

Heart Structure, Function and Arrhythmias

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<http://thevirtualheart.org>

This document has three purposes.

First, it provides information about the heart's function and structure along with information about some arrhythmias using interactive visualization techniques.

Second, it demonstrates how 3D PDF files can be used to include not only images or movies but also interactive three-dimensional structures that can be manipulated by users to personalize their reading experience.

Third, it shows an example of the future of documents. Many magazines and scholarly journals will benefit from inclusion of interactive three-dimensional visualizations in the future.

Introduction.

The heart is a powerful muscle that pumps blood throughout the body by means of a coordinated contraction. The contraction is generated by an electrical activation, which is spread by a wave of bioelectricity that propagates in a coordinated manner throughout the heart. Under normal conditions, the sinoatrial node initiates an electrical impulse that propagates through the atria to the atrioventricular node, where a delay permits ventricular filling before the electrical impulse proceeds through the specialized His-Purkinje conduction system that spreads the electrical signal at speeds of meters per second throughout the ventricles. This electrical impulse propagates diffusively through the heart and elevates the voltage at each cell, producing an action potential, during which a surge in intracellular calcium initiates the mechanical contraction. The normal rhythm is altered when one or more spiral (reentrant) waves of electrical activity appear. These waves are life-threatening because they act as high-frequency sources and underlie complex cardiac electrical dynamics such as tachycardia and fibrillation. ***In the following pages we describe in more detail the heart's structure and function and illustrate some of these lethal arrhythmias with movies and interactive 3D animations.***

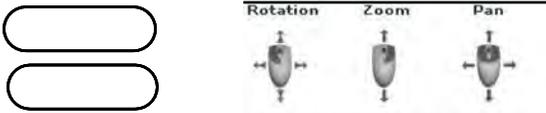


Figure 1. The Heart. **This is an interactive 3D heart.** Click in the window to interact with it. The heart can be rotated, zoomed and panned by using the mouse as indicated in the figure. In addition, pre-defined animations can be played by clicking the "Explore" and "Spin" buttons. The object light, background and other properties can be changed by using the menu that appears on the top of the figure once it has been activated.

Right Atrium: The upper right chamber of the heart. During the normal cardiac cycle, the right atrium receives deoxygenated blood from the body (blood from the head and upper body arrives through the superior vena cava, while blood from the legs and lower torso arrives through the inferior vena cava). Once both atria are full, they contract, and the deoxygenated blood from the right atrium flows into the right ventricle through the open tricuspid valve

Left Atrium: The upper left chamber of the heart. During the normal cardiac cycle, the left atrium receives oxygenated blood from the lungs through the pulmonary veins. Once both atria are full, they contract, and the oxygenated blood from the left atrium flows into the left ventricle through the open mitral valve.

Superior Vena Cava: One of the two main veins bringing deoxygenated blood from the body to the heart. Veins from the head and upper body feed into the superior vena cava, which empties into the right atrium of the heart.

Inferior Vena Cava: One of the two main veins bringing deoxygenated blood from the body to the heart. Veins from the legs and lower torso feed into the inferior vena cava, which empties into the right atrium of the heart.

Aorta: The central conduit from the heart to the body, the aorta carries oxygenated blood from the left ventricle to the various parts of the body as the left ventricle contracts. Because of the large pressure produced by the left ventricle, the aorta is the largest single blood vessel in the body and is approximately the diameter of the thumb. The aorta proceeds from the left ventricle of the heart through the chest and through the abdomen and ends by dividing into the two common iliac arteries, which continue to the legs.

Atrial septum: The wall between the two upper chambers (the right and left atrium) of the heart.

Pulmonary trunk: A vessel that conveys deoxygenated blood from the right ventricle of the heart to the right and left pulmonary arteries, which proceed to the lungs. When the right ventricle contracts, the blood inside it is put under pressure and the tricuspid valve between the right atrium and right ventricle closes. The only exit for blood from the right ventricle is then through the pulmonary trunk. The arterial structure stemming from the pulmonary trunk is the only place in the body where arteries transport deoxygenated blood.

Pulmonary veins: The vessels that transport oxygenated blood from the lungs to the left atrium. The pulmonary veins are the only veins to carry oxygenated blood.

Pulmonary Valve: One of the four one-way valves that keep blood moving properly through the various chambers of the heart. The pulmonary valve separates the right ventricle from the pulmonary artery. As the ventricles contract, it opens to allow the deoxygenated blood collected in the right ventricle to flow to the lungs. It closes as the ventricles relax, preventing blood from returning to the heart.

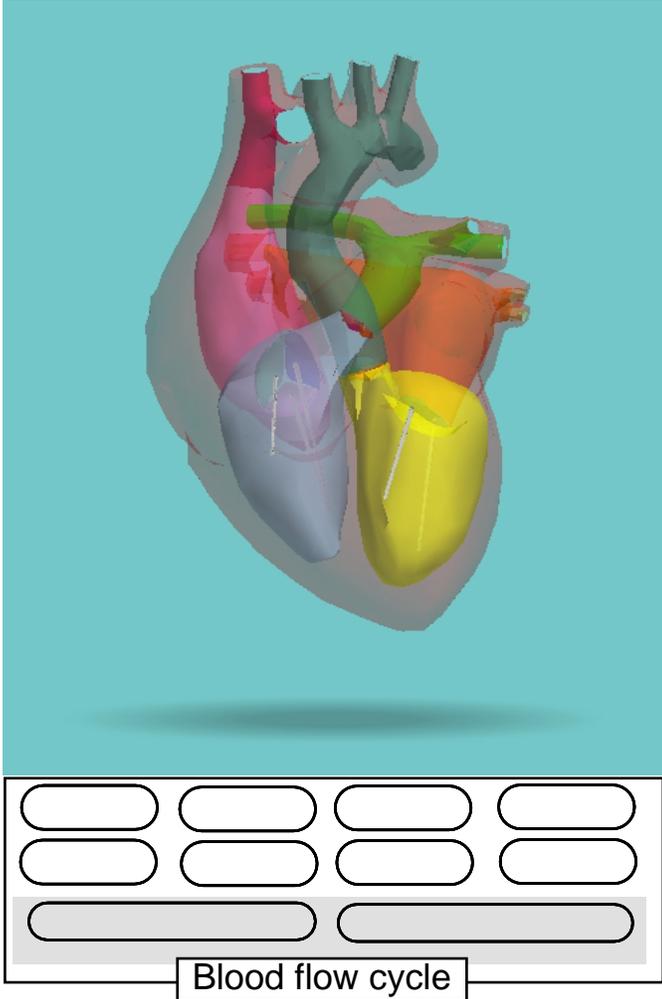
Aortic Valve: One of the four one-way valves that keep blood moving properly through the various chambers of the heart. The aortic valve, also called a semi-lunar valve, separates the left ventricle from the aorta. As the ventricles contract, it opens to allow the oxygenated blood collected in the left ventricle to flow throughout the body. It closes as the ventricles relax, preventing blood from returning to the heart. Valves on the heart's left side need to withstand much higher pressures than those on the right side. Sometimes they can wear out and leak or become thick and stiff.

Mitral Value: One of the four one-way valves that keep blood moving properly through the various chambers of the heart. The mitral valve separates the left atrium from the left ventricle. It opens to allow the oxygenated blood collected in the left atrium to flow into the left ventricle. It closes as the left ventricle contracts, preventing blood from flowing backwards to the left atrium and thereby forcing it to exit through the aortic valve into the aorta. The mitral valve has tiny cords attached to the walls of the ventricles. This helps support the valve's small flaps or leaflets.

Tricuspid Valve: One of the four one-way valves that keep blood moving properly through the various chambers of the heart. Located between the right atrium and the right ventricle, the tricuspid valve is the first valve that blood encounters as it enters the heart. When open, it allows the deoxygenated blood collected in the right atrium to flow into the right ventricle. It closes as the right ventricle contracts, preventing blood from flowing backwards to the right atrium, thereby forcing it to exit through the pulmonary valve into the pulmonary artery.

Atria: The two upper cardiac chambers that collect blood entering the heart and send it to the ventricles. The right atrium receives blood from the superior vena cava and inferior vena cava. The left atrium receives blood from the pulmonary veins. Unlike the ventricles, the atria serve as collection chambers rather than as primary pumps, so they are thinner and do not have valves at their inlets.

Ventricles: The two lower cardiac chambers that collect blood from the upper chambers (atria) and pump it out of the heart. Because the ventricles pump blood away from the heart, they have thicker walls than the atria so that they can withstand the associated higher blood pressures. The right ventricle pumps oxygen-poor blood through the pulmonary artery and to the lungs. The left ventricle pumps oxygen-rich blood through the aorta and to the rest of the body.



Blood Flow

The heart's cycle begins when oxygen-poor blood from the body flows into the right atrium. Next the blood flows through the right atrium into the right ventricle, which serves as a pump that sends the blood to the lungs. Within the lungs, the blood releases waste gases and picks up oxygen. This newly oxygen-rich blood returns from the lungs to the left atrium through the pulmonary veins. Then the blood flows through the left atrium into the left ventricle. Finally, the left ventricle pumps the oxygen-rich blood out through the aorta and from there to all parts of the body. The human body has about 5.6 liters (6 quarts) of blood, all of which circulates through the body three times every minute.

Figure 3. Interactive 3D heart with blood flow cycle. By clicking on the buttons eight stages of flow are shown. Oxygen-depleted blood is shown in blue and oxygen-rich blood in red. Oxygen-poor blood returns to the heart via the superior and inferior venae cavae (Stage 1) and enters the right atrium (Stage 2). It then proceeds to the right ventricle (Stage 3) and is pumped to the lungs via the pulmonary trunk (Stage 4). After the blood is oxygenated in the lungs, it travels through the pulmonary veins (Stage 5) to the left atrium (Stage 6). From here it moves to the left ventricle (Stage 7), which provides a powerful contraction that pushes the blood through the aorta (Stage 8) and throughout the body. While the cycle is shown sequentially, the right and left sides of the heart operate together, so that, for instance, Stages 2 and 6 occur simultaneously.

Arrhythmias

During normal rhythm, the heart beats regularly, producing a single coordinated electrical wave that can be seen as a normal electrocardiogram (ECG). During arrhythmias such as ventricular tachycardia and ventricular fibrillation, this normal behavior is disrupted and the ECG records rapid rates with increased complexity.

The underlying cause of many arrhythmias is the development of a reentrant circuit of electrical activity that repetitively stimulates the heart and produces contractions at a rapid rate. During tachycardia, a single wave can rotate as a spiral wave, producing fast rates and complexity. During fibrillation, a single spiral wave can degenerate into multiple waves. Because contraction is stimulated by the pattern of electrical waves, arrhythmias can compromise the heart's ability to pump blood and sometimes may be lethal.

Figure 4, shows an example of one of these arrhythmias. ventricular tachycardia, driven by a fast rotating spiral wave of electrical activity. The colors show the voltage on the heart's surface following the color bar.



3-D Movie

Figure 4. Interactive heart showing ventricular tachycardia, a type of arrhythmia produced by a rotating spiral wave of electrical activity. Before playing the movie, press the "Set" button. The movie shows a couple of rotations of the reentrant wave. Individual movie frames can be viewed by using the frame buttons. The heart can then be rotated to visualize the spiral on the full surface of the heart from any point of view.

Sinus rhythm is the normal rhythm of the heart and results from proper activation of the entire heart in proper sequence. The sinoatrial (or sinus) node located in the right atrium spontaneously beats periodically to begin each activation, which proceeds to activate both atria before reaching the atrioventricular (AV) node. At the AV node, which under normal circumstances is the only electrical connection between the atria and ventricles, activation proceeds more slowly to allow for optimal ventricular filling. The activation then enters the His-Purkinje system, which allows a rapid spreading throughout the ventricles and induces a strong, synchronized contraction. Any variation from normal sinus rhythm is termed an arrhythmia.

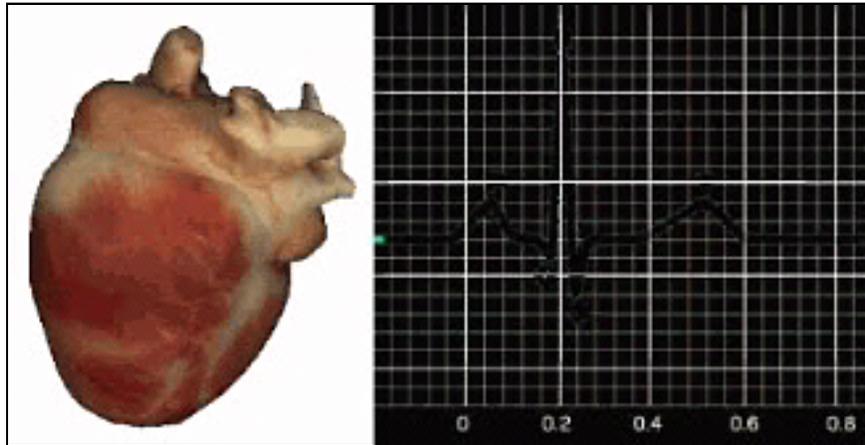


Figure 5. Simulation and electrocardiogram corresponding to the heart's normal sinus rhythm. The atrial contraction is initiated by the depolarization wave (shown in yellow), which originates from the sinoatrial node and corresponds to the P wave on the ECG. After a delay passing through the atrioventricular node, the activation passes to the ventricles and produces a contraction. The QRS complex indicates ventricular depolarization (shown in yellow), while the T wave corresponds to ventricular repolarization.

Ventricular fibrillation is an immediately life-threatening arrhythmia in which the heart's electrical activity and associated contraction become disordered and ineffective. It is characterized by rapid, irregular activation of the ventricles and thereby prevents an effective mechanical contraction. Blood pressure instantaneously drops to zero, leading to death within minutes due to lack of cardiac output unless successful electrical defibrillation is performed; spontaneous conversion to sinus rhythm is rare. During ventricular fibrillation, the ECG has no distinctive QRS complexes but instead consists of an undulating baseline of variable amplitude. Although the sinus node continues to function properly, P waves cannot be discerned in the VF waveform. Ventricular tachycardia in many cases can degenerate to ventricular fibrillation. One mechanism believed to be responsible for the rapid, unsynchronized contraction of the ventricles is the continuous reactivation of one or more electrical circuits in the ventricles, which can appear as three-dimensional spiral or scroll waves of electrical activity. These waves prevent the ventricles from contracting in a coordinated manner, thereby compromising the heart's ability to pump blood.

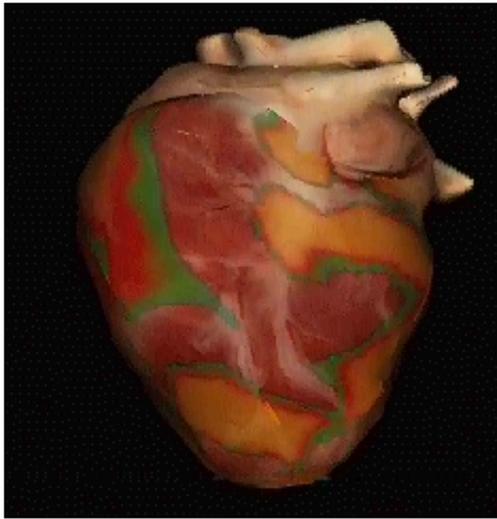


Figure 6. Simulation of Ventricular fibrillation (Play movie).

Ventricular tachycardia is a rhythm characterized by wide, bizarre QRS complexes and frequent ventricular premature contractions in a row. VT may be paroxysmal or chronic and often signifies underlying myocardial disease. Mechanisms include reentry, increased automaticity, and triggered activity. VT is potentially life-threatening, as it can degenerate rapidly to ventricular fibrillation and result in sudden death.

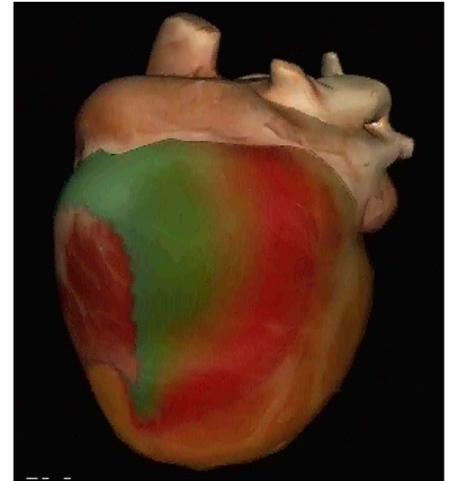


Figure 7. Simulation of ventricular tachycardia (Play movie)

Atrial flutter is an AV node-independent intra-atrial macro-reentry rhythm, in which the atrial anatomy sustains a loop of continuous depolarization, often around the tricuspid valve annulus in the right atrium. Atrial flutter can be paroxysmal or chronic and may be associated with extremely rapid ventricular response rates. Variable degrees of AV block often modify AV conduction, which changes between 1:1 and 3:1 or 2:1. Atrial flutter often induces electrical remodeling and thereby can serve as a precursor to atrial fibrillation.

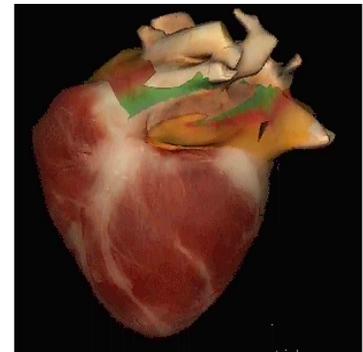


Figure 8. Simulation of atrial flutter

Atrial fibrillation is characterized by rapid, irregular activation of the atria. Causes can include reentry and abnormal automaticity. Atrial fibrillation is one of the most commonly seen supraventricular arrhythmias. AF can be paroxysmal or chronic. Chronic AF often causes a markedly elevated ventricular response rate and thereby contributes to the clinical signs of heart failure. AF also can occur in the absence of overt structural heart disease as lone AF, which can feature a normal

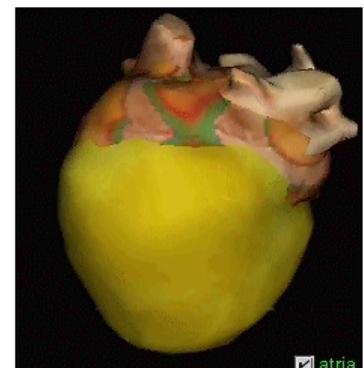


Figure 9. Simulation of atrial fibrillation

Acknowledgements

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Further information

<http://thevirtualheart.org>

http://www.scholarpedia.org/article/Cardiac_arrhythmia

<http://www.hrsonline.org> Heart Rhythm Society.

<http://www.americanheart.org> American heart Association.