Cardiac Action Potentials and Excitation of the SA Node

2nd year Students

Cardiac Action Potentials

The mechanism by which action potentials are conducted along the membranes of heart cells is basically similar to other excitable tissues like neurons and skeletal muscle cells. It involves the controlled exchange of ions across cellular membranes. However, different types of heart cells express unique combinations of ion channels that produce different action potential shapes.

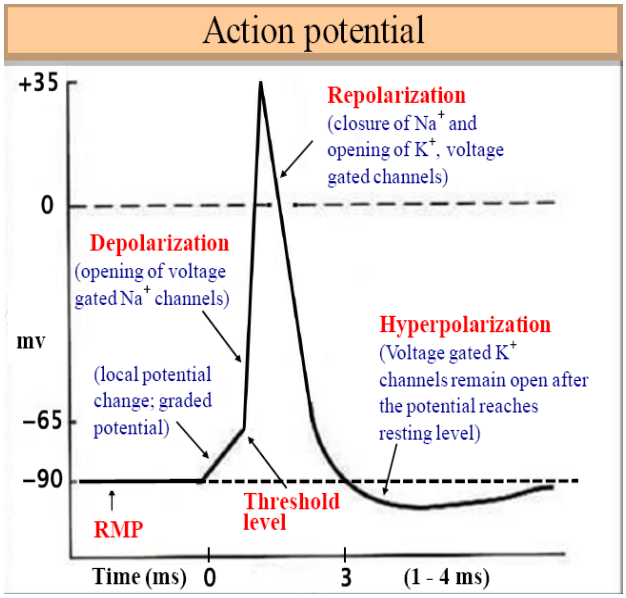
(((As in skeletal muscle cells and neurons, the resting membrane is much more permeable to K^+ than to Na^+. Therefore, the resting membrane potential is much closer to the K^+ equilibrium potential (- 90 mV) than to the Na^+ equilibrium potential (+ 60 mV). Similarly, the depolarizing phase of the action potential is due mainly to the opening of voltage-gated Na^+ channels. Sodium ion entry depolarizes the cell and sustains the opening of more Na^+ channels in positive feedback fashion.

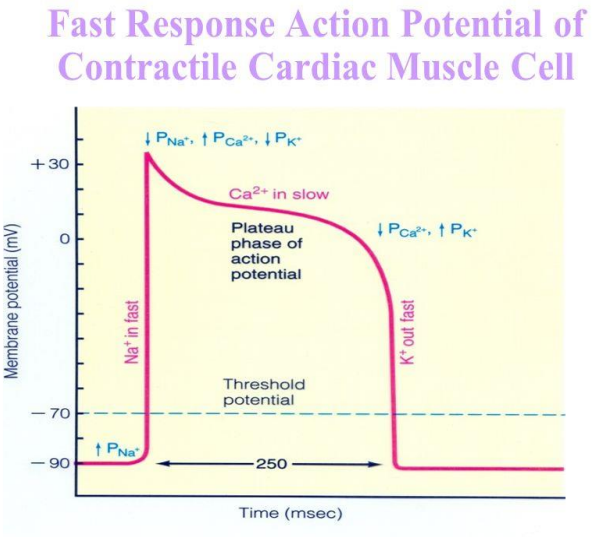
Also, as in skeletal muscle cells and neurons, the increased Na^+ permeability is very transient because the Na^+ channels inactivate quickly. However, unlike other excitable tissues, the reduction in Na^+ permeability in cardiac muscle is not accompanied by immediate repolarization of the membrane to resting levels. Rather, there is a partial repolarization caused by a special class of transiently open K^+ channels, and then the membrane remains depolarized at a plateau of about 0 mV for a prolonged period. The reasons for this continued depolarization are

(1) K^+ permeability declines below the resting value due to the closure of

the K^+ channels that were open in the resting state, and

(2) A large increase in the cell membrane permeability to Ca^{++}occurs.)))





The action potentials of atrial muscle cells are similar in shape to those just described for ventricular cells, but the duration of their plateau phase is shorter.

In contrast, there are extremely important differences between action

potentials of cardiac muscle cells and those in nodal cells of the conducting system. The SA node cell does not have a steady resting potential but, instead, undergoes a slow depolarization. This gradual depolarization is known as a **pacemaker potential;** it brings the membrane potential to threshold, at which point an action potential occurs.

Three ion channel mechanismscontribute to the pacemaker potential. The **first** is a progressive reduction in K^+ permeability. **Second**, pacemaker cells have a unique set of channels, depolarizing, Na^+ current **The third** pacemaker channel is a type of Ca^{++} channel Although SA node and AV node action potentials are basically similar in shape, the pacemaker currents of SA node cells bring them to threshold more rapidly than AV node cells, which is why SA node cells normally initiate action potentials and determine the pace of the heart.

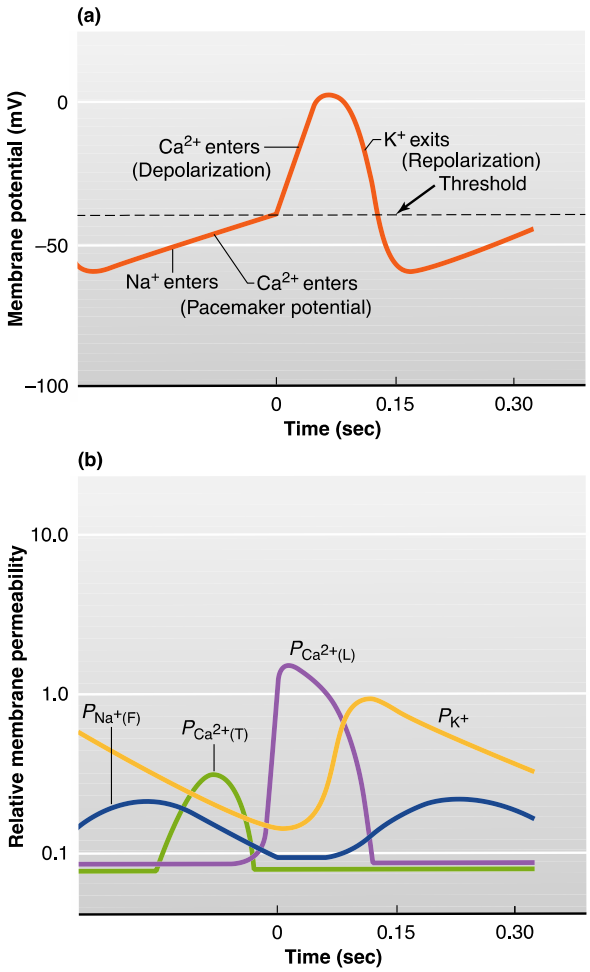


Figure 2:*(a) Membrane potential recording from a cardiac nodal cell. Labels indicate key ionic movements in each phase. A gradual reduction in K^+ permeability also contributes to the pacemaker potential (not shown), and the Na^+ entry in this phase is through nonspecific cation channels.*

(b) Simultaneously measured permeabilities through four different ion channels during the action potential shown in (a).

Automatic Electrical Rhythmicity of the Sinus Fibers:

Some cardiac fibers have the capability of *self-excitation*, a process that can cause automatic rhythmical discharge and contraction. This is especially true of the fibers of the heart's specialized conducting system, including the fibers of the sinus node. For this reason, the sinus node ordinarily controls the rate of beat of the entire heart. Thus, the pacemaker potential provides the SA node with **automaticity,** the capacity for spontaneous, rhythmic self-excitation. The inherent rate of the SA node—the rate exhibited in the total absence of any neural or hormonal input to the node—is approximately 100 depolarization's per minute.

Because other cells of the conducting system have slower inherent pacemaker rates, they normally are driven to threshold by action potentials from the SA node and do not manifest their own rhythm. However, they can do so under certain circumstances and are then called ***ectopic pacemakers.***

Atrioventricular Node:

The atrial conductive system is organized so that the cardiac impulse does not travel from the atria into the ventricles too rapidly; this delay allows time for the atria to empty their blood into the ventricles before ventricular contraction begins. It is primarily the AV node and its adjacent conductive fibers that delay this transmission into the ventricles.

The AV node is located in the posterior wall of the right atrium immediately behind the tricuspid valve. Note that the impulse, after traveling through the internodal pathways, reaches the AV node about 0.03 second after its origin in the sinus node. Then there is a delay of another 0.09 second in the AV node itself before the impulse enters the penetrating portion of the AV bundle, where it passes into the ventricles. A final delay of another 0.04 second occurs mainly in this penetrating AV bundle, which is composed of multiple small fascicles passing through the fibrous tissue separating the atria from the ventricles.

Thus, the total delay in the AV nodal and AV bundle system is about 0.13 second. This, in addition to the initial conduction delay of 0.03 second from the sinus node to the AV node, makes a total delay of 0.16 second before the excitatory signal finally reaches the contracting muscle of the ventricles.

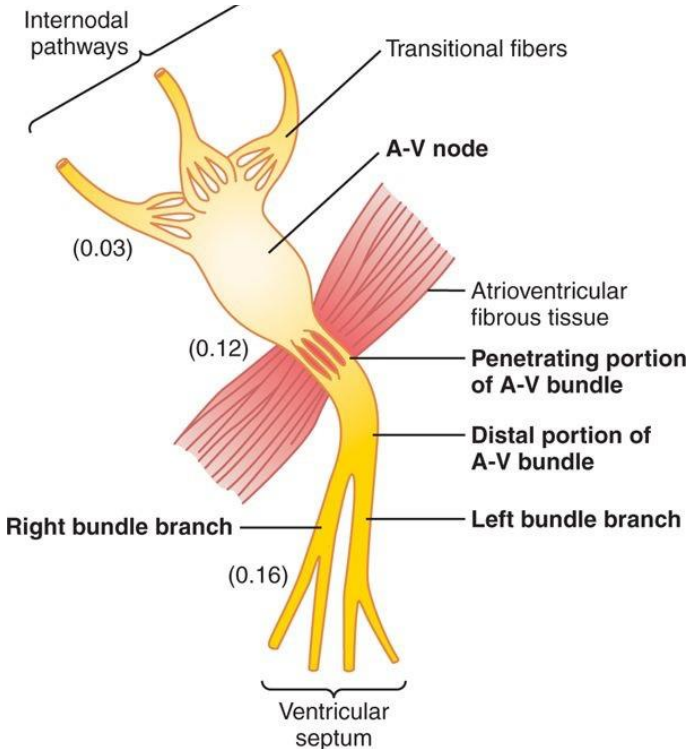
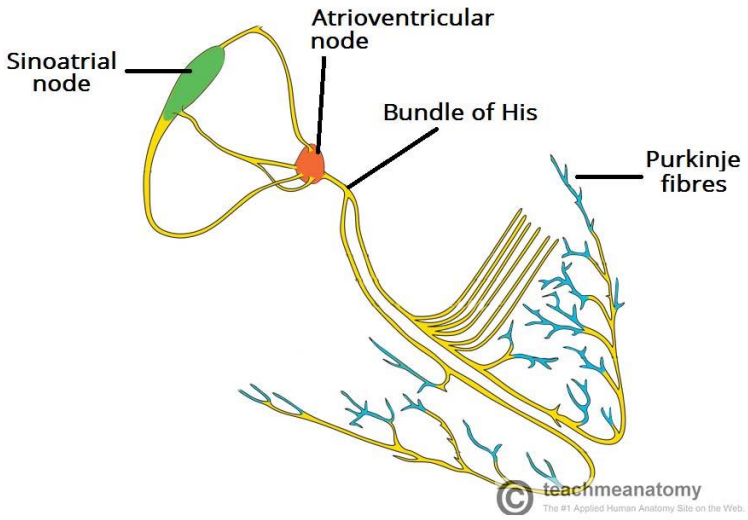


Figure 3:*Organization of the AV node. The numbers represent the interval of time from the origin of the impulse in the sinus node. The values have been extrapolated to human beings.*

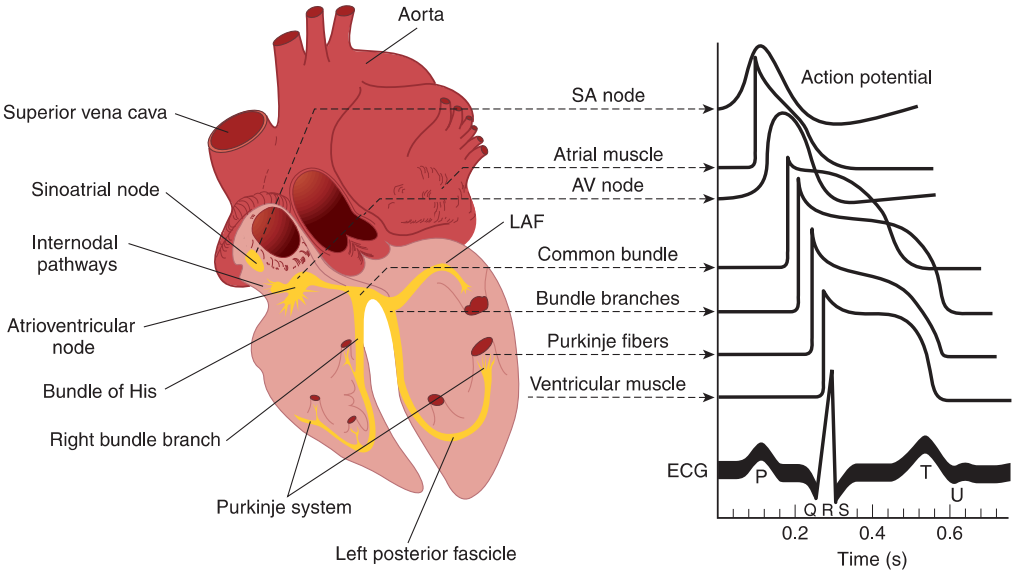
The slow conduction in the transitional, nodal, and penetrating AV bundle fibers is caused mainly by diminished numbers of gap junctions between successive cells in the conducting pathways, so there is great resistance to conduction of excitatory ions from one conducting fiber to the next. Therefore, it is easy to see why each succeeding cell is slow to be excited.

Purkinje fibers are very large fibers, even larger than the normal ventricular muscle fibers, and they transmit action potentials at a velocity of 1.5 to 4.0 m/sec.



Tissue	Conduction Rate (m/s)
SA node	0.05
Atrial pathways	1
AV node	0.05
Bundle of His	1
Purkinje system	4
Ventricular muscle	1

Table 1:*Conduction speeds in cardiac tissue.*



Why then does the sinus node rather than the AV node or the Purkinje fibers control the heart's rhythmicity? The answer derives from the fact that the discharge rate of the sinus node is considerably faster than the natural self-excitatory discharge rate of either the AV node or the Purkinje fibers

Thus, the sinus node controls the beat of the heart because its rate of rhythmical discharge is faster than that of any other part of the heart. Therefore, the sinus node is virtually always the pacemaker of the normal heart.

Abnormal Pacemakers-"Ectopic" Pacemaker

Occasionally some other part of the heart develops a rhythmical discharge rate that is more rapid than that of the sinus node. For instance, this sometimes occurs in the AV node or in the Purkinje fibers when one of these becomes abnormal. In either case, the pacemaker of the heart shifts from the sinus node to the AV node or to the excited Purkinje fibers. Under rarer conditions, a place in the atrial or ventricular muscle develops excessive excitability and becomes the pacemaker.

A pacemaker elsewhere than the sinus node is called an "*ectopic*" *pacemaker*. An ectopic pacemaker causes an abnormal sequence of contraction of the different parts of the heart and can cause significant debility of heart pumping.

Another cause of shift of the pacemaker is blockage of transmission of the cardiac impulse from the sinus node to the other parts of the heart. The new pacemaker then occurs most frequently at the AV node.

When AV block occurs-that is, when the cardiac impulse fails to pass from the atria into the ventricles through the AV nodal and bundle system-the atria continue to beat at the normal rate of rhythm of the sinus node, while a new pacemaker usually develops in the Purkinje system of the ventricles and drives the ventricular muscle at a new rate somewhere between 15 and 40 beats per minute.

Control of Heart Rhythmicity and Impulse Conduction by the Cardiac Nerves: Sympathetic and Parasympathetic Nerves

The heart is supplied with both sympathetic and parasympathetic nerves. The parasympathetic nerves are distributed mainly to the SA and AV nodes, to a lesser extent to the muscle of the two atria, and very little directly to the ventricular muscle. The sympathetic nerves, conversely, are distributed to all parts of the heart, with strong representation to the ventricular muscle, as well as to all the other areas.

Parasympathetic (Vagal) Stimulation Can Slow or Even Block Cardiac Rhythm and Conduction- "Ventricular Escape."

Stimulation of the parasympathetic nerves to the heart (the vagi) causes the hormone *acetylcholine* to be released at the vagal endings. This hormone has two major effects on the heart. First, it decreases the rate of rhythm of the sinus node, and second, it decreases the excitability of the AV junctional fibers between the atrial musculature and the AV node, thereby slowing transmission of the cardiac impulse into the ventricles.

Weak to moderate vagal stimulation slows the rate of heart pumping, often to as little as one-half normal. And strong stimulation of the vagi can stop

completely the rhythmical excitation by the sinus node or block completely transmission of the cardiac impulse from the atria into the ventricles through the AV mode. In either case, rhythmical excitatory signals are no longer transmitted into the ventricles, but then some small area in the Purkinje fibers, usually in the ventricular septal portion of the AV bundle, develops a rhythm of its own and causes ventricular contraction at a rate of 15 to 40 beats per minute. This phenomenon is called *ventricular escape.*

Mechanism of the Vagal Effects

The acetylcholine released at the vagal nerve endings greatly increases the permeability of the fiber membranes to potassium ions, which allows rapid leakage of potassium out of the conductive fibers. This causes increased negativity inside the fibers, an effect called *hyperpolarization*, which makes this excitable tissue much less excitable.

In the sinus node, the state of hyperpolarization decreases the "resting" membrane potential of the sinus nodal fibers to a level considerably more negative than usual, to -65 to -75 millivolts rather than the normal level of -55 to -60 millivolts. Therefore, the initial rise of the sinus nodal membrane potential caused by inward sodium and calcium leakage requires much longer reaching the threshold potential for excitation. This greatly slows the rate of rhythmicity of these nodal fibers. If the vagal stimulation is strong enough, it is possible to stop entirely the rhythmical self-excitation of this node.

Effect of Sympathetic Stimulation on Cardiac Rhythm and Conduction

Sympathetic stimulation causes essentially the opposite effects on the heart

to those caused by vagal stimulation, as follows: First, it increases the rate of sinus nodal discharge. Second, it increases the rate of conduction, as well as the level of excitability in all portions of the heart. Third, it increases greatly the force of contraction of all the cardiac musculature, both atrial and ventricular.

Mechanism of the Sympathetic Effect

Stimulation of the sympathetic nerves releases the hormone *norepinephrine* at the sympathetic nerve endings. Norepinephrine in turn stimulates *beta-1 adrenergic receptors*, which mediate the effects on heart rate. The precise mechanism by which beta-1 adrenergic stimulation acts on cardiac muscle fibers is somewhat unclear, but the belief is that it increases the permeability of the fiber membrane to sodium and calcium ions. In the sinus node, an increase of sodium-calcium permeability causes a more positive resting potential.

The increase in permeability to calcium ions is at least partially responsible for the increase in contractile strength of the cardiac muscle under the influence of sympathetic stimulation, because calcium ions play a powerful role in exciting the contractile process of the myofibrils.