

Spiral Waves and the Heart: Spatiotemporal Organization of Cardiac Rhythms

Abstract:

The heart contracts in response to electrical waves that propagate through cardiac muscle. Normally, the electrical waves propagate smoothly to effect a coordinated, effective contraction. However, in pathologic states, normal wave propagation can be disrupted, causing wave fronts to break into multiple waves. Once initiated, these multiple waves often appear as spiral waves that may be stable or, more often, destabilize by fractionating into new waves. Spiral waves repetitively excite the tissue at faster rates and following an altered activation sequence, both of which compromise the heart's ability to pump effectively.

This talk will describe the current understanding of the spatiotemporal organization of electrical waves in the heart during normal rhythm and arrhythmias using state-of-the-art experiments, theory, and simulations.

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Heart disease is one of the main causes of death in industrialised countries. In the United States, one-third of deaths are due to heart disease. The most common type of heart disease is coronary heart disease, in which one or more of the coronary arteries cannot provide oxygen-saturated blood to the heart anymore. The heart might still pump, but the presence of the oxygen-deprived region weakens the heart's contraction and leaves the heart vulnerable to other types of disease. If the one or more coronary arteries are completely blocked, the result is a heart attack.

Another type of heart disease is stroke, in which blood vessels to the brain become blocked. Heart failure, which consists of weakened pumping, is another common type of heart disease. A contributing factor to all these forms of heart disease is high blood pressure. A final type of heart disease is cardiac arrhythmia, which consists of a disruption to the normal electrical of the heart. This talk will mainly focus on the electrophysiological properties of the heart.

Although there are many types of arrhythmias, our focus will be on tachycardia and fibrillation. Arrhythmias can be associated with other types of heart disease; for example, certain types of arrhythmias can increase the risk of stroke. Arrhythmias can occur in the upper chambers of the heart (atria), in the lower chambers (ventricles) or in both. Arrhythmias can be characterized by either an increased or decreased heart rate.

In this talk tachyarrhythmias, those with an increased and often irregular heart rate, will be the focus.

Atrial fibrillation is the uncoordinated contraction the upper chambers of the heart and can be dangerous because blood is no longer expelled properly, leading to blood pooling and an increased risk of clot development. Blood clotting in these chambers, in turn, increases the risk of thromboembolism, which can cause stroke. Atrial fibrillation is a rapid rhythm, and the ventricles cannot keep up with this frequency, resulting in an irregular ventricular rhythm. However, it is not immediately life-threatening, and individuals can live with atrial fibrillation for many years, although their quality of life may suffer.

Ventricular fibrillation, on the other hand, is always **life threatening**. The heart's contraction is no longer coordinated; it can no longer pump effectively. This condition results in hundreds of thousands of deaths **each** year in the United States alone because the body cannot receive **enough** oxygen.

Tachycardia is a less dangerous rhythm, although in many cases ventricular tachycardia degenerates quickly into fibrillation. In ventricular tachycardia there is an accelerated heart rate, although the atria continue to beat normally.

According to NationMaster.com, the Netherlands has the highest reported per capita incidence of cardiac arrest in the world, with over 180,000 deaths per one million people.

How does electricity play a role in the heart?

At the cellular level, different ion concentrations are maintained inside and outside the cell by the cell membrane to maintain a certain environment. Ions can move across the semi-permeable membrane through specialised protein structures called ion channels, which can be voltage- and/or time-dependent. The ion concentration gradients (calcium, potassium, sodium) across the membrane give rise to an electrical gradient. In response to an electrical stimulus, such as a depolarizing current from neighboring cells with higher membrane potentials, a cardiac cell produces an electrical response called an action potential. During the action potential, sodium and calcium ions enter the cell and potassium ions exit the cell through ion channels; at the end of the action potential, specialized pumps and exchangers work against the concentration gradient to restore normal resting conditions. The action potential triggers contraction.

Cardiac tissue has much in common with other types of muscle in the body; for example, like skeletal muscle cells cardiac muscle forms fibers that provide contractile force. The anatomical structure of the heart with atria, the ventricles, and the blood vessels entering and leaving the heart is very complicated.

The left ventricle is much thicker than the right ventricle, as the left ventricle is responsible for pumping blood throughout the body.

Muscle fibers wrap around the heart, which allows for more efficient contraction of the heart.

Normal sinus rhythm occurs as a healthy synchronisation between atria and ventricles: first the atria are activated electrically followed by the ventricles. You can see a smooth coordinated electrical wave through the heart during normal sinus rhythm.

Flavio Fenton

When the heart's normal electric rhythm is disrupted, spiral waves can occur; these re-entrant waves are closely associated with tachycardia and fibrillation. How do spiral waves form and destabilize and why are they dangerous?

An important property governing when spiral waves form is refractoriness. Essentially, after being electrically stimulated and producing an action potential, a cell must wait for a certain period of time before another action potential can be elicited by another stimulus. Many systems have this property: for example, when you flush a toilet you have to wait before you can flush again. If you try to flush again too quickly, the water in the tank has not been replenished. The presence of a refractory period is what can allow spiral waves to be formed.

When a second action potential wave is induced after an earlier wave the timing of the second wave determines whether a spiral wave develops. If the second wave is too late, a normal full wave pattern is produced. If it is too early, the entire wave occurs during the refractory period and is blocked. However, it can be possible to introduce a second wave in the wake of the first wave in such a way that it is blocked in the direction toward the first wave but can propagate away from the first wave. As the tissue closer to the first wave recovers, the new wave can curl around and propagate in that direction as well, producing a pair of counter-rotating spiral waves.

Spiral waves can develop in response to a premature beat that may originate in any part of the heart. It can be easier to induce spiral waves when the heart is more electrophysiologically heterogeneous, such as after a heart attack, which changes the electrophysiology of the region of the heart whose blood supply was compromised. However, it is possible to initiate spiral waves in normal tissue as well.

Spiral waves can follow different types of trajectories depending on the tissue electrophysiology. Most commonly, spirals follow linear trajectories, but they can also follow circular, flower-petal, or hypermeandering trajectories.

Why are spiral waves dangerous? First, they override the natural pacemaker of the heart and cause the heart to beat more rapidly, as their rotation is faster than sinus rhythm. Second, spiral waves are often not stable, especially in the ventricles. A spiral wave, once initiated, often breaks up into multiple waves associated with multiple localized contractions, which compromises the heart's ability to pump blood.

In general, a single spiral wave is associated with tachycardia, whereas multiple spiral waves are associated with fibrillation and sudden cardiac death.

How does destabilisation of spiral waves happen?

There are a number of different mechanisms. One is associated with an alternating long-short pattern of activation associated with alternating wavelengths. In this scenario, short wavelengths may become too short and become blocked, leading to wave breaks. This pattern can repeat itself, resulting in the continual formation of multiple spiral waves.

Spiral waves can also break into multiple waves without an alternation in wavelengths because wave may become blocked in some directions but not in others. The heart's contraction must follow the electrical activity and so it too becomes fractionated and uncoordinated.

Three-dimensional spiral waves are called scroll waves and go through the depth of the tissue. Scroll waves rotate around a vortex-like structure, just as a spiral wave rotates around a wave tip. If the

ends of the vortex are on the surface of the heart, the wave resembles a scroll, but if the ends of the vortex connect back to each other to form a ring, the wave resembles a torus. The vortex lines essentially connect the tips of all the spiral waves that can be seen in planes through the scroll wave. Scroll waves can have very complicated dynamics that can be characterized in part by the interactions of vortex filaments, such as ring creation, fusion, and pinching. These interactions in three dimensions can also destabilize waves and produce fibrillation.

There are main ways of resetting arrhythmias:

1. Strong electrical shocks, by means of defibrillation or cardioversion.
2. Multiple small electrical shocks that have lower energy and synchronize the tissue to allow resumption of sinus rhythm.
3. Anti-arrhythmic drugs, which can make the rhythm more regular.

When we understand how spiral waves behave, we might provide better treatments for arrhythmias. For example, instead of one big shock, we can treat fibrillation with smaller shocks of lower energy to minimize tissue damage. As an example, we can measure the frequency of the arrhythmia and then give 5 pulses at the frequency of the arrhythmia or a little faster. With each pulse, the tissue becomes increasingly synchronized, so that normal sinus rhythm can resume after the final shock. In this way it may be possible to terminate arrhythmias with less energy and little damage. Similarly, it is sometimes possible to restore normal patterns using anti-arrhythmic drugs. These drugs can alter the tissue electrophysiology, such as by making the wavelength and refractory time a little longer, so that spiral waves will terminate themselves.

Spiral waves can occur in many other systems, such as the brain and other types of neural tissues as well as certain types of chemical reactions, the aggregation of social amoebae, and fluid dynamics.

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