a protein called actin. It also contains membranous structures called the sarcoplasmic reticulum (in which calcium ions are stored) and channels called T-tubules (which are extensions of the muscle cell membrane). When a nerve impulse arrives at a muscle fiber, it initiates a wave of electrical activity that spreads from the muscle cell membrane first into the T tubules and then into the sarcoplasmic reticulum (SR). The SR then releases calcium ions, which initiates sliding of the thin filaments past the thick ones by a rather complicated series of biochemical events.

Action Potential

The graphic associated with this menu shows action potential with numbers. The diagram becomes animated to show action potential.

General text

The action potential is a dynamic representation of the instantaneous electrochemical difference between the inside and outside of a single cardiac cell.

Detailed text

Changes in transmembrane potential over time are called action potentials. They represent the electric currents generated by the depolarization and repolarization of the muscle cell membrane. The graph of an action potential can be obtained via microscopic electrodes placed in isolated myocardial fibers. They are *not* the same as the electrocardiographic (ECG) tracings recorded by placing electrodes on the body surface.

The functioning of all muscle and nerve cells depends on action potentials. These cells respond to action potentials by contracting and relaxing, simultaneously transmitting the action potential on to adjoining cells. The ability to respond to and transmit an action potential is called excitability. Muscles and nerves are said to be composed of excitable cells.

Threshold Potential and Refractoriness

The graphic associated with this module shows that a stimulus produces no response in the effective refractory period but does produce a response in the relative refractory period. The diagram is animated to show the impulse arriving and the response.

General text

In order for myocardial contraction to occur, there are two requirements that must be met. First, the cell must depolarize to a certain critical *threshold potential* in order for an action potential to be elicited. If an exciting stimulus does not cause sufficient depolarization, nothing further will happen.

Detailed text

The second requirement for contraction is that the cell must not be in an *effective refractory period*, a period during repolarization when the myocardial cell is either totally or partially insensitive to exciting stimuli. This is because the ions must have sufficient time to redistribute before the cell can attain the polarized state. During the first part of repolarization, the cell is totally unable to depolarize and contract again, no matter how strong the exciting stimulus. This is called the *absolute refractory period.* Later in repolarization, the cell may exhibit a weak but complete response to some stimuli. This is called the *relative refractory period.*

Automaticity

The graphic associated with this module shows the SA node emitting a wave of depolarization. The diagram is animated with sequential waves of depolarization emanating from the SA node.

General text

Myocardial cells can contract spontaneously as well as respond to incoming stimuli. The ability of myocardial cells to undergo spontaneous depolarization and generate action potentials is called *automaticity.*

Detailed text

Cells that depolarize spontaneously at the fastest rate are called *pacemaker cells*. Although almost any cell in the myocardium can function automatically under some conditions (eg, disease) this property is normally reserved for the sinoatrial (SA) node. Pacemaker cells in the SA node depolarize at a predetermined rate and the other myocardial cells simply respond accordingly. Waves of depolarization emanate from the pacemaker in a steady rhythm, setting the pace for cardiac contraction.

Relation of the cardiac conduction system to other systems and organs

As regulator of the heart rate, the cardiac conduction system is obviously uniquely related to the heart. Because of its effect on heart rate, it is innervated abundantly by sympathetic and parasympathetic fibers of the autonomic nervous system. The sympathetic fibers that accelerate the heart rate and the parasympathetic fibers that slow it, terminate within the SA and AV nodes.