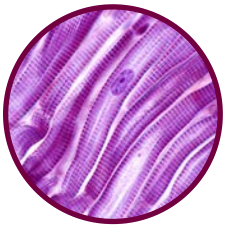
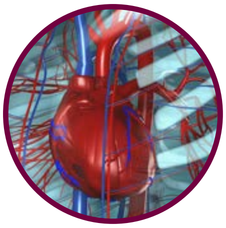
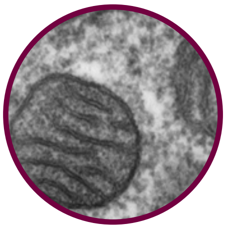
UNIT 2

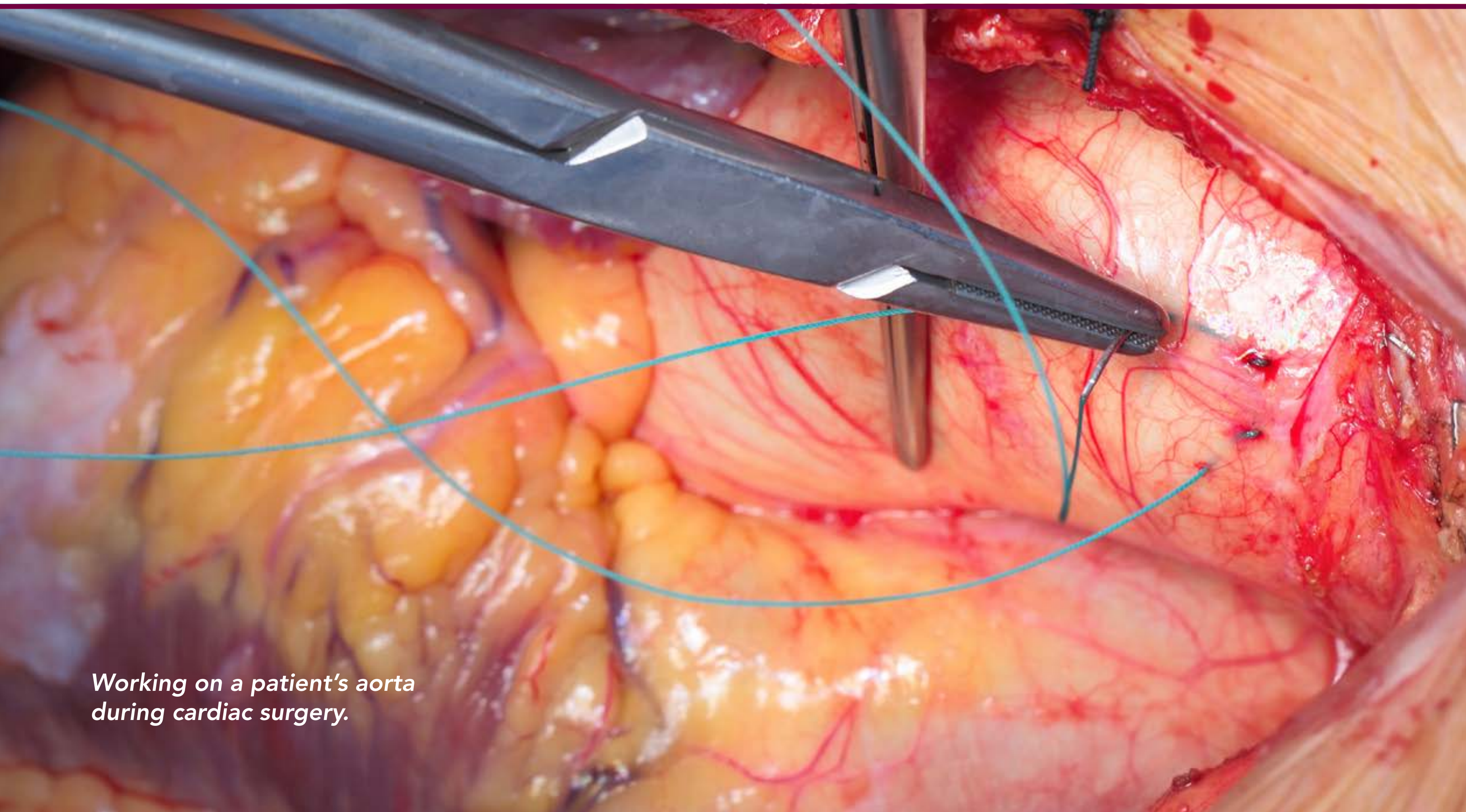
CARDIOVASCULAR & RESPIRATORY SYSTEMS

wonders of the HUMAN BODY

THE HEART

A normal heart is about the size of a person's fist. It is mostly made of **cardiac muscle**. There are two other kinds of muscle — skeletal muscle and smooth muscle. Muscles that enable you to walk or use your hands are examples of skeletal muscles. So is your diaphragm. Muscles that move your food through your digestive tract and the muscles that surround your arteries in order to allow them to influence your blood pressure are examples of smooth muscles. Cardiac muscle cells are designed to communicate efficiently with each other to pass along the electrical impulses that cause the heart to contract. Cardiac muscle cells are packed with **mitochondria**, tiny power-generators that keep the heart muscle continually supplied with energy. Incredibly, the heart only rests for about a fourth of a second during each "heartbeat." After all, the heart cannot afford to take a break!



Working on a patient's aorta during cardiac surgery.

The heart in an average adult pumps around 5 liters of blood every minute when resting. In a trained athlete, the heart can pump up to 33 liters per minute during vigorous exercise. On average, the heart moves 7,200 liters of blood per day. You've only got about 5 liters of blood altogether, so you can imagine that the blood circulates throughout the entire cardiovascular system many, many times in a day.

The heart "beats" on average around 72 times a minute when at rest. A young, healthy person's heart may beat up to 200 times a minute while exercising vigorously.

To keep up this steady pace, the many mitochondria in the muscle cells constantly use oxygen to convert glucose (a form of sugar) to energy. Therefore, those cells must be constantly supplied with oxygen. Without oxygen they cannot contract or even survive. If cardiac muscle cells are damaged by lack of oxygen, they have very little capacity to regenerate or replace themselves. Dead cardiac cells are replaced with scar tissue, but scar tissue cannot help pump. When people eat "heart healthy" foods and do "aerobic exercise," they are trying to keep their heart tissues in good shape to work well for a lifetime.

The Heart, a Workhorse

To really understand how much work the heart does, let's do some calculations.

We will base our calculations on a person with an average heart rate of 72 beats per minute. At rest, the heart pumps roughly 70 mL (2.4 ounces) per beat. So . . . if the heart beats 72 times a minute, that means it beats 4,320 times in an hour, 103,700 times in a day, 37,843,000 times in a year. So, in a person who is 70 years old, for instance, the heart has already beat roughly 2,649,000,000 times. That is almost 3 billion heartbeats (yeah, that's billion, not million)!

The average heart pumps 5 liters of blood a minute.

Looking further, if the heart pumps 70 mL per beat, that means it pumps 5 liters a minute, 302 liters per hour, 7,257 liters (1917 gallons) per day, 2,649,000 liters (699,798 gallons) per year. So the heart of our 70-year-old would have pumped 185,431,680 liters (48,985,000 gallons)!

And your heart does all this without taking any time off. It works 24 hours a day, seven days a week. So you would think it wise to keep your heart healthy, right?

Location of the Heart

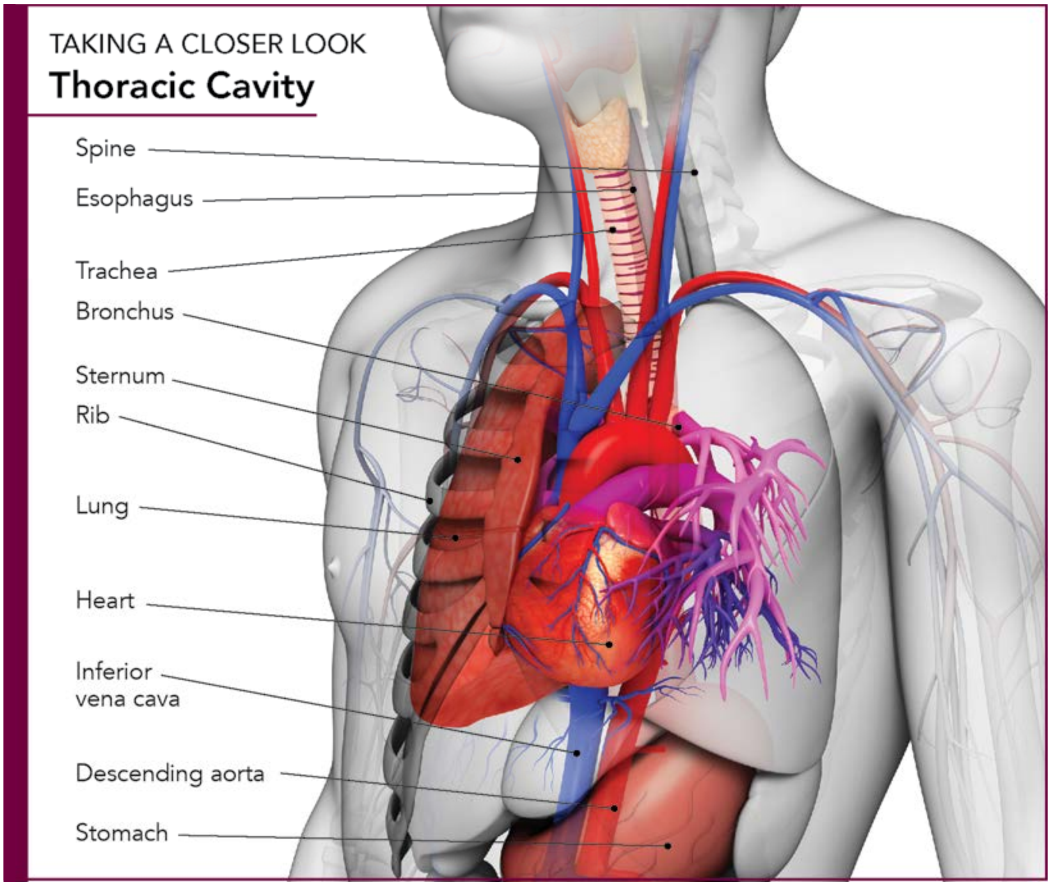
Your heart is in the center of your chest, under your *sternum*, or breastbone. The heart is shaped sort of like an upside-down pyramid. It is pointed so that its apex is below the middle of your left collarbone. That is why when you put your hand over your heart to say a pledge, you place your hand a little to the left of the sternum, because this is where the "beats" of the heart can be easily felt.

Your thoracic cavity, or chest cavity, has three main compartments. The left and right are occupied by your lungs. Your heart is in the middle one — the *mediastinum*. (The word comes from the Latin word for "middle.") The heart isn't alone in this space. Also in the mediastinum are some important nerves, the large blood vessels (and lymphatic vessels) that enter and leave the heart, and the esophagus and trachea. The esophagus carries the food you swallow to your stomach. The trachea carries the air you breathe to your lungs. There is a lot of traffic in the mediastinum, and with the ever-beating heart the mediastinum is a busy place!

If we look at the mediastinum from front to back at the level of the heart, we'd see the sternum in front, then the heart. Behind the heart is the esophagus, but not the trachea. The trachea splits into the right and left bronchi before it reaches as low as the heart. Behind the esophagus is the descending aorta, and then the spine.

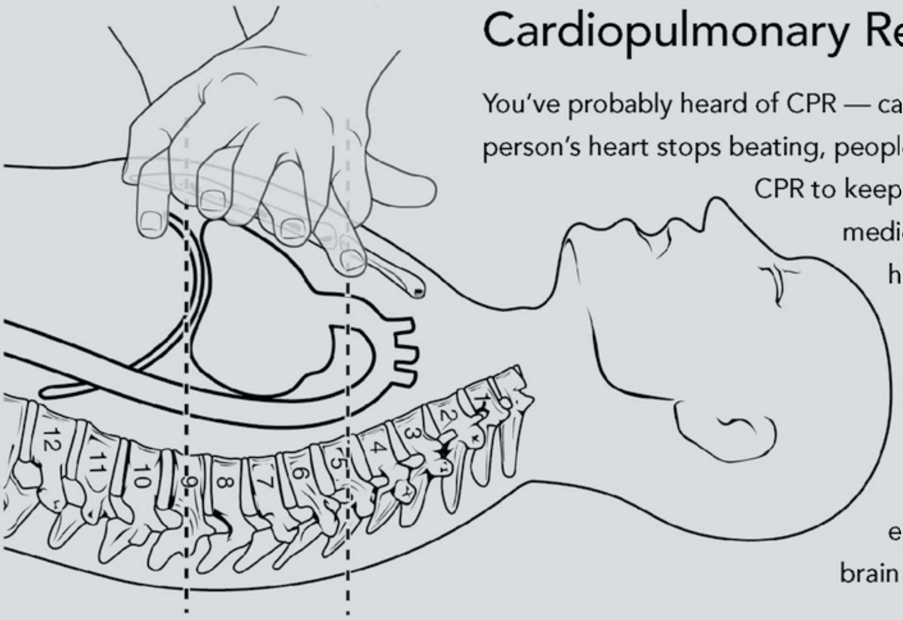
TAKING A CLOSER LOOK

Thoracic Cavity



Then, below the mediastinum is the diaphragm. The diaphragm is a large sheet of skeletal muscle that separates the chest cavity from the abdominal cavity.

Cardiopulmonary Resuscitation (CPR)



You've probably heard of CPR — cardiopulmonary resuscitation. When a person's heart stops beating, people trained in this form of first aid can start CPR to keep the blood circulating until emergency medical help can arrive. Now that you see the heart is really between the sternum and the spine — and not way off to the left — you can see how CPR works. With proper training, a person can press on the chest to squeeze the heart between the sternum and the spine, forcing enough blood out of the heart to keep the brain and body supplied with some oxygen.

The Pericardium

As the heart pumps, it constantly rubs against the other structures in the mediastinum. You might think that would create a lot of friction. Friction would generate heat and lots of wear and tear on the outer surface of the heart. To prevent this, God designed the heart with its own lubrication system. (After all, blisters from friction like you get on your feet wouldn't do your heart any good!)

Like many other organs that we'll learn about, the heart grows inside a pushed in, double-layered, balloon-like sac during embryonic development. Imagine a slightly inflated balloon containing a tiny bit of lubricating fluid. Now imagine pushing your fist into the balloon so that two layers of rubber are against your fist. Try it yourself with a few drops of cooking oil inside a slightly inflated balloon. Is your hand inside the balloon? Not exactly. But when you wiggle your fist, the oiled rubber surfaces should slide smoothly against each other. The oil prevents friction.

Your heart is inside just such a sac, the *pericardium*. *Peri* means "around." This sac goes around the heart. The *pericardial sac* has an outer layer called the *fibrous pericardium* and an inner layer called the *serous pericardium*.

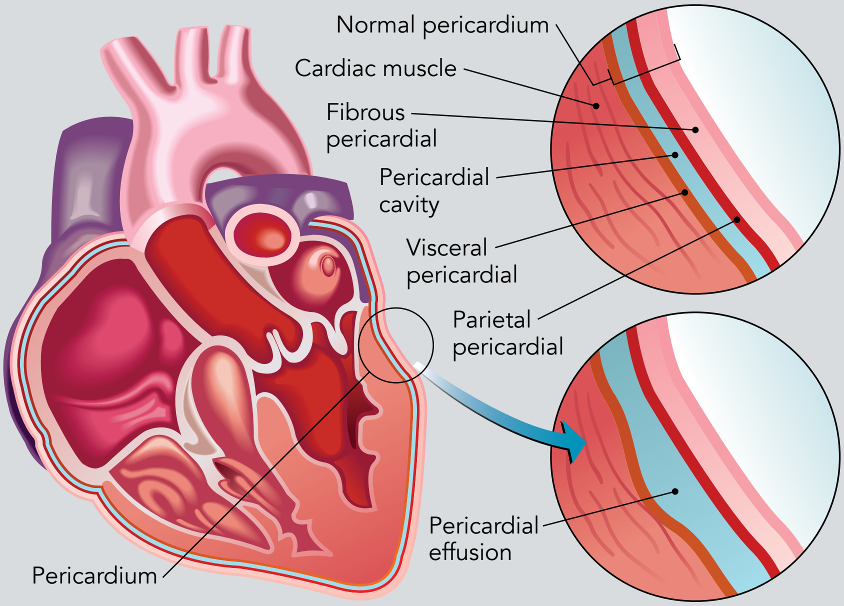
The fibrous pericardium is composed of tough, inelastic connective tissue. It serves to protect the heart, and to hold the heart in position in the chest.

The serous pericardium itself is made of two layers. The inner layer of the serous pericardium is called

Pericarditis

Occasionally, the pericardium can become inflamed. This condition is known as pericarditis.

It can occur suddenly, and it causes chest pain that is quite often severe. This pain sometimes radiates to the left shoulder and can be mistaken for a heart attack. The inflammation can be the result of a viral, bacterial, or fungal infection. Other causes include malignancy (cancer), heart attack, and trauma.



Some cases of pericarditis are quite mild and are treated with medication that controls inflammation. Other cases can be more aggressive and cause thickening of the pericardial sac, which can limit the movement of the heart. At times, the inflammation is severe enough that fluid begins to collect inside the pericardial sac. (This is called a **pericardial effusion**). Small amounts of fluid are easily tolerated and often resolve with treatment. However, in certain cases the amount of fluid that accumulates in the pericardial sac is enough to compress the heart and alter its ability to pump blood. This dangerous condition is a medical emergency known as **cardiac tamponade**. It is most often treated by inserting a needle into the pericardial sac and draining the fluid.

the visceral pericardium. The *visceral pericardium* is a thin layer stuck to the outer surface of the heart, just like the inner layer of balloon rubber was against your fist. The outer layer of the serous pericardium is called the *parietal pericardium*. The parietal pericardium is fused to the fibrous pericardium.

The visceral pericardium secretes a small amount of fluid, known as *pericardial fluid*, that provides lubrication between the visceral pericardium and the parietal pericardium. This fluid minimizes friction as the heart beats. You see, our Master Designer thought of everything!

If we peeled back the pericardium, we'd see the great vessels emerging from the upper part of the heart. The upper end of the heart is called the *base*, even though it is on the top, because it forms the broader part of the pyramid-like heart's shape. (The *apex* is the pointy bottom end.) Peeling back the pericardium would also reveal the coronary arteries and the cardiac veins running across the surface of the heart and sending their smaller branches down into the muscle of the heart.

The Layers of the Heart

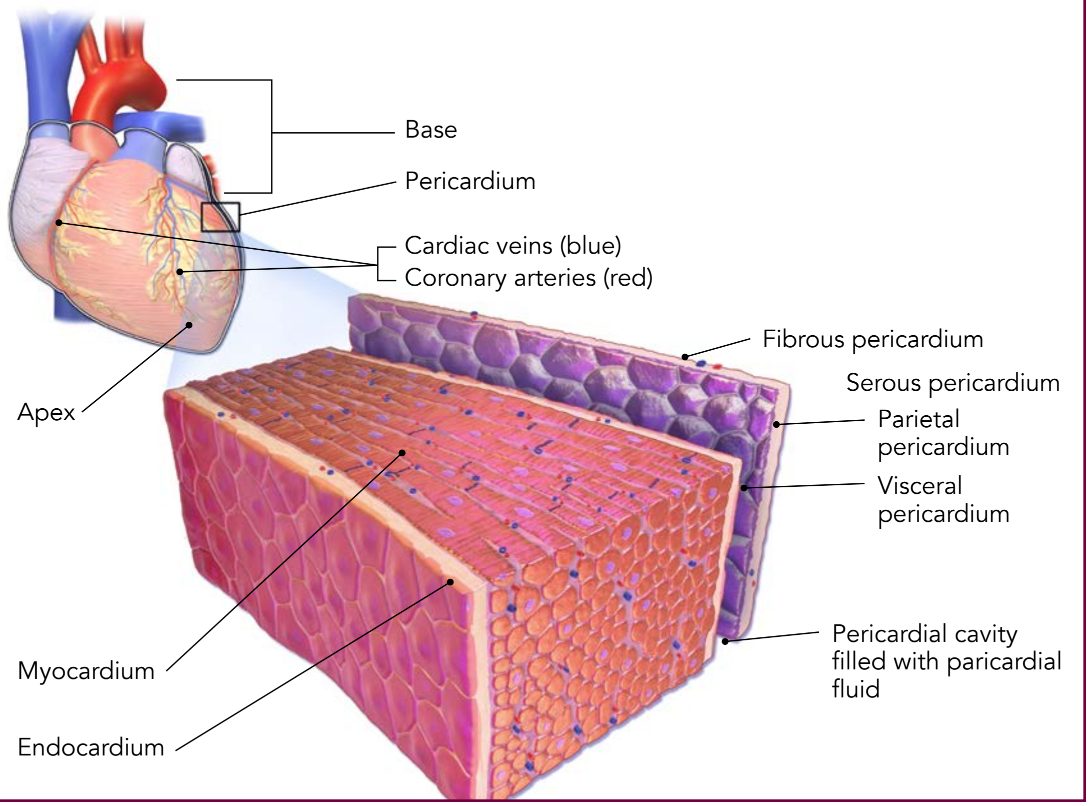
The wall of the heart consists of three layers: the *epicardium*, the *myocardium*, and the *endocardium*. Now you can see how thinking of anatomical names as word puzzles can help you! *Peri*, as in "pericardium," means "around," and the pericardium surrounds the heart. *Epi* means "outer," *myo* means "muscle," and *endo* means "inner." And of course *cardium* means "heart"! Therefore, these words are names for the layers of the heart itself.

Remember, we said that the pericardium consists of the outer parietal pericardium and the inner visceral pericardium, which is plastered to the surface of the heart. The outermost layer of the heart is actually the visceral layer of the pericardium. Where this membrane contacts the heart it is called the *epicardium*. It is made mostly of connective tissue and provides a protective covering for the surface of the heart.

The middle layer forms the bulk of the heart and is called the myocardium. As you might expect, knowing that *myo* means "muscle," this layer

TAKING A CLOSER LOOK

Pericardium and Layers of the Heart



is primarily cardiac muscle. The myocardium makes up about 95 percent of the mass of the heart. This is the layer that is responsible for the contraction of the heart. There is also some connective tissue in the myocardium. This connective tissue helps hold the cardiac muscle fibers in proper orientation so they can work together to make the heart contract properly.

The innermost layer of the heart wall is a smooth, thin lining called the endocardium. The *endocardium* lines the heart chambers and covers the valves of the heart. It also extends into the blood vessels attached to the heart. Because it is very smooth, the endocardium minimizes friction as blood passes through the heart. Healthy endocardium keeps blood from clotting as it moves through the heart.

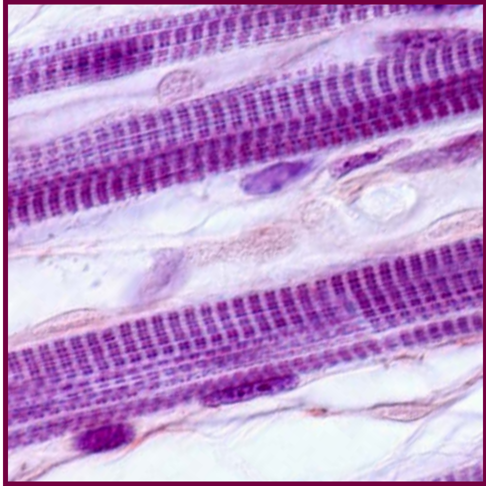
Cardiac Muscle

Let's take some time to examine the myocardium in more detail.

You have learned that there are three types of muscle: skeletal muscle, smooth muscle, and cardiac muscle. The myocardium is mainly composed of cardiac muscle. As we will see, cardiac muscle is both similar to and different from skeletal muscle.

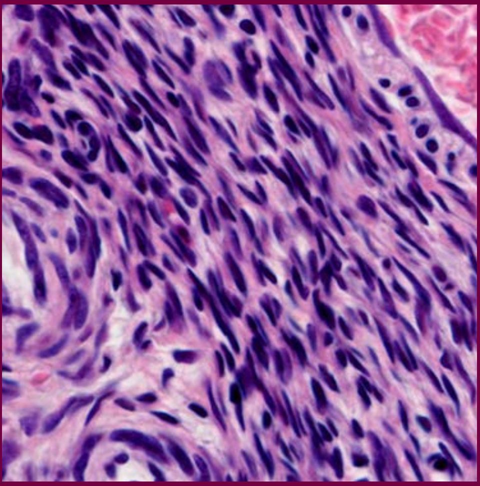
Like skeletal muscle, cardiac muscle is striated. However, the striations are not as easily seen in cardiac muscle. Cardiac muscle cells are shorter and fatter than skeletal muscle cells. Also, cardiac muscle cells branch and connect with one another in a somewhat irregular pattern. Like all cells, cardiac muscle cells are surrounded by a plasma membrane (also called a cell membrane). At the end of cardiac

Muscle Tissue Types



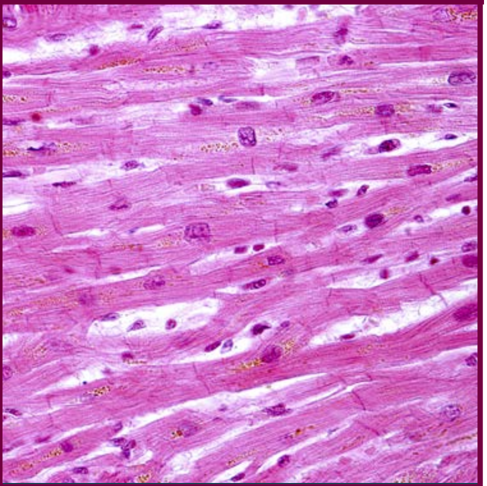
Skeletal Muscle Tissue

Skeletal muscle is attached to the bones of the skeleton. When it contracts, it allows us to move our arms and legs, or grasp something with our hands, or smile when we're happy. It has a structure that is distinct from other types of muscle.



Smooth Muscle Tissue

Smooth muscle is found in the walls of most of the hollow organs of the body. For example, it is found in the walls of our digestive tract where it helps push our food as it is digested. Smooth muscle is found in blood vessels, the urinary tract, the respiratory tract, the prostate, among other places. Smooth muscle is not under our direct control, and is sometimes referred to as involuntary muscle.



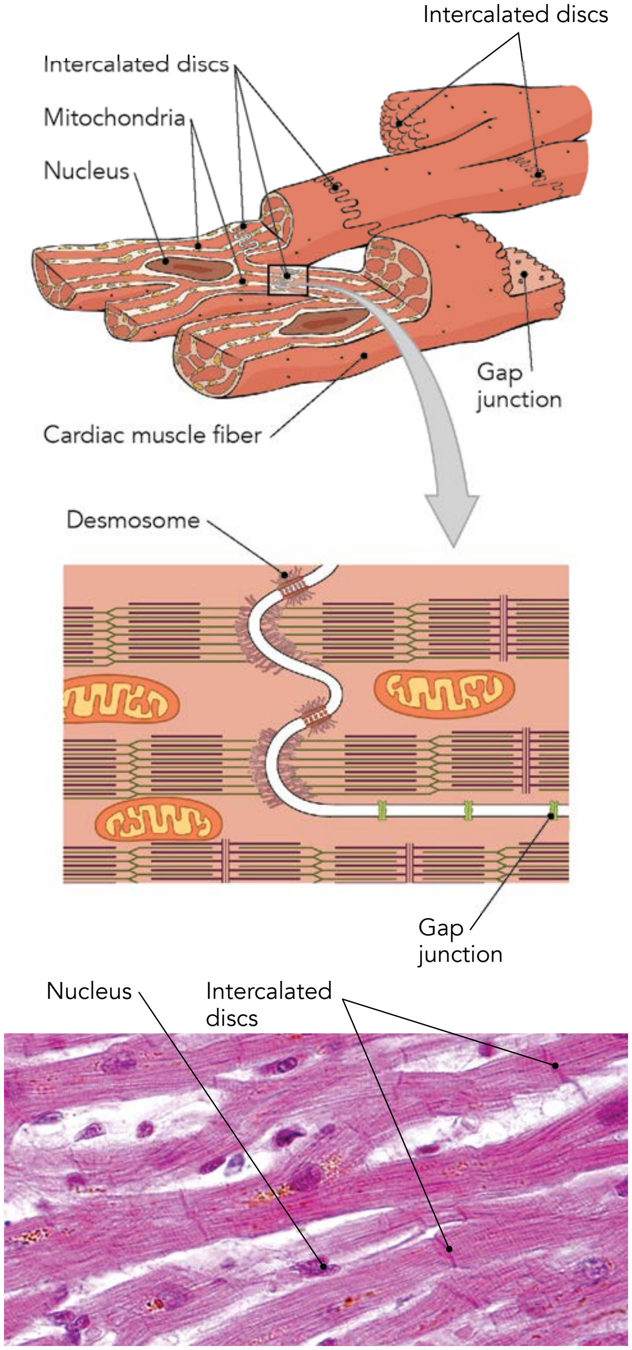
Cardiac Muscle

The third type of smooth muscle is cardiac muscle. It is found only in the walls of the heart. This type of muscle is also an involuntary muscle.

muscle cells are thick areas of the surrounding plasma membrane called *intercalated discs*. These intercalated discs form a special interlocking connection between the cells. Each intercalated disc contains two special structures that are very important to the proper function of cardiac muscle. One of these is called a *desmosome*, which helps hold the muscle fibers together as they contract. Also found in the intercalated disc are *gap junctions*. The junctions provide a route for electrical signals to be transmitted from muscle cell to muscle cell. These gap junctions ensure efficient transmission of electrical signals, which allows the cardiac muscle to contract in a coordinated fashion.

TAKING A CLOSER LOOK

Cardiac Muscle



Cardiac muscle also differs from skeletal muscle in the number of mitochondria it contains. Mitochondria generate energy for the cell, and even though skeletal muscles need energy, they don't need nearly as much as the heart's muscle. Mitochondria make up about 25 percent of the volume of a cardiac muscle cell. In contrast, mitochondria account for only about 2 percent of the volume of a typical skeletal muscle cell. This, of course, makes perfect sense when you think about it, right? A large part of the time a skeletal muscle is at rest so its energy needs would be low. On the other hand, cardiac muscle is constantly active, constantly beating. The much greater number of mitochondria would give the cardiac muscle the energy production necessary to support this high level of activity.

Skeletal muscle responds to the voluntary control of your nervous system. Your conscious command can make skeletal muscle contract. On the other hand, cardiac muscle is involuntary. It does not require conscious command to contract. It is not under your conscious control. This is really the only way the heart could work. None of us would live very long if we had to think about every heartbeat!

Two Pumps in One

We said the heart is a pump, but really, it is two pumps. The heart is two pumps operating side by side, simultaneously. The right side of the heart pumps blood to the lungs. The left side of the heart pumps blood to the brain and the body. One heart, two pumps.

The heart's two pumps must be perfectly synchronized. Deoxygenated blood has given up most of its oxygen supply to the body's tissues. This deoxygenated blood returns to the right side of the heart and gets pumped out to the lungs. There it will be resupplied with oxygen. At exactly the same time, oxygenated (oxygen-rich) blood returns to the left side of the heart from the lungs and gets pumped out to the brain and body. If there is even the slightest mismatch between the two sides, problems can develop quickly. A healthy heart is perfectly balanced and keeps blood moving in a coordinated fashion, shuttling it first through the right-side pump, then to the lungs, and then through the left-side pump.

Since the pump on the right circulates blood to the lungs, the right-sided circulation is called the *pulmonary circulation*. *Pulmonary* means "lung." The pump on the left sends blood to all the body's other *systems*, so the left-sided circulation is called the *systemic circulation*.

We will learn the names for the large blood vessels entering and leaving the heart, but we'll first need to learn the difference between an artery and a vein. An *artery* is the name given to a blood vessel in which blood moves *away* from the heart. When blood leaves the heart to go to the lungs, it travels in arteries. And when blood leaves the heart to go to the body and brain, it also travels in arteries. Of course, the blood going to the lungs is deoxygenated, and the blood going to the body is oxygenated. So the blood in arteries can be carrying lots of oxygen or very little.

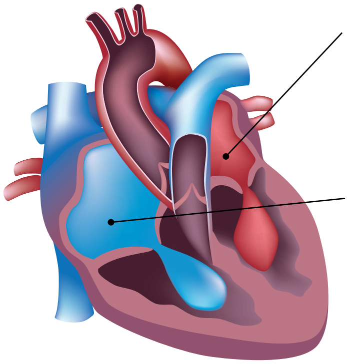
Vessels carrying blood *toward* the heart are called *veins*. Now you know that both oxygenated and deoxygenated blood can be carried in arteries. What about veins? The same is true. Some large veins (called *vena cavae* — a word that means big "cavernous" veins) carry deoxygenated blood back to the right side of the heart. And some other large veins (*pulmonary veins*) carry freshly oxygenated blood from the lungs to the left side of the heart. So, as with the arteries, veins can be carrying blood rich in oxygen or blood with very little.

Confusing, right? Well, we will try and give you a hand.

You may have seen drawings of the circulatory system and noticed that some of the blood vessels are colored red and some blue. Artists often draw the blood vessels this way to show you which vessels carry oxygenated blood and which vessels carry deoxygenated blood. Oxygenated blood has recently passed through the lungs to pick up a full load of oxygen using the hemoglobin in its red blood cells. Deoxygenated blood has already dropped off most of its oxygen supply in the tissues and is ready to be sent back to the lungs to pick up some more. All blood is red, but oxygenated blood is a brighter red and deoxygenated blood has a more purplish-red color. Even though deoxygenated blood is not really

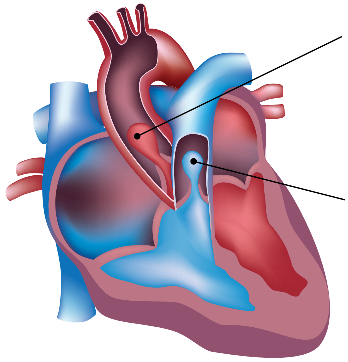
TAKING A CLOSER LOOK

Pulmonary vs Systemic Circulation



Systemic circulation - The left side pump fills with oxygen-filled blood from the lungs.

Pulmonary circulation - The right side pump fills with oxygen-depleted blood from the body.



Systemic circulation - The left side pump pushes the oxygen-filled blood to the body.

Pulmonary circulation - The right side pump pushes the oxygen-depleted blood to the lungs.

blue, the blood vessels carrying it are most often illustrated as blue to help people see the difference more clearly.

Chambers of the Heart

The human heart has four chambers.

Two chambers belong to the pump on the right — the right atrium and the right ventricle. These chambers are responsible for circulating blood to the lungs. Again, this is known as the pulmonary circulation.

The other two chambers belong to the pump on the left — the left atrium and the left ventricle. These chambers work to push blood out to the body tissues to supply them with oxygen and nutrients. This is the systemic circulation.

The word *atrium* means "entry room" or "receiving room." The *atria* (plural of atrium) collect blood as it returns to the heart. Blood that has already dropped off most of its oxygen supply enters the right atrium. (This is *deoxygenated* blood.) The left atrium collects oxygen-rich blood returning from the lungs.

Do arteries or veins bring this blood to the heart's atria? Hopefully, you said, "veins." Remember, *veins* bring blood *to* the heart. The veins that bring blood from the lungs to the left atrium are called *pulmonary* veins because they *come from the lungs*. The veins that bring blood back from the brain and the body are called *vena cavae*. The big vein from the upper body and brain is called the *superior vena cava*, and the big vein from the lower body is called the *inferior vena cava*. The name *vena cava* means "hollow vein," and *cavae* is the plural of *cava*. The words *superior* and *inferior* mean "upper" and "lower," respectively.

What kind of blood would you find in the superior and inferior vena cavae?[1] How about the pulmonary veins?[2] See, it's not really all that hard, is it?

The right and left atria collect blood and then send it on to the ventricles. As the atria fill, the pressure within the atria rises as a result of the increasing amount of blood. Then, when the ventricles relax, this pressure starts pushing blood from the atria

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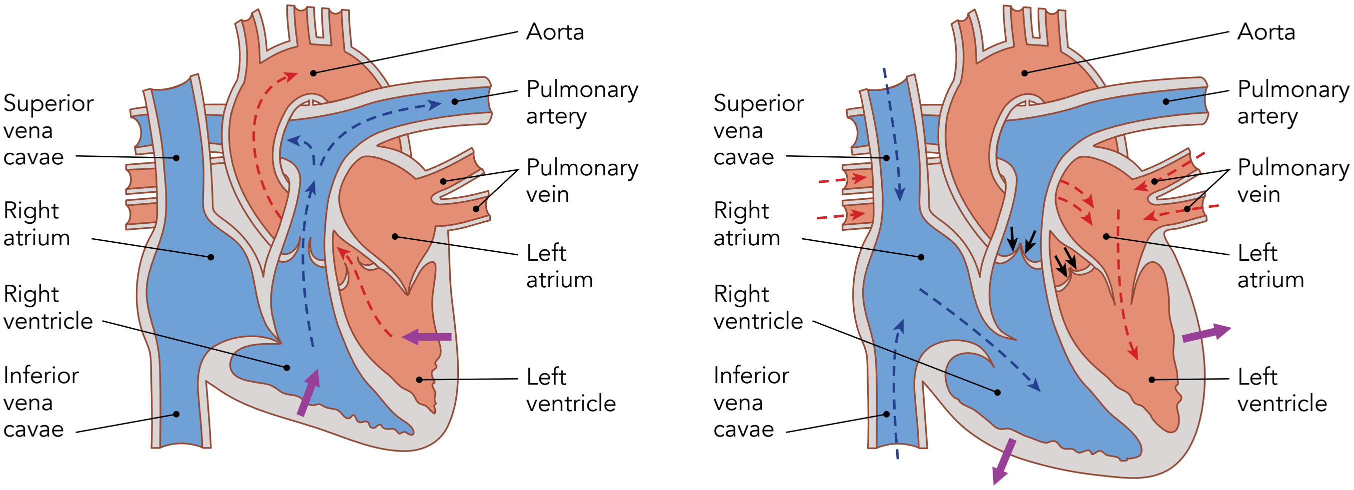
[1] Deoxygenated blood returns to the heart via the superior and inferior vena cavae.

[2] Oxygenated blood returns to the heart from the lungs through the right and left pulmonary veins.

TAKING A CLOSER LOOK

Chambers of the Heart



Ventricular Systole

Ventricular Diastole

into the ventricles through the valves connecting them even before the atria contract. Just before the ventricles pump, the atria squeeze to push an extra bit of blood into the ventricles. After the atria empty, it's time for the ventricles to squeeze hard and push blood out to the lungs and body.

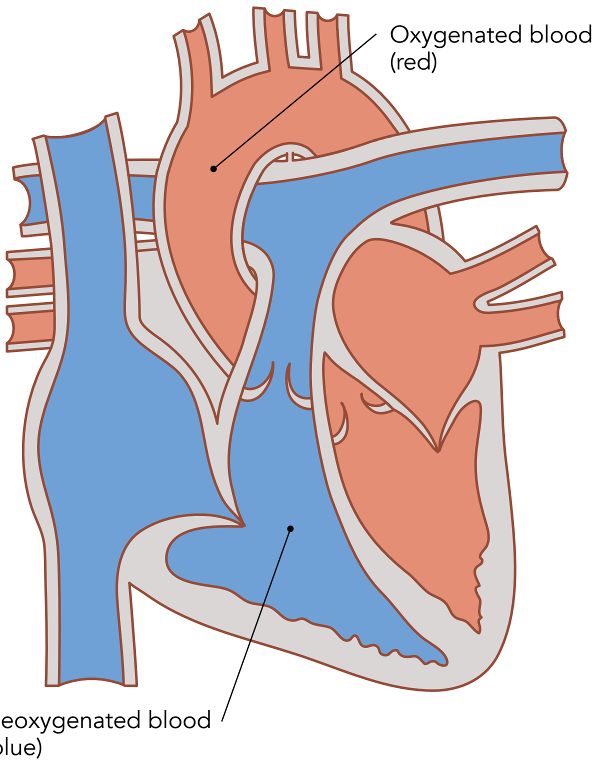
The right ventricle is part of the pump on the right, and it pushes oxygen-poor (deoxygenated) blood out through the pulmonary artery to the lungs. The left ventricle is part of the pump on the left, and it pushes blood out through a large artery called the *aorta*. This oxygen-rich (oxygenated) blood is sent through the aorta's branches to the brain and to the entire body.

The walls of the ventricles are made of thicker muscle than the atrial walls, but the ventricles are not the same. Remember, the right and left sides must always have the volume of blood they pump in and out perfectly matched. Even though this balance must be maintained, the two ventricles are different from one another. You see, the right ventricle only has to pump blood to the lungs, a short distance away. And it doesn't take much pressure to push blood through the pulmonary circulation. In contrast, the left ventricle pumps blood out to the entire body. It must push blood through the miles and miles of blood vessels that make up the systemic circulation. The pressure in the systemic circulation is much higher than in the pulmonary circulation. Therefore, the muscle of the left ventricle is much thicker than that of the right ventricle. In fact, the muscular wall of the left ventricle is typically two to three times thicker. This thick muscle allows the left ventricle to generate the great force needed to force blood through the entire body.

Pattern of Blood Flow

TAKING A CLOSER LOOK

Oxygen-rich vs Oxygen-poor Blood



Now that you've learned about the four chambers of the heart and the major vessels entering and leaving the heart, you should be able to trace the path of blood as it travels through this marvelous double-pump. Oxygen-poor blood enters the right atrium from the superior and inferior vena cavae. At the same time, oxygen-rich blood is brought by the pulmonary veins to the left atrium. (There are four pulmonary veins, two from the left lung and two from the right lung.) Blood flows from the right atrium into the right ventricle. At the same time, blood flows from the left atrium into the left ventricle.

After each atrium contracts, pushing that last little bit of blood into the ventricles, the ventricles give a mighty squeeze. Oxygen-poor blood from the right ventricle goes out through the pulmonary artery. The pulmonary artery soon branches to the right and left, and each of these subdivides and branches many times to carry blood to the lungs. At the same time, the left ventricle pushes oxygen-rich blood out of the heart through the aorta. The aorta goes upward, sends off some branches, and then arches downward where it continues as the descending aorta to carry blood to the lower body.

Be sure you understand that the right and left pumps fill and then contract simultaneously. Then see if you can trace the path of a red blood cell as it enters the heart, travels to the lungs, returns to the heart, and is sent out through the aorta. Then see if you can do it without looking at the illustrations. If you don't get it right away, relax. It will be easy for you in no time.

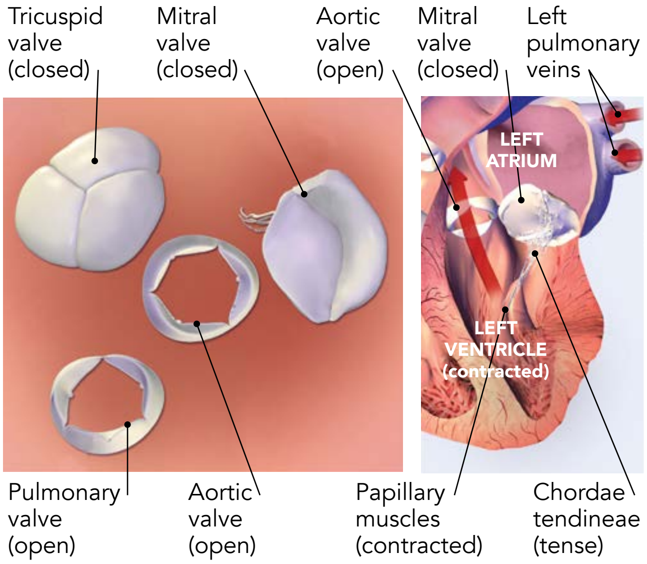
Heart Valves

You know that most of the rooms in your home have doors. It is obvious why those doors are there. But are there rooms that don't have doors? Those rooms were designed for a reason. The rooms that have no doors allow access in and out much more easily, right? On the other hand, you've probably seen businesses that have one-way doors — separate doors for going in and for going out.

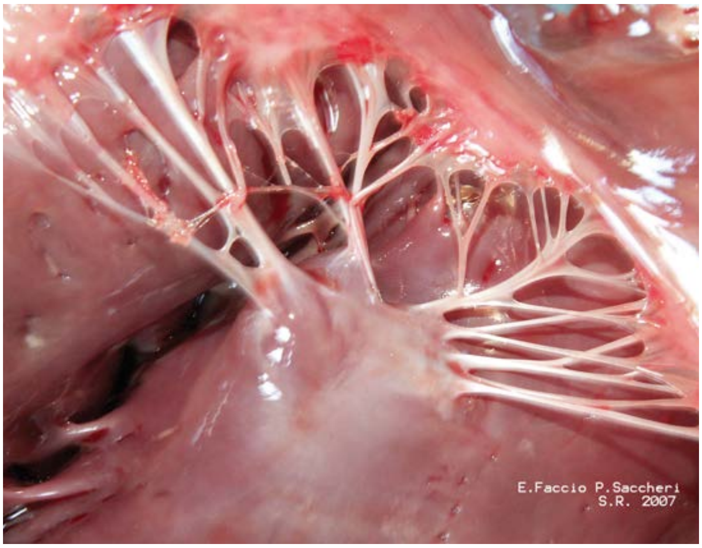
Which design do you think would work best for the heart's "rooms," its chambers? What would happen to the blood in the ventricles when the ventricles squeezed if the heart's rooms had no doors? If you said some blood would go backward into the atria, you see the problem. The ventricles would waste much of their effort if part of the blood went backward. To keep this from happening, the chambers are separated by one-way valves. A valve must allow the blood to flow freely in one direction but then shut to stop any back-flow.

TAKING A CLOSER LOOK

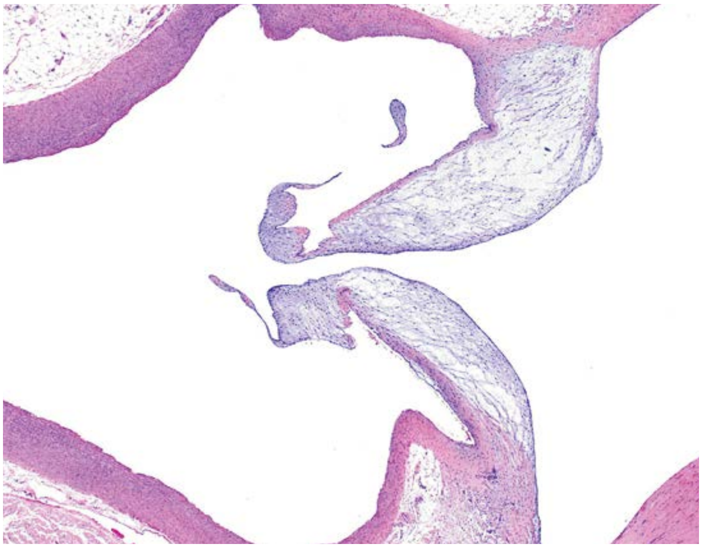
Valves of the Heart



Blood passes from the right atrium into the right ventricle through the *tricuspid valve*. Blood passes from the left atrium into the left ventricle though the *bicuspid valve*, also known as the *mitral valve*. Notice that both of these valves have "cusp" in the



Chordae tendineae



Aortic valve

name. A *cusp* is like a little parachute that fills with blood from the ventricle under pressure, distending the cusp back toward the atrium as the ventricle squeezes. The cusps keep the blood from flowing back into the atria. The tricuspid valve consists of three ("tri") cusps, and the bicuspid (mitral) valve has two ("bi") cusps. The name *mitral* is used for the bicuspid valve because the two cusps look a little like a bishop's headdress, called a miter.

If these cusps were not secured to the walls of the ventricles, the high-pressure blood filling them would push back into the atria. The cusps are therefore tethered to the ventricular walls. The ties that bind these cusps to the ventricular wall are called *chordae tendineae*. This Latin name means "heart strings." As the high-pressure blood distends the cusps, it is kept from being pushed back into the atria by these little tethers.

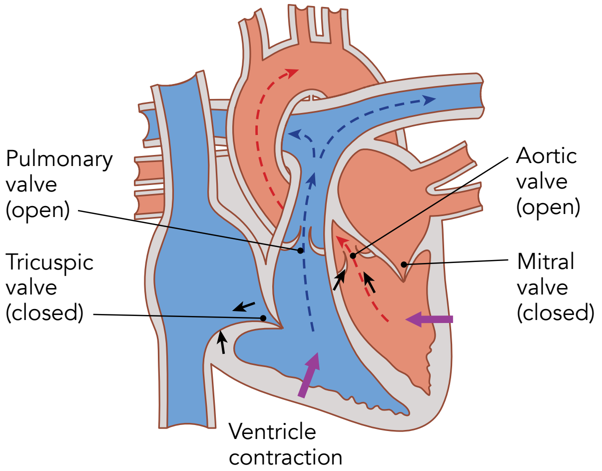
Heart Strings

Already you can probably see the great design in this arrangement. But there could be a problem: when the ventricles contract, they shrink. And as they shrink, the chordae tendineae (heart strings) tethering the cusps must somehow get shorter. Otherwise, the cusps would push back into the atria! God designed an amazing feature to keep the chordae tendineae tight as the ventricles shrink. These little cords are attached to the ventricular walls by tiny papillary muscles. As the ventricles contract, the papillary muscles also contract, being perfectly coordinated with the ventricles. These muscles keep the chordae tendinae taut and stabilize the cusps of the valves. (No way this is just a cosmic accident, right?).

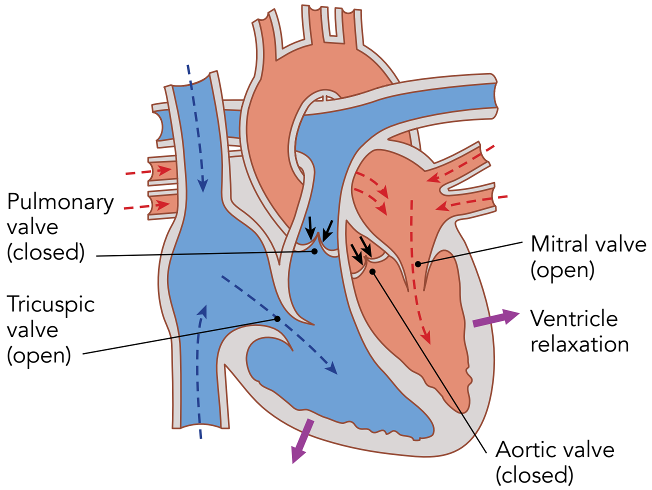
The heart's valves do not require a doorman to close them. The pressure of the blood inside the ventricles pushes them shut. We could even say the pressure makes them slam shut. But they make no noise. You've probably heard that the heart makes a "lub-dub" sound with each beat. The "lub" sound comes from the closure of the tricuspid and mitral valves, but it isn't the "slamming shut" that makes the "lub." It isn't even the silent squeezing of the ventricles that makes the "lub" sound. The "lub" comes from the turbulence of the blood rushing against the valves. (Think of the sound a wave makes as it crashes into a beach. Moving liquids, whether water

TAKING A CLOSER LOOK

Heart Sounds



The first heart sound (S1), is caused by the closure of the mitral and tricuspid valves at the beginning of ventricular contraction (systole)



The second heart sound (S2), is caused by the closure of the aortic and pulmonary valves at the end of ventricular systole or blood, are powerful!) Of course, since the "lub" happens when the tricuspid and mitral valves close, it may be easier for you to think of the "lub" as the result of the doors slamming shut.

When the blood leaves the heart through the pulmonary artery and the aorta, another set of valves is needed to keep it from flowing backward into the ventricles. If any blood flowed backward, the ventricles would have to do extra work by pushing it out again with the next beat. Such an arrangement would not be very efficient! (In fact, this very problem happens when valves are damaged, as we will discuss later.)

These valves — the valves guarding the exit from the ventricles — are called *semilunar valves*. As you know already, *lunar* means "moon," so *semilunar* means "half-moon-shaped." Each "ventricular exit" valve consists of three of these crescent-shaped cusps. The semilunar valve between the right ventricle and the pulmonary artery is called the *pulmonary valve*. The semilunar valve between the left ventricle and the aorta is called the *aortic valve*.

The semilunar valves do not have any chordae tendineae. The pressure in the pulmonary artery and the aorta is not high enough to force them backward into the ventricles, so none are needed.

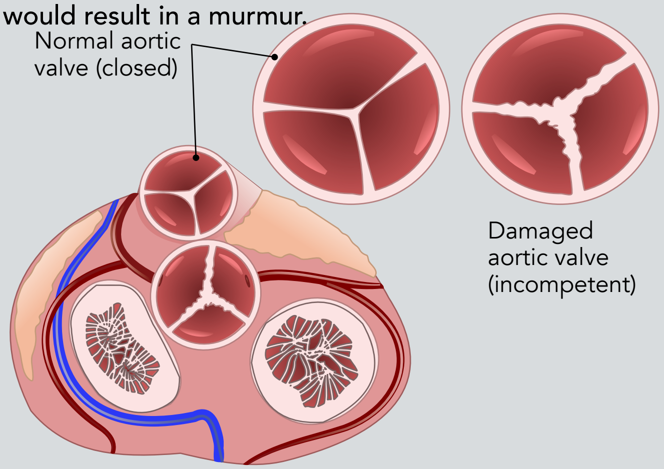
Just as the tricuspid and mitral valves needed no doorkeeper, the pulmonary and aortic valves need no doorkeeper to open or shut them. Fluid pressure does the job. When the ventricles begin to contract, the pressure they generate slams the tricuspid and mitral valves shut. The pressure in the ventricles then quickly rises, forcing the pulmonary and aortic valves to silently open. The blood in the ventricles rushes out through the open valves. When the ventricles have finished their contraction, the semilunar cusps swing closed and balloon slightly toward the ventricles, filling with blood but not leaking backward into the ventricles.

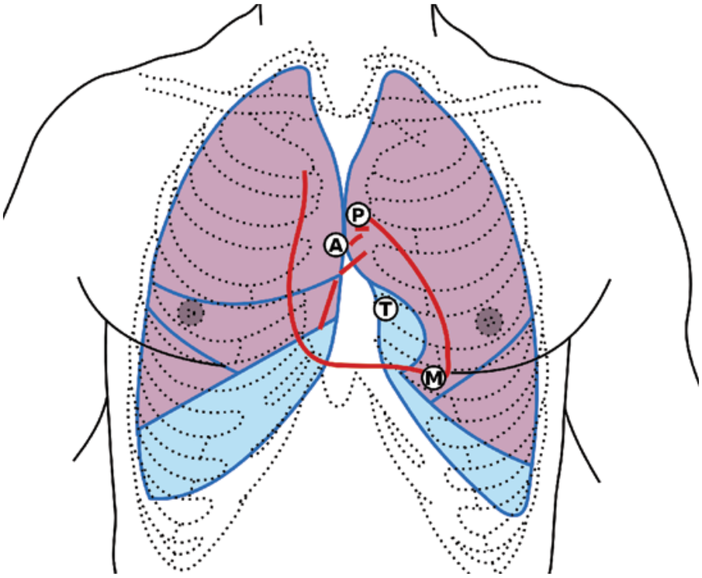
Heart Murmurs

A doctor often listens to the heart from several locations because the heart sounds transmitted to the chest wall can give a clue about the condition of the different valves. Damaged valves can cause different types of **murmurs**. The location, timing, and type of sound help the doctor know what sort of damage is causing it.

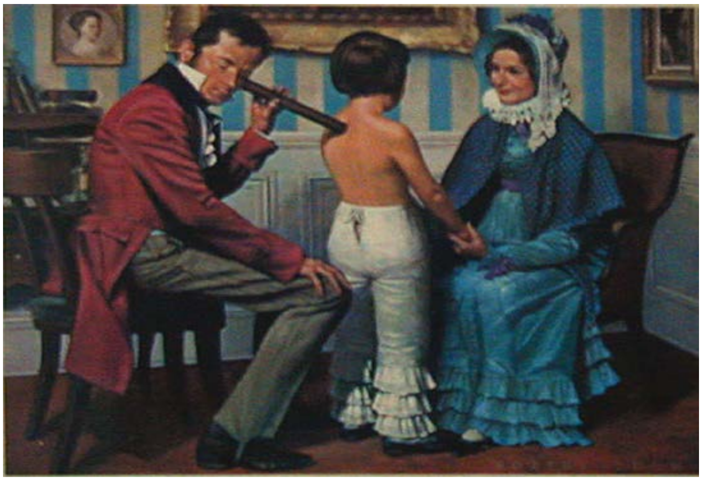
If a valve is damaged and allows blood under high pressure to leak backward, a whooshing murmur may be heard. We say such a valve is **incompetent** because it isn't doing the job a valve is designed for — preventing the back-flow of blood. For instance, were the mitral valve to become incompetent, when the left ventricle contracts, some blood would be pushed back through the valve into the left atrium. The turbulence of the blood passing through the damaged valve would produce a murmur.

If a damaged valve is stiff and does not open normally, the outflow of blood is impeded. This is known as **stenosis**. A whooshing murmur will be heard due to the blood struggling to get through. As an example, if the aortic valve were damaged and became stiff or scarred, it might not open as it should. Then when the ventricle contracts, the blood would not as easily pass into the aorta. Again, the turbulence produced by the forcing of blood through the abnormally small opening would result in a murmur.





Optimal stethoscope position for listening to heart valves. Heart valves are labeled (Mitral, Tricuspid, Aortic, Pulmonary).



René-Théophile-Hyacinthe Laennec (1781-1826) invented the stethoscope in 1816. The first stethoscope was a simple hollow wooden cylinder. It allowed doctors to listen to the heart and lungs without having to place their ears directly on the patient. Even though that device is primitive by today's standards, it was revolutionary in its day.

If the first heart sound, the "lub," results from turbulence during the simultaneous closure of the tricuspid and mitral valves, what do you think causes the second sound, the "dub"? The turbulence of blood created when the semilunar valves close creates this second heart sound. If you have the opportunity to borrow a stethoscope, you can listen to your own heart's sound. The heart sounds can both be heard at many locations on the chest wall.

The Cardiac Cycle — What Happens In a Heartbeat

The *cardiac cycle* is the name given to the five steps involved in filling the heart's chambers and pumping the blood. We will now examine this process more closely. All five steps must take place — in just the right order — every time your heart beats.

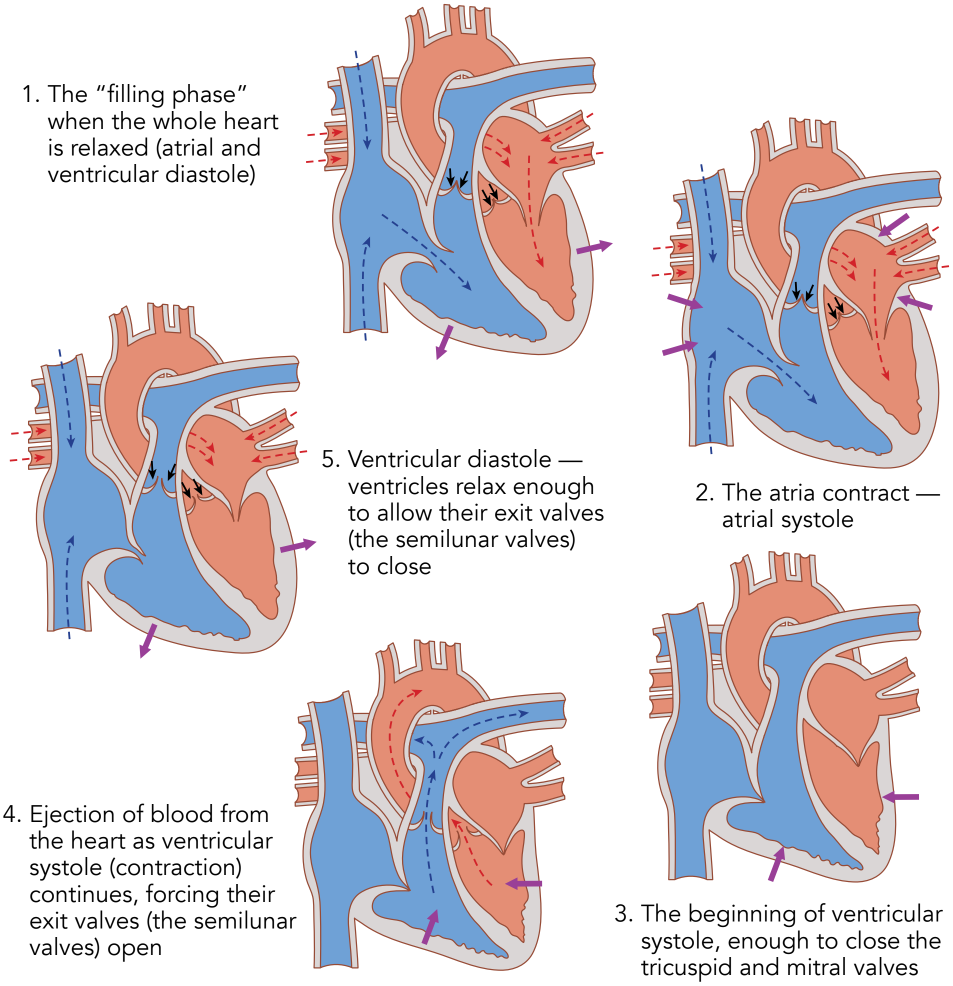
There are specific terms used to describe what a heart chamber is doing during the different steps in the cardiac cycle. The period of time when a heart chamber is contracting is called *systole* (pronounced "sis-tuh-lee"). The phase during which the chamber is relaxing is called *diastole* (pronounced "dī-as-tuh-lee"). Now let's apply those terms — *systole* and *diastole* — to each of the four steps in the cardiac cycle. (Later we will see that these words help us understand a measurement called "blood pressure." You may have even had yours measured!)

The first step in the cardiac cycle is the "filling phase." While they fill with blood, the atria and ventricles are all in diastole. That is, all the chambers are relaxed. Since the heart muscle is relaxed, the pressure inside them is low. This low pressure allows the atria and then the ventricles to fill with blood. First, blood enters the atria. As they fill, blood pushes the tricuspid and mitral valves open, allowing blood to flow into the ventricles too. At the end of this phase, the ventricles are about 75 percent full.

During this phase what do you think is happening with the heart's "exit-doors" — pulmonary and aortic valves? Since the pressure in the ventricles is low at this point, both of these valves will be closed, right? Otherwise, the blood would flow backward into the ventricles. The pressures in the pulmonary artery and the aorta are keeping the pulmonary and aortic valves closed for now.

TAKING A CLOSER LOOK

The Cardiac Cycle



1. The "filling phase" when the whole heart is relaxed (atrial and ventricular diastole)

2. The atria contract — atrial systole

3. The beginning of ventricular systole, enough to close the tricuspid and mitral valves

4. Ejection of blood from the heart as ventricular systole (contraction) continues, forcing their exit valves (the semilunar valves) open

5. Ventricular diastole — ventricles relax enough to allow their exit valves (the semilunar valves) to close

After this passive filling of the ventricles, the atria simultaneously contract. This is *atrial systole*. The squeezing of the atria pushes more blood into the ventricles to help really fill them up. This atrial "squeeze" is the second step in the cardiac cycle, and it adds another 25 percent or so to the filling of the ventricles.

Next comes relaxation of the atria (*atrial diastole* — the second step) and then contraction of the ventricles, or *ventricular systole*. During this, the third step of the cardiac cycle, the ventricles begin to contract. As a result of this contraction the pressure in the ventricles increases enough to slam the tricuspid and mitral valves shut, causing the "lub" sound.

During the fourth step of the cardiac cycle, blood is forcefully ejected from the heart. The increasing pressure from the ventricular contraction forces the pulmonic and aortic valves (the semilunar valves) to open, and the blood rushes out into the pulmonary artery and the aorta.

Finally, in the fifth and final step of the cardiac cycle, the ventricles relax. Because of this relaxation, the pressure in the ventricles decreases. The higher pressure in the pulmonary artery and the aorta causes the semilunar valves to close. Thus, blood is prevented from flowing backward into the ventricles. This is *ventricular diastole*, and it is the end point of one complete cardiac cycle.

So, the five steps in the cardiac cycle are:

1. the "filling phase" when the whole heart is relaxed (atrial and ventricular diastole)
2. the atria contract — atrial systole
3. the beginning of ventricular systole, enough to close the tricuspid and mitral valves
4. ejection of blood from the heart as ventricular systole (contraction) continues, forcing their exit valves (the semilunar valves) open
5. ventricular diastole — ventricles relax enough to allow their exit valves (the semilunar valves) to close

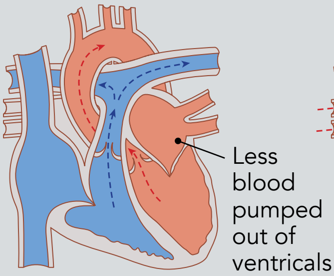
Congestive Heart Failure

The pumping action of the heart is nothing short of amazing. The right side of the heart sends blood to the lungs, and the left side of the heart pumps blood out to the body. Each side pumps the same amount of blood, at the same time, and the process takes place in a coordinated fashion. This precise balance continues day in and day out.

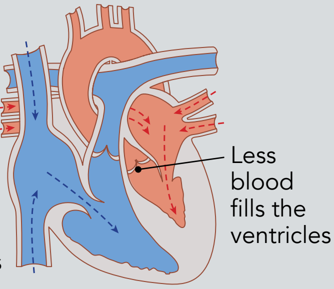
However, we live in a fallen, cursed world. Things go wrong. At times the heart does not function correctly. A heart weakened by disease or heart attack will not be as efficient or pump as powerfully. This is called "heart failure." With heart failure, the heart still works, but one or both of its pumps is weak.

Since the heart consists of two pumps, it is possible for either pump system to function abnormally. If either of the pumps fails to keep up with the amount of blood it is supposed to pump, blood will back up, like cars in a traffic jam. We sometimes say that traffic is "congested," and the same word can be used for blood that backs up due to heart failure. **Congestive heart failure** can be a problem caused by failure of either the right or the left side of the heart to keep up.

If the pump on the right side of the heart fails to pump properly, the blood returning to the heart from the body is not pumped to the lungs efficiently. Then, the vena cavae and other systemic veins that bring blood to them become **congested** with excessive blood. Remember, this is like a traffic jam — traffic congestion — with blood instead of cars. Blood is backed up. Due to this **congestion**, the pressure in these vessels increases. The most noticeable result of this is swelling in the legs and feet. This swelling is called **peripheral edema**. (**Edema** is swelling caused by fluid accumulating in tissues. **Peripheral** means the swelling happens in parts of the body far away from the heart.)



Weakened heart muscle
can't squeeze as well



Stiff heart muscle
can't relax normally

If the pump on the left side of the heart fails to do its job properly, the oxygenated blood returning from the lungs is not adequately pushed out to the body. Now, if the normal amount of blood is being pumped to the lungs by a correctly functioning right heart pump, but the left heart pump cannot keep up with this volume of blood, what do think will happen? The blood will back up into the lungs! This time the "traffic congestion" backs up into the lungs. This problem is called **pulmonary edema** (fluid in the lungs). Pulmonary edema causes patients to be quite short of breath and make it difficult to exercise or even to walk. In its most severe forms, pulmonary edema can lead to death.

The degree of heart failure can be assessed by the severity of the patient's symptoms, such as shortness of breath or how much exercise they can do. Also, it can be quite helpful to obtain a measurement of the patient's ejection fraction — the fraction of the blood ejected during systole. The lower the ejection fraction, the more severe the heart failure is said to be.

Treating heart failure is challenging. Patients are often given drugs that cause the body to get rid of the excess fluid that accumulates in the lungs or other tissues. There are also certain drugs that can help damaged cardiac muscle contract more efficiently and make the heart pump better. However, these drugs can also have serious side effects at higher doses, so they must be used cautiously. In certain very severe cases, a heart transplant may even be considered.

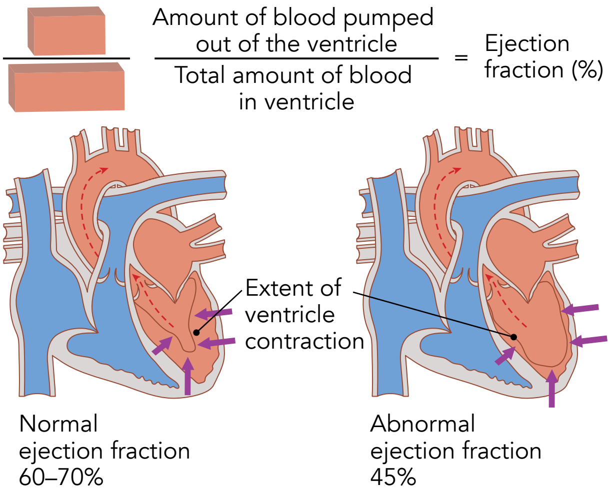
That is what happens every time your heart beats! What do you think happens next? Remember this is a *cycle*, so when the fifth step is completed, the whole cycle begins again. The heart's chambers are all relaxed and the valves are in the right position so that they can fill with blood and the heart can beat again.

How Empty Is Empty?

When you wring out a washcloth or sponge, is it completely dry? No. It still contains some water. You cannot squeeze it enough to make it dry. Likewise, after your heart's ventricles contract, they still contain some blood. Not every drop of blood gets emptied from the ventricles as they squeeze. In fact, a healthy heart only empties around 60–70 percent of its contents with each beat! This percentage is called the *ejection fraction*. If a person's heart is not working properly, its ejection fraction may be far lower than this. Measuring the ejection fraction can be very important for physicians when they are caring for patients with heart problems.

TAKING A CLOSER LOOK

Ejection Fraction



What the Heart Needs

The heart pumps oxygen-rich blood to every organ in the body. But how does the heart get the oxygen-rich blood it needs? After all, the heart needs a constant supply of oxygen and fuel (in the form of sugar called glucose) in order to keep pumping constantly, day in and day out, for a lifetime! Therefore, God designed the *coronary circulation* — a way for the heart to pump blood to itself.

When something goes terribly wrong with the coronary circulation, a person can have a heart attack. You may know of someone this has happened to. Once you see how the coronary circulation works and why it is so important, you will understand what a heart attack is.

You might wonder why the heart needs its own separate blood supply. After all, the heart is a pump that pumps blood. It is filled with blood most of the time. So why can't it just get the things it needs from the blood in its chambers?

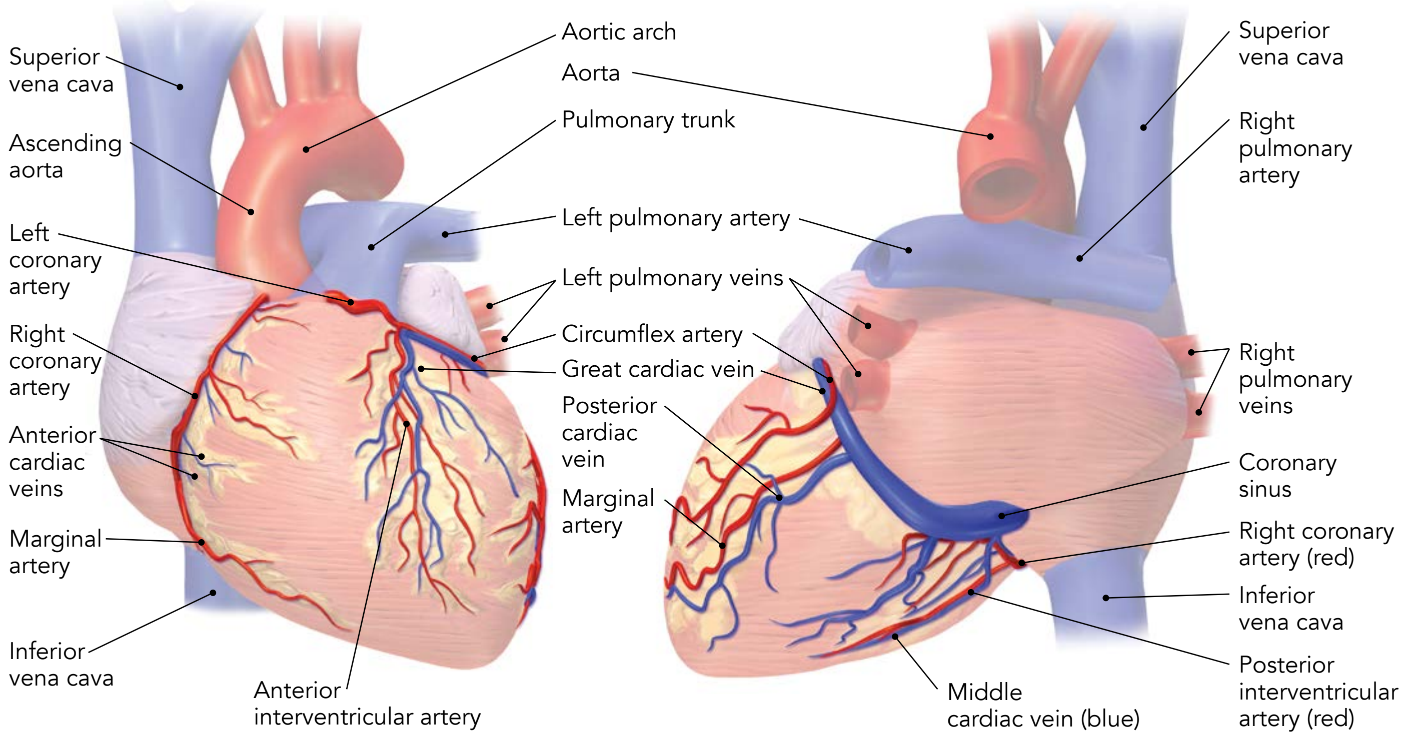
What it comes down to is this: because the heart works constantly, it needs *lots* of oxygen and nutrients. Even though the left ventricle is filled with oxygen-rich blood, the heart wall is just too thick for nutrients to seep into it. A more efficient system is needed to supply the heart muscle — the *myocardium* — with oxygen and fuel.

The *coronary circulation* is a system of arteries and veins that delivers oxygen-rich blood to the heart muscle and carries away deoxygenated blood.

The coronary circulation begins just past the aortic valve. Right after the place where blood exits the heart's left ventricle, two arteries branch from the very first part of the aorta (called the *ascending aorta*). These are the *right and left coronary arteries*. They divert a little of the blood flowing into the aorta toward the heart's muscular walls.

TAKING A CLOSER LOOK

Coronary Circulation



The *right coronary artery* primarily supplies the right atrium and the right ventricle. It divides and divides into many smaller arterial branches to completely supply the right side of the heart.

The *left coronary artery* supplies the left side of the heart. It has two major branches. One of these — the left anterior descending artery, or LAD — supplies the front (*anterior*) walls of both the right and left ventricle as well as the wall of myocardium between the ventricles. (This muscular wall between the ventricles is called the interventricular septum). The other branch — the circumflex artery — brings blood to the left atrium and the left ventricle's back (*posterior*) wall. The two main branches divide and subdivide into many smaller vessels to ensure complete circulation to the left side of the heart.

After supplying the heart's muscular walls with the oxygen and fuel they need, deoxygenated blood returns to the right atrium through several cardiac veins.

SO SIMPLE YET SO COMPLEX
Designed by the Master

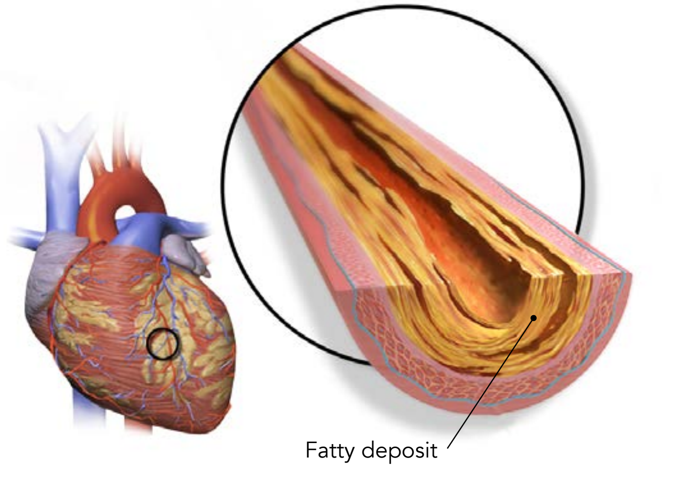
Try This

Squeeze one hand into a tight fist. Then try to push a finger into that fist. You can't! It won't fit if the fist is tightly contracted. Likewise, if your heart is busy squeezing hard — contracting — how can its muscular walls have room to let blood flow through the coronary circulation to bring them the oxygen and fuel they must have to keep working? Well, God is a great engineer. This is the solution He designed: As the heart relaxes during diastole, the pressure in the aorta pushes blood into the coronary arteries to supply the heart. The heart muscle receives most of the oxygen and fuel it needs during the relaxed parts of each heartbeat, enough to keep it going until the next diastole.

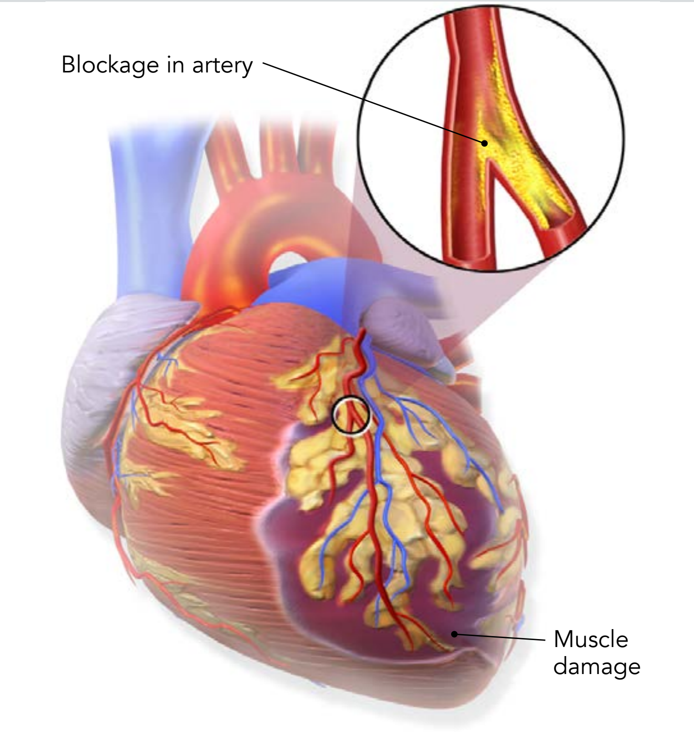
Coronary Artery Disease

It is possible that you know someone who has suffered a heart attack. If not, I expect you have at least heard the term "heart attack." A heart attack can be very serious and is often fatal. Every year over 700,000 people in America have a heart attack!

The primary problem that leads to a heart attack is called **coronary artery disease**. You already know what a coronary artery is. Coronary arteries are the arteries that keep the heart's muscular walls supplied with freshly oxygenated blood. Coronary artery disease, abbreviated CAD, occurs when the lining inside a coronary artery becomes thick. As the lining thickens, the channel inside the artery becomes smaller and smaller. Less and less blood is able to squeeze through the narrowing opening. Severe narrowing is called a "blockage."



Eventually, the blood flowing through this narrowed artery cannot adequately supply the needs of the myocardium. The situation where adequate oxygen is not delivered to the heart muscle is called **myocardial ischemia**. Coronary artery disease can involve a single "blockage" in only one coronary artery or several blockages in multiple coronary arteries. Obviously, the more blocked arteries, the more serious the situation.

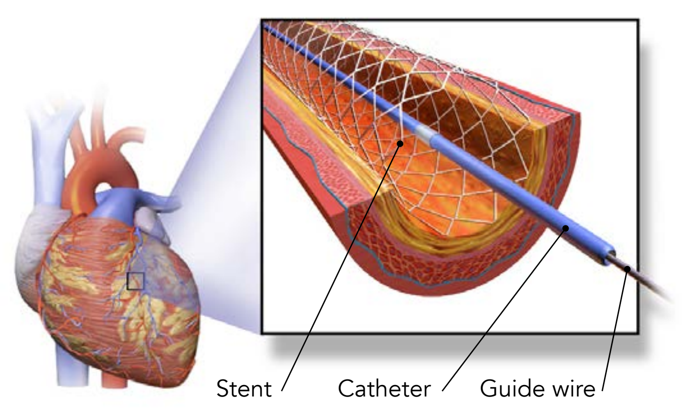


Myocardial ischemia is not the same thing as a heart attack, but it can lead to one. There are degrees of myocardial ischemia. Some people with myocardial ischemia experience episodes of **angina pectoris**, which literally means "strangled chest." A person with angina pectoris has episodes of chest pain, usually described as a tightness or a burning sensation in the chest. Some feel like their chest is in a vise. Often the pain radiates to the left arm, neck, or jaw. Angina pectoris can occur with activity (so-called "stable" angina) or at rest ("unstable" angina). The underlying problem is that due to restriction of blood flow. the heart muscle does not get adequate oxygen to meet its needs, thus resulting in chest pain. However, with angina alone the situation is intermittent, and there is no permanent damage to the heart muscle.

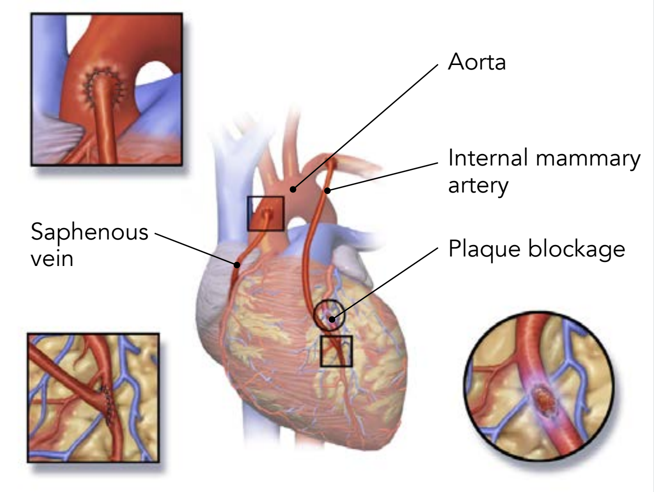
As coronary artery disease worsens, there is increasing danger of myocardial infarction (often called an "MI"). This is commonly known as a heart "attack." Here the disease in the coronary artery (or arteries) has progressed to the point that the myocardium can no longer get the amount of oxygen it needs, and some of the heart muscle dies. Logical, isn't it? If an artery that takes oxygen to a certain part of the heart becomes blocked, then the muscle tissue in that part of the heart is at risk of death. Myocardial infarctions can range from relatively mild to fatal. The severity depends on how much myocardium is damaged and how efficiently the remaining heart muscle functions.

Treatment for coronary artery disease depends on its severity. If it is very mild, a patient may be treated with simple things like exercise, medication, and changes in diet. For more serious blockages, patients may undergo a procedure to open or to by-pass the blockage in order to improve blood flow to the heart.

There are two main sorts of procedures used to deal with a coronary artery blockage. One is called **coronary angioplasty**. (By the way, the author of this book has undergone this procedure.) Here, using special dye and a type of x-ray called fluoroscopy, a tiny wire is threaded through the blockage and a balloon is inflated to open up the artery. Most often, a small mesh device, called a stent, is then put in place in the coronary artery to help keep it open.



In the most severe cases of coronary artery disease, **coronary artery bypass surgery** is done to route blood around a blockage. In bypass surgery, a section of a vein from the person's arm or leg is removed and used as a bypass graft. One end of the vein is attached to the aorta, and the other end is attached to the diseased coronary artery at a point past the blockage. Thus, the blockage is effectively "bypassed," and blood flow is restored to the heart muscle at risk for damage.



Coronary artery disease is a type of **cardiovascular disease**, a term that includes heart attacks and strokes and other diseases of the heart and blood vessels. Cardiovascular disease is the world's leading cause of death. Heart attacks are the leading cause of death in the United States.

Who is most likely to have a heart attack? Some people are at greater risk than others. A **risk factor** is something that puts a person at greater risk of suffering a particular thing than other people. Some risk factors are beyond a person's control. However, there are some things you can do to lower the risk of ever having a heart attack. There are many risk factors that can lead to heart disease. These include (but are not limited to) smoking, a lack of exercise, obesity, poor diet (especially diets high in fats), high cholesterol, diabetes, and high blood pressure.

We need to take all the steps we can to take good care of our hearts. So make a lifelong practice of getting plenty of exercise (and, no, video games are not exercise), maintain a healthy weight, get in the habit of primarily eating nutritious foods (I'm not saying don't eat hot fudge sundaes, I'm just saying don't make a regular habit of them), and never, ever . . . let me say it again . . . never, EVER, start smoking!

Now is the time to learn a heart healthy lifestyle!

Beats

As we mentioned earlier, cardiac muscle is involuntary. This means you don't have to think about your heart beating. It happens all on its own. Unlike skeletal muscle, you have no conscious control over the contraction of cardiac muscle. For example, you can willfully make skeletal muscle move . . . reaching for a glass or throwing a ball. However, you cannot will your heart to beat.

It turns out that just beating isn't enough. Not only must the heart beat (and even be able to speed up when you are running), but both sides must beat simultaneously. Remember, the heart is really two pumps. How does it get the timing right so that both sides pump simultaneously? The answer is electrical. Your heart has a built-in system to produce an electrical signal that triggers the heart muscle in each pump to beat . . . and to do it over and over and over again.

SO SIMPLE YET SO COMPLEX
Designed by the Master

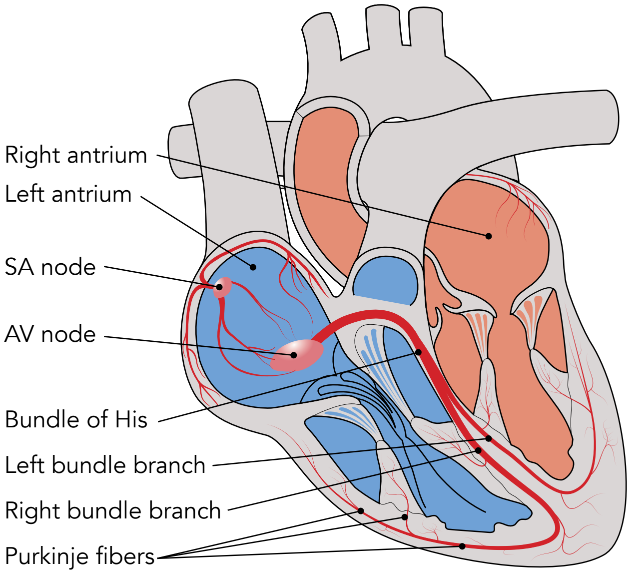
The Pumping Heart

Most of the heart consists of cardiac muscle cells. The vast majority of these muscle cells are in the business of contracting. They are responsible for the pumping action of the heart. However, about 1 percent of these cells have a very special property and are not primarily involved in heart contraction. These special cells are the ones that *stimulate* the contractions! These cells have the ability to spontaneously generate an electrical signal all on their own. These are called *autorhythmic* ("self-rhythm") cells. They repeatedly produce electrical signals that stimulate the heart to contract.

These autorhythmic cells generate electrical impulses without any outside stimulus from the nervous system. Even if all nerve fibers to the heart were severed, the heart would continue to beat. For example, hearts removed from a body to be transplanted continue to beat for several hours, even though all nerve fibers to the heart have been cut. (This does not mean that the nervous system is not important. Nervous system input can play an important role in controlling the heart *rate* as we will see.)

TAKING A CLOSER LOOK

Cardiac Conduction System



These autorhythmic cells have two important jobs. First, they function as the *pacemaker* for the heart. That is, they establish and maintain the basic rhythm of the heart. They trigger the start of each and every heartbeat. They set the pace! Second, they are lined up to form a pathway that helps move the electric signals through the heart from muscle cell to muscle cell in a very orderly fashion.

The cardiac conduction system is also called the *intrinsic conduction system*. *Intrinsic* means this conduction system is completely contained within the heart; it does not bring in messages from outside the heart. This intricate network of rhythm-generating cells is designed to distribute signals to the cardiac muscle in an orderly way to ensure that the heart contracts in a coordinated manner. If the heart's chambers did not coordinate their squeezing action, chambers would start squeezing before they filled. Furthermore, just as a toothpaste tube squeezed near the top traps toothpaste in the bottom of the tube, so a heart that doesn't squeeze in a coordinated manner would not empty blood very well. Let's take a closer look at the way the electrical system of the heart is designed to avoid this sort of problem.

The Cardiac Conduction System

The cardiac conduction system (or intrinsic conduction system) has two "nodes" that set the pace of the heartbeat. The first node to fire signals the beginning of a heartbeat. This pacesetter is the *sinoatrial node*, also called the *SA node*. The SA node is a small group of cells located in the upper portion of the right atrium's wall, near the entrance of the superior vena cava. The SA node is the heart's main pacemaker. The SA node initiates each electrical *impulse* that stimulates the heart to contract. On average, the SA node generates an impulse 72 times a minute. The SA node generates impulses faster than the other pacemaking node. Therefore, under normal circumstances, the SA node controls the heart rate. For that reason, the basic rhythm of the heart is called *sinus rhythm*.

Once generated, the impulse from the SA node travels through the muscle cells themselves. The impulse spreads throughout both atria causing them to contract. Atrial contraction squeezes the blood from each atrium into the ventricles.

At the end of its journey through the atria, the electrical impulse produced by the SA node reaches another group of cells called the *atrioventricular node* (AV node). The AV node is located in the wall (or *septum*) between the right and left atria, just above the tricuspid valve. It is the job of the AV node to send the electrical signal on to the ventricles. That signal makes the ventricles contract. (If, however, the SA node fails for some reason, the AV node can act as a backup system and stimulate the heart to beat.) Do you see a problem here?

These electrical impulses travel very rapidly. What would happen if the atria and the ventricles all contracted at the same time? The atria would not be able to squeeze their blood into the ventricles because the ventricles would be contracting too. And without getting re-filled with blood from the atria, the ventricles would soon have no more blood to pump out to the body and the lungs. The entire heart would stop pumping blood. Not a good situation at all, right? The beating of the heart must be coordinated, so that the atria both contract before the ventricles do.

God has designed the cardiac conduction system to avoid this problem. When the SA node "fires," both

How Fast?

As we examined the cardiac conduction system, we saw that the SA node is the primary pacemaker of the heart. The SA node beats at an average rate of 72 beats a minute.

Are there other pacemaker locations in the heart? As it turns out, there are.

If the SA node ceased to function (say, as a consequence of disease or aging), the AV node would take over the pacemaker duties. However, the heart rate generated by the AV node is around 50 beats per minute.

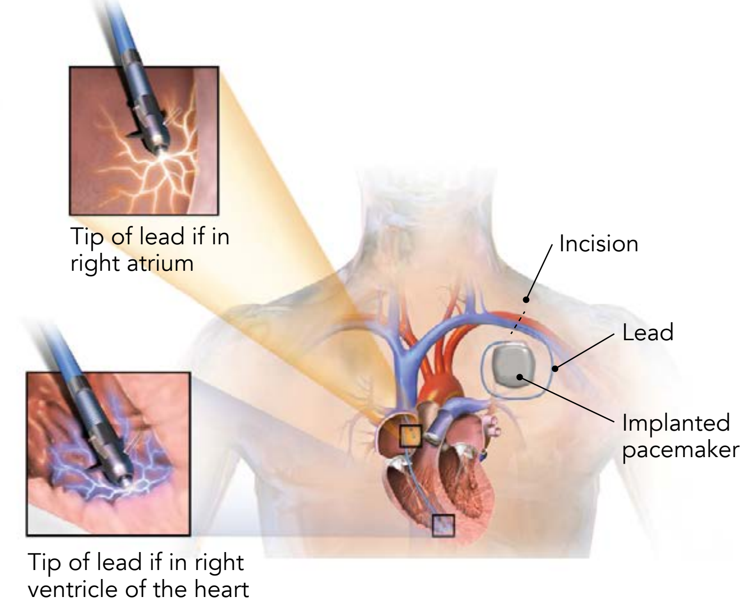
And if both the SA and AV nodes stopped working, the Purkinje fibers also have the potential to act as a pacemaker. Purkinje fibers can only generate a heart rate of around 30 beats as minute. This is certainly not ideal, nor is it as efficient as a properly functioning SA node.

God designed two backup systems to keep the heart beating if its chief pacemaker malfunctions.

atria respond almost instantly, and then the AV node "fires." But when the AV node fires, the ventricles do *not* respond immediately. Instead, the AV node's electrical signal is delayed by about 0.1second (that's one-tenth of a second . . . not very long at all . . . but long enough). This delay happens because the cells in the fibers near the AV node do not transmit the electrical impulse as rapidly. (They have fewer *gap junctions*, little gateways between cells, and that slows down the passage of the impulse from cell to cell.) Once through the AV node and these signal-slowing muscle fibers, the signal travels normally (that is, very rapidly) through the remainder of the conduction system.

After leaving the AV node, the signal is carried by the *atrioventricular bundle* (sometimes called the *bundle of His*) into the ventricles. You might be thinking, "Wait a minute, we just saw that this impulse was carried through the atria though the muscle cells themselves. Why can't the signal that passed through the atria reach the ventricles the same way?" Good question. The answer is that the atria and ventricles are separated by the connective tissue that makes up the fibrous skeleton of the heart. This fibrous tissue acts as sort of an insulator that stops the electrical signal from passing directly. The only electrical pathway between the atria and the ventricles is the atrioventricular bundle. Here is

Pacemakers



Even though a healthy heart does have the ability to generate its own conduction signals, there are circumstances when the cardiac conduction system does not function correctly. At times due to aging or illness, the pacemaker center (SA node) may not generate signals rapidly enough to maintain adequate blood pressure. Or perhaps as the consequence of a heart attack, the AV node is damaged and cannot conduct the electrical signals to the ventricles properly.

In many situations like these a patient may require the implantation of a pacemaker. A pacemaker is a small battery-powered device that can help control a patient's heartbeat. The device is attached to a small electrode that is placed in the heart. An electrical signal is sent from the pacemaker to stimulate the heart to beat.

The simplest style of pacemaker has one electrode that is threaded into the right ventricle (under fluoroscopic guidance). The pacemaker itself is usually placed in a small surgically created pocket under the skin just below the left collarbone. The pacemaker can monitor the patient's heartbeat, and if a beat is not detected within a certain period of time, the pacemaker sends an electrical impulse to stimulate the heart. If a normal heartbeat is detected, then the pacemaker would not fire.

Pacemakers have become more and more sophisticated. These devices can be programmed for a wide range of heart rates. Some pacemakers have multiple electrodes and can pace both the atrium and the ventricle. Other pacemakers sense activity levels and can adjust the patient's heart rate to match.

but one more example of the marvelous design of the heart. Without this electrical barrier it would not be possible to control the pumping action of the heart so precisely.

Very soon after reaching the ventricles, the atrioventricular bundle splits into two branches, the *right bundle branch* and the *left bundle branch*. These two bundles proceed down through the *interventricular septum* (the wall between the ventricles) toward the apex of the heart. The right bundle branch delivers the impulse to the right ventricle and the left bundle branch signals the left ventricle. In the septum, the bundle branches also to small branches that penetrate deep into the myocardium of the ventricles. These are called Purkinje fibers. Because the *Purkinje fibers* deliver the electrical signals to their final destination, they are vital for maintaining the heart's smooth, coordinated pumping action. Purkinje fibers cause the heart to contract from the bottom up and not from the top down.

Heart Squeeze

When the AV node's signal is transmitted, the heart muscle cells in the ventricles do not contract at the same time. What would happen if they did? The blood in the ventricles would get a hard squeeze, but it wouldn't move efficiently toward the aorta and pulmonary artery. To avoid this problem, God has designed the heart's conduction system to start responding to the signal from the apex (the sort of pointy part at the bottom of the heart) and move toward the top of the ventricles. The heart's muscle cells are arranged in a spiral so that they contract and efficiently push the blood in the ventricles out, squeezing from the apex upward. So the heart really does squeeze from the bottom up, and that's the most efficient way!

Think of squeezing a tube of toothpaste. Is it better to squeeze it from the top or the bottom?

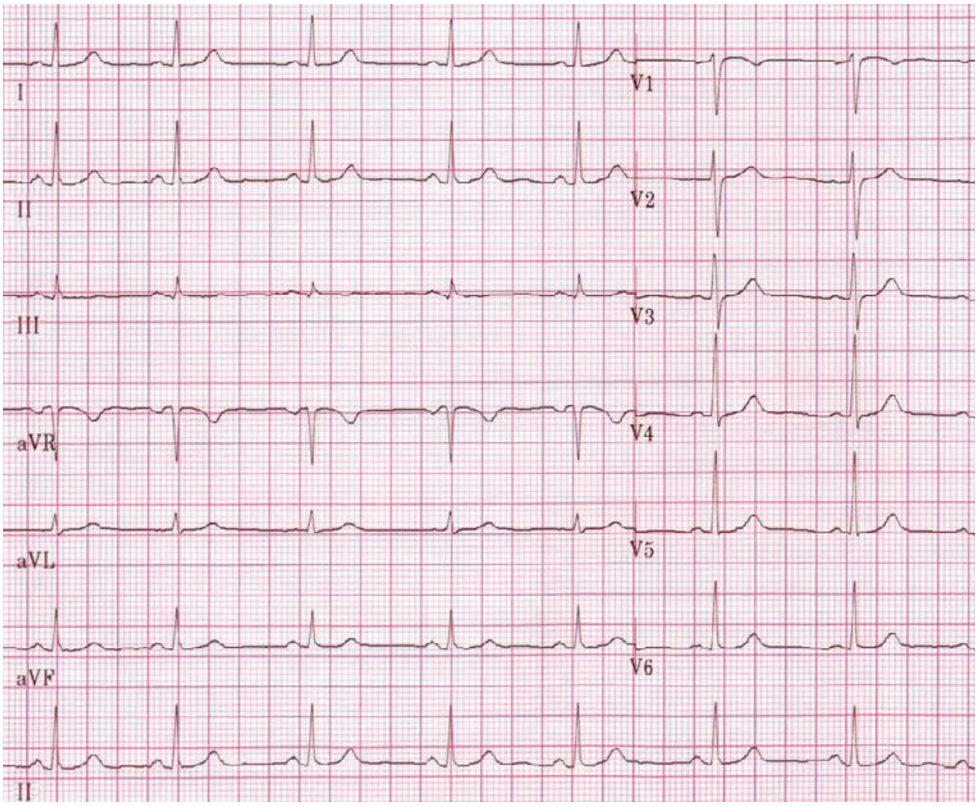
Remember, the heart's conduction system is designed (1) to set its own pace by generating an electrical impulse and (2) to send that signal to all parts of the heart in a coordinated manner that first triggers the atria to squeeze blood into the ventricles and then causes the ventricles to squeeze that blood out from the bottom to the top. See if you can name the parts of the conduction system in the order an impulse travels through them.

The Electrocardiogram

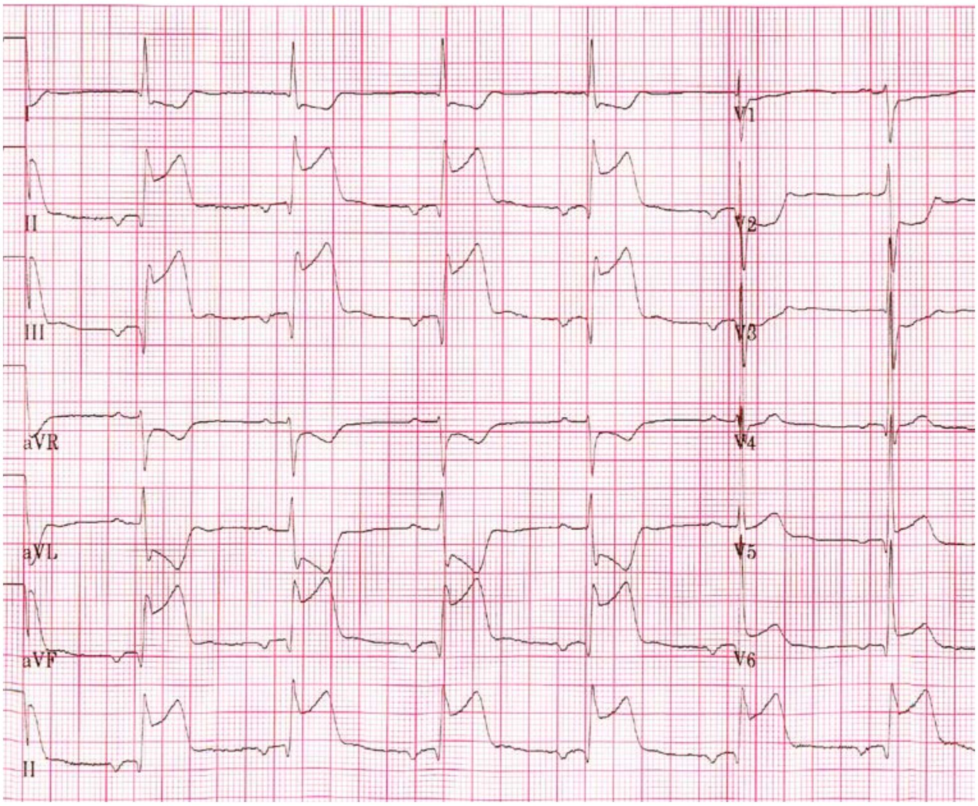
The electrical impulses transmitted through the heart can be detected on the body's surface. The heart's electrical signals can be measured with an electrocardiograph. The recording that is produced from this is called an *electrocardiogram* (abbreviated ECG or EKG).

To record an ECG, one electrode (called a *limb lead*) is placed on each arm and leg. (This does not hurt.) Then six other electrodes are placed across the front of the chest. These are the *chest leads*. Multiple

Getting an Electrocardiogram



Normal 12 lead Electrocardiogram



12 lead electrocardiogram of patient having a heart attack. Note the distinct differences from the normal EKG above.

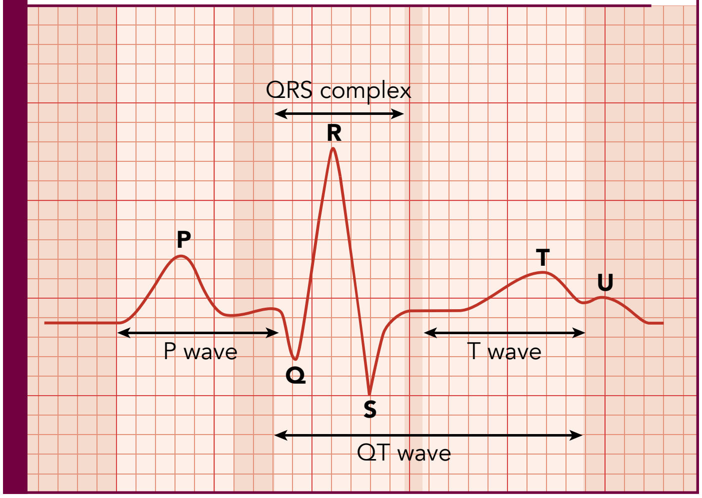
leads are necessary in order to measure the electrical signals from many different positions relative to the heart. The electrocardiograph machine amplifies the signals obtained by the various electrodes and prints out the patterns as an electrocardiogram.

The ECG tracing is a reflection of the electrical signal being transmitted through the cardiac conduction system. As your eyes move from left to right along the tracing, you are seeing a measurement of the electrical signal as it signals each part of the heart in turn. The ECG shows us the electrical signal that instructs the heart to beat and reveals how well that signal travels through the heart, but it does not actually show the heart's response to that signal — the squeezing of the muscle. Other techniques, such as the *echocardiogram*, show the actual beating of the heart.

The first major wave seen on the ECG is called the *P wave*. The P wave reflects the electrical signal that begins the domino effect that ultimately makes the heart beat one time. The P wave reflects the movement of the electrical impulse from the SA node through the myocardium of the atria. About 0.1 second after the P wave begins, the atria contract. The flat segment between the P

TAKING A CLOSER LOOK

Electrocardiogram



wave and the beginning of the QRS represents the time after the signal has passed through the atria and is being delayed in the AV node. Remember, it is this delay at the AV node that gives the atria time to squeeze their blood into the ventricles before they contract.

The second large wave seen in a typical ECG is called the *QRS complex*. During the time reflected in the QRS complex the electrical impulse is moving through the ventricles. The QRS complex has a complicated appearance due to the paths that the electrical impulses travel as they move through the ventricular myocardium. This is the time when the ventricles contract. The QRS lasts about 0.1 second.

The last wave in an ECG is the *T wave*. During this time, the ventricle is starting to relax. The ventricles are preparing to receive the next electrical impulse. The duration of the T wave is about 0.16 second, and during this time the electrical system of the heart resets itself in preparation for the next heartbeat.

Then the process begins again.

By understanding the pattern and timing of normal ECGs, doctors can use abnormal ECG patterns to help diagnose and treat patients. In fact, ECGs have become one of the most important tools in modern medicine. Damaged cardiac muscle, for instance, might not transmit the electrical signal properly, and this can be revealed in the ECG. ECGs can be particularly helpful in diagnosing coronary artery disease and cardiac rhythm disorders.

Cardiac Output

To more completely understand how the heart works, there is another concept you must understand. This is known as cardiac output.

Cardiac output (CO) is the amount of blood pumped by the heart in one minute. Cardiac output can vary from minute to minute. For example, when you are running, your leg muscles need more oxygen, right? Of course they do. So what do you think happens to the output of the heart when these muscles need more oxygen? It increases!

When you are asleep, your leg muscles need less oxygen, right? So what happens to the heart output when less oxygen is needed? It is not as high.

Cardiac output is the product of two things: the heart rate (HR) and the stroke volume (SV). *Heart rate* means just what it says, the rate of the heart in beats per minute. *Stroke volume* is the amount (volume) of blood pumped with each heartbeat.

The relationship can be shown this way:

$$CO = HR \times SV$$

So let’s calculate an average cardiac output. If the average heart rate is 72 beats per minute, and the stroke volume is 70mL, then

$$CO = 72 \text{ beats/minute} \times 70\text{mL/beat}$$

$$CO = 5040\text{mL/minute}$$

$$CO = 5.04 \text{ liters/minute}$$

$$(CO = 1.33 \text{ gallons/minute})$$

This is a typical cardiac output for an adult at rest.

There are two ways that the cardiac output increases — either the heart rate increases or the stroke volume increases. As you are aware, with exercise, the heart rate increases. You've probably felt your heart beating very fast at the end of a sprint. What you may not realize is that with exercise, your heart's stroke volume — the amount of blood pumped out with each beat — can also increase. If, while running, your heart rate goes to 110 beats per minute and the stroke volume increases to 100 mL (3.4 ounces) per minute, what is the cardiac output?

CO = 110 beats/minute x 100 mL/beat
CO = 11,000mL/minute
CO = 11 liters/minute
(CO = 2.9 gallons/minute)

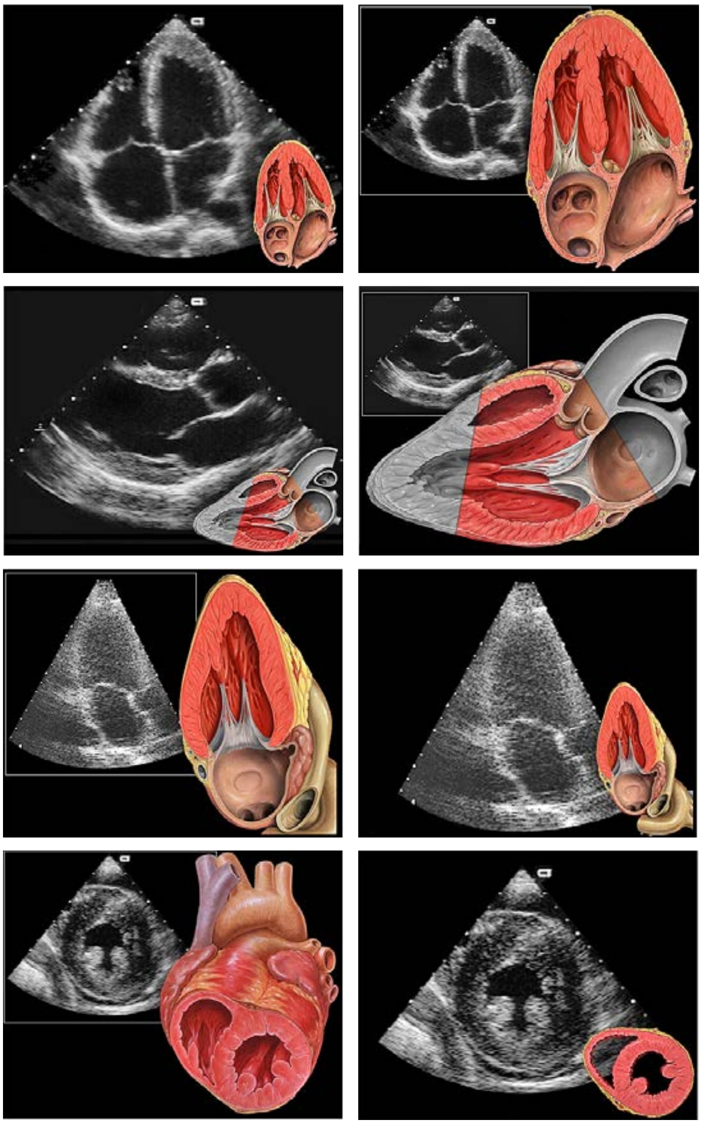
So we see that with only mild increases in heart rate and stroke volume, the cardiac output more than doubles! Soon we'll see how the body can let the heart know that it must pump out more blood — that is, that it must increase its cardiac output.

Echocardiogram

An echocardiogram is an ultrasound of the heart. Whereas the EKG evaluates the heart's function by measuring electrical conduction, an echocardiogram uses sound waves to see inside the heart. Using a *transducer* placed on the patient's chest, sound waves are painlessly bounced off various parts of the heart. The resulting pictures show the heart's shape, its walls, valves, and even the blood flowing through its chambers.

By using sound waves to see inside the heart and make measurements, doctors can determine if the heart is working normally or not. Do the walls move properly? Are they too thick? Is the heart enlarged? Do the valves close completely, or does blood leak back through them? How much blood do the heart's chambers pump out with each squeeze? The heart's ejection fraction, a valuable way to assess how well it is pumping, can be calculated based on information from the echocardiogram.

Here you can see samples of echocardiographic images.



Cardiac Reserve

Some people's hearts are able to increase their cardiac output more than others. A healthy person who runs regularly, for instance, may be able to increase his or her cardiac output much more than a person with heart disease can. We say their *cardiac reserve* is greater.

Cardiac reserve is the difference between the cardiac output at rest and cardiac output during maximal exertion. The average person's heart can increase its output about five times above its resting output. That would be around 24 liters/minute (6.5 gallons/minute). In a highly trained athlete, the maximum cardiac output during heavy exertion might reach 33 liters/minute (9 gallons/minute), or seven times the resting CO.

Regulation of Stroke Volume

Increasing cardiac output requires an increased heart rate, or increased stroke volume, or both. Let's look at ways the stroke volume can increase.

Stroke volume, remember, is how much blood the heart pumps out during one heartbeat. The heart, no matter how healthy, does not empty itself completely during a beat. There is always some blood left behind. Therefore, stroke volume is the difference between the amount of blood in the left ventricle when it is completely relaxed and the amount of blood remaining in the left ventricle when it has just finished contracting.

The ventricle's time of relaxation and filling is called *diastole*, you recall, so the amount of blood in the ventricle when it is full is known as the *end diastolic volume*. *Systole* is the time of contraction, so the amount of blood left in the ventricle after it contracts is called the *end systolic volume*. We could sum this up like this:

End diastolic volume – End systolic volume = Stroke volume

We've said that the heart can increase its stroke volume in order to supply the body's increased needs, like when you want to run. There are several factors that affect stroke volume, but the two most important are *preload* and *contractility*. Preload depends on how much blood is in the left ventricle before it squeezes. Contractility involves how hard the ventricle squeezes. Let's look at these two things more closely.

Cardiac muscle cells contract most efficiently when they are stretched somewhat before they begin contracting. *Preload* is the amount that cardiac muscle is stretched by the blood in the ventricle before it contracts. The more blood that enters the ventricle, the more its walls are stretched. This stretching helps increase the force of the contraction of the muscle. Imagine blowing up a balloon. The more air you blow into a balloon, the more the balloon stretches. Up to a point, the more the ventricle is stretched (preloaded), the stronger will be its contraction.

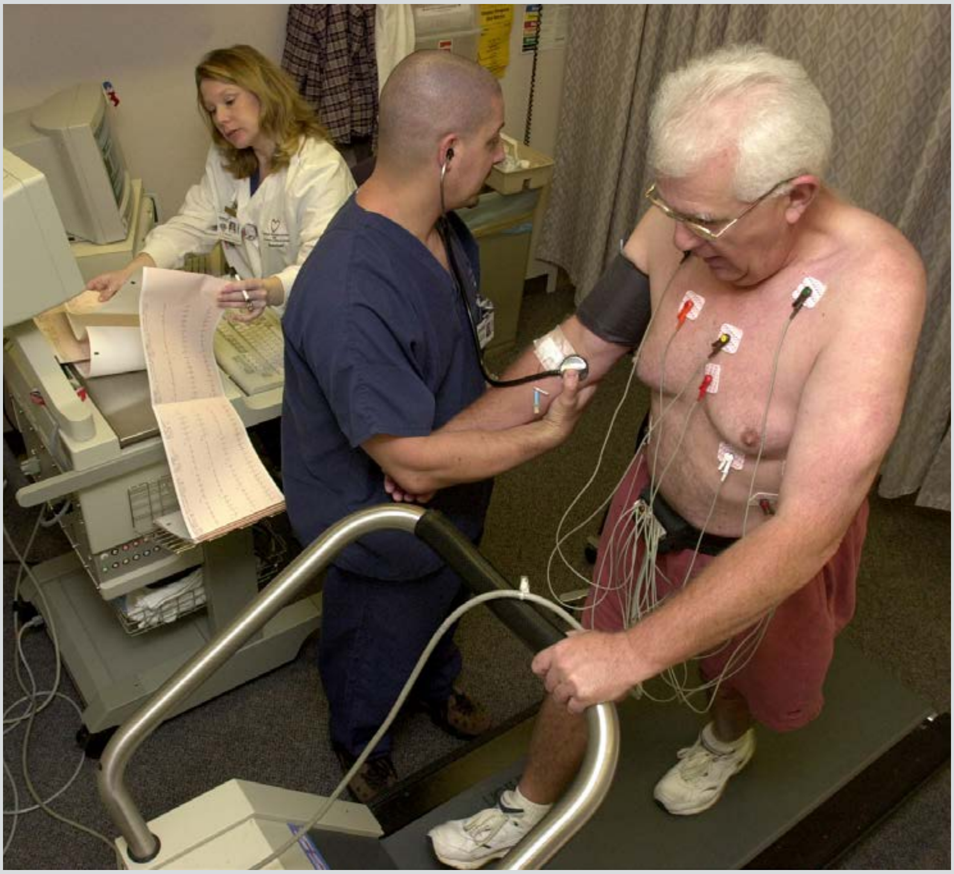
Preload depends on the amount of blood that can enter the ventricle before it beats. Let's consider how preload can change. The heart's *rate* can alter its preload. If it beats slowly, there is more time between beats. This allows more time for blood to fill the ventricles and increases stroke volume. The opposite can occur with extremely fast heart rates. A very rapidly beating heart leaves little time between beats to fill the ventricle, and the stroke volume could consequently decrease.

The heart muscle's contractility also helps determine stroke volume. *Contractility* refers to how hard the muscle can contract when it is stretched to a certain point. When you are running, your body can send messages to the heart to increase contractility. Some of the most important chemical messengers in the body are called hormones. *Hormones* travel through the blood stream to deliver their messages to many destinations in the body. The hormones *epinephrine* and *norepinephrine* (also called *adrenaline* and *noradrenaline*) can increase the contractility of cardiac muscle, making the muscle squeeze more forcefully. When the heart squeezes harder, it empties more completely with each beat. Thus, stroke volume increases.

Stress Testing

A heart suffering from coronary artery disease might have sufficient blood circulation to function normally at rest but not when stressed with exercise. Therefore, one of the most common tests performed to detect coronary artery disease is called an exercise test, or a "stress" test.

An exercise stress test is performed by having the patient walk on a treadmill while connected to an EKG monitor. Every few minutes, the speed and incline of the treadmill are increased, thus demanding more work from the patient's heart. (Those patients unable to walk on a treadmill can be tested using vigorous arm exercises or an exercise bicycle.) The test ends when the patient cannot continue or when a specified heart rate is achieved.



During the stress test certain characteristic EKG patterns may suggest the presence of coronary artery disease. Abnormal heart rhythms also commonly develop during the exertion of the stress test. These rhythms are recorded on the EKG tracings for evaluation.

Although primarily thought of as a test to detect disease, stress tests are also useful in other ways. For example, special types of stress tests are sometimes used to evaluate and monitor the conditioning of healthy athletes as a part of their training regimen.

Regulation of Heart Rate

We said the increased cardiac output requires an increased heart rate, or increased stroke volume, or both. Just as there are factors that regulate stroke volume, there are factors that regulate heart rate. The SA node is the heart's main pacemaker. The SA node is part of the heart's *intrinsic* conduction system — a signaling network *inside* the heart — but it responds to input from the nervous system, hormones, and other stimuli.

Everyone knows that our heart beats faster when we are frightened or excited. This increase in heart rate is due in large part to stimulation of the cardiac conduction system by the nervous system. Nerve fibers from the *sympathetic nervous system* release a chemical (norepinephrine) that binds to special receptors on the heart. Sympathetic nerve stimulation causes the SA node to fire more rapidly, and thus increases the heart rate.

The nervous system can also cause the heart rate to decrease. The *parasympathetic nervous system* has effects opposite to the sympathetic nervous system. (We will learn much more about these two divisions of the nervous system in other volumes of *Wonders of the Human Body*.) Parasympathetic fibers release a different chemical (acetylcholine) to slow the speed at which the SA node fires.

The primary pacemaker of the heart, the SA node, fires at an average of 72 beats per minute. However, the SA node is actually "pre-set" at a rate of nearly 100 beats per minute. The SA node fires at a slower average rate because it is reined in the parasympathetic nervous system's input.

Heart rate can be influenced by other things, such as hormones — chemical messengers that travel though the blood stream. One of these — adrenaline (also called epinephrine) — is made by the adrenal glands when you are exercising and when you are frightened. Adrenaline (epinephrine) increases heart rate. Thyroxine, a hormone produced by the thyroid gland, can also increase the heart rate. Fever can increase the heart rate, and an abnormally low body temperature can lower the heart rate.