

**Cardiovascular Lab Supplemental Resource**

- Basic Design of the Cardiovascular System
  - A. Systemic circulation– to/from all organs of the body except lung alveoli
  - B. Pulmonary circulation– to/from lung alveoli
- Organization of the Heart
  - A. Heart
    - 1. Hollow organ about the size of a fist
    - 2. Located in thoracic cavity
    - 3. Lies mostly to the left
  - B. Pericardium
    - 1. Protects and anchors the heart
  - C. Heart – chambers
    - 1. Four chambers total that create two pumps
    - 2. Can be dividing into right and left
      - a. 2 atria
      - b. 2 ventricles
    - 3. Right side of the heart
      - a. Serves pulmonary circuit (blood leaves through the pulmonary trunk)
    - 4. Left side of the heart
      - a. Serves systemic circuit (blood leaves through aorta)
    - 5. Top two chambers
      - a. Atria
      - b. Great vessels
        - 1) Right (blood enters the heart through these veins)
          - i. Superior vena cava
          - ii. Inferior vena cava
        - 2) Left (blood enters the heart through these veins)
          - i. Pulmonary veins
    - 6. Bottom two chambers
      - a. Ventricles
      - b. Great vessels

1) Right (blood leaves the heart through this artery)

i. Pulmonary trunk

2) Left (blood leaves the heart through this artery)

i. Aorta

7. Heart – valves

a. Ensure one way flow of blood

1) Right

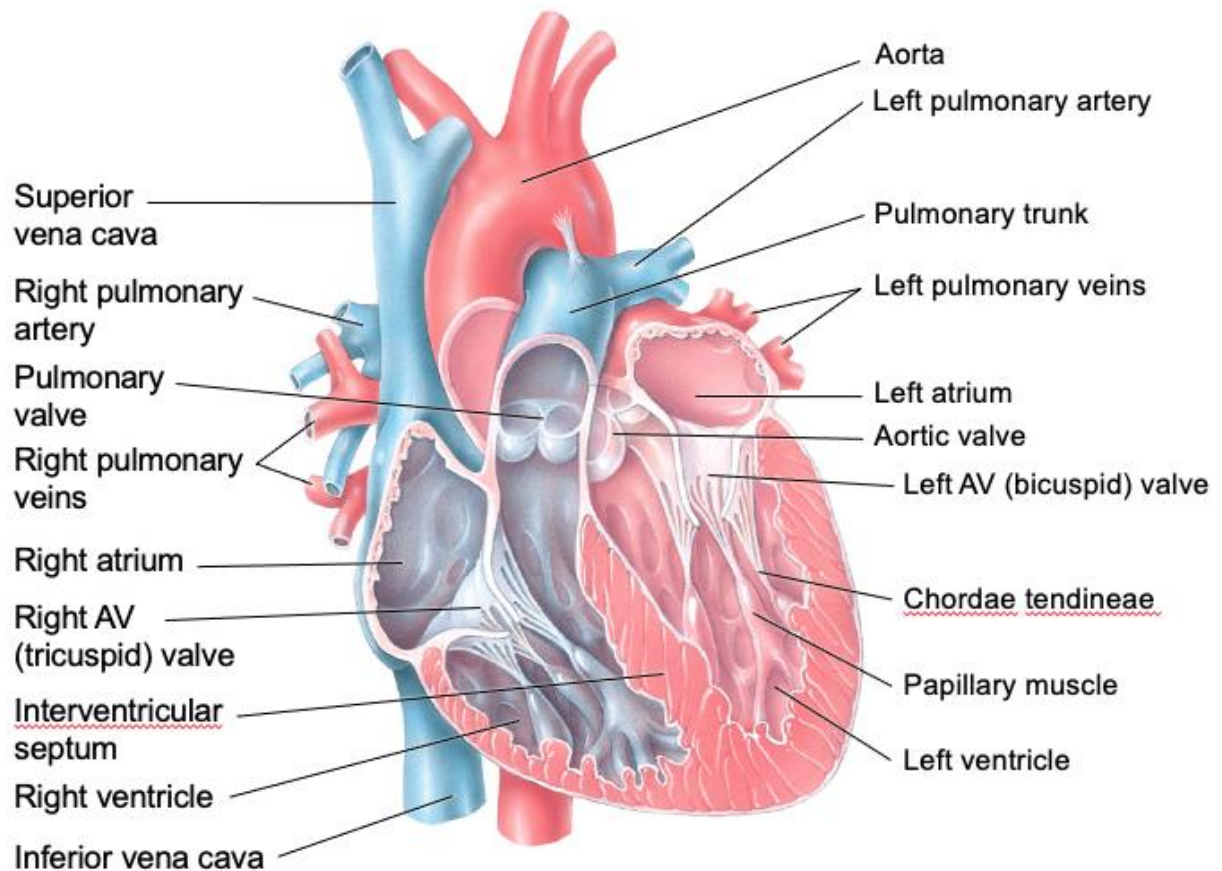
i. Right atrioventricular valve or Tricuspid

ii. Pulmonary semilunar valve

2) Left

i. Left atrioventricular valve or Bicuspid or mitral

ii. Aortic semilunar valve



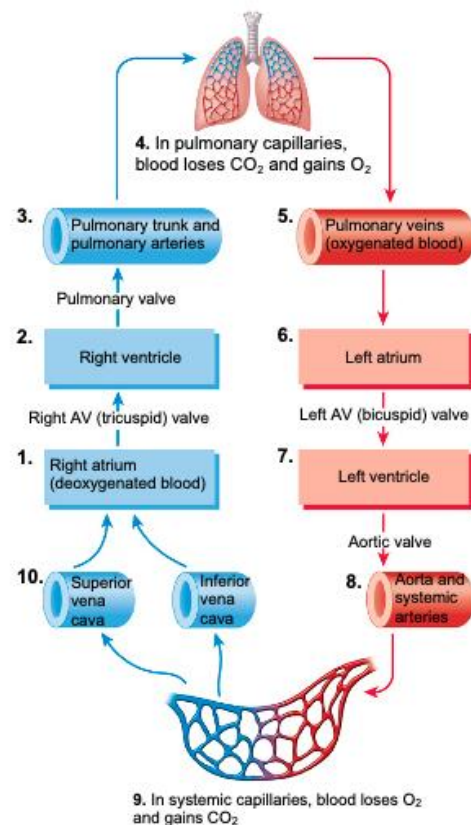
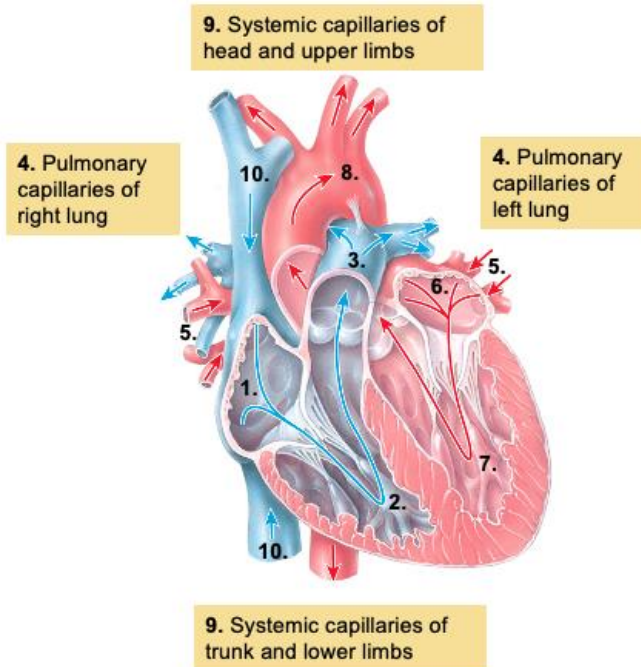
(b) Frontal section of heart

### D. Blood flow through the heart

8. Blood comes from systemic circuit into the right atrium from the superior and inferior vena cava
9. From the right atrium blood flows through the tricuspid valve to the right ventricle
10. The right ventricle will pump blood through the pulmonary semilunar valve into the pulmonary trunk
11. Blood goes to the lungs to get oxygenated
12. Blood comes back to the heart via the pulmonary veins
13. Pulmonary veins deliver blood into the left atrium
14. From the left atrium blood travels through the bicuspid valve into the left ventricle
15. Left ventricle pumps blood out of the aortic semilunar valve and into the aorta
16. Aorta helps distribute blood of the systemic organs of the body

#### Key:

- Oxygenated blood
- Deoxygenated blood



- Cardiac Muscle Tissue and the Cardiac Conduction System

A. Cardiac muscle tissue – structure

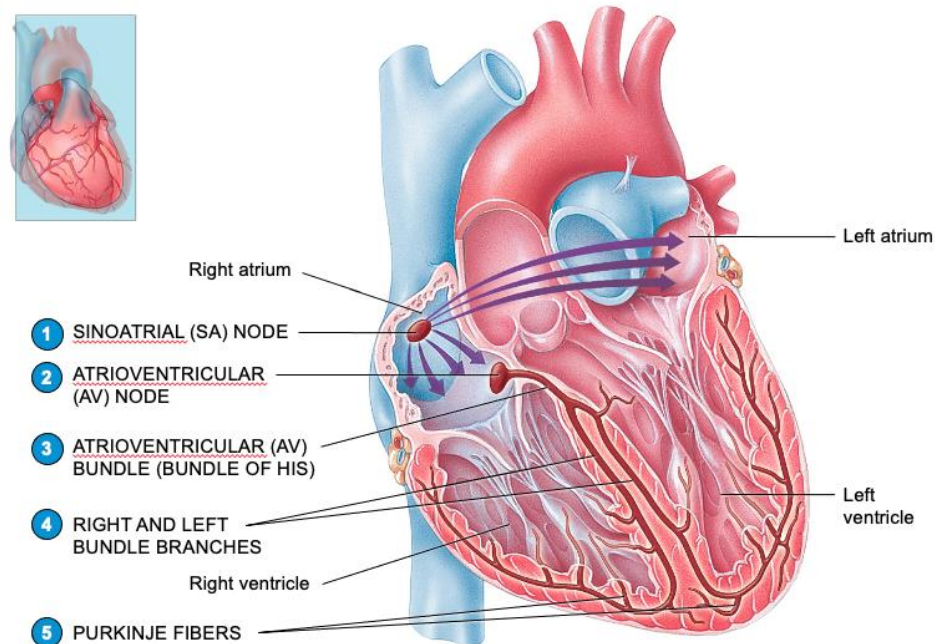
1. Interconnected cells act as a functional syncytium
2. Gap channels allow cardiac cells depolarize and contract at the same time

B. Heart muscle shares properties with both skeletal and smooth muscle

C. Conduction system

Cardiac muscle does not require any external stimulation to contract. Contractions occur because action potentials within cardiac muscle itself are spontaneously generated on a periodic basis. This built-in rhythm is termed autorhythmicity. Cardiac muscle, as a functional syncytium, consists of two types of muscle fibers: autorhythmic fibers and contractile fibers. Autorhythmic fibers, also known as pacemaker cells, spontaneously generate action potentials. They account for only a very small number of cells in the functional syncytium and are usually grouped together. Because autorhythmic fibers contain essentially no myofibrils, they are unable to contract. Contractile fibers constitute the great majority of cells in the functional syncytium. They have the necessary myofibrils to contract but do not have the ability to initiate action potentials. Instead, they become excited and then contract together in response to action potentials conducted to them from autorhythmic fibers via gap junctions.

1. Collection of modified muscle cells (nodal/pacemaker)
2. Initiate and conduct action potentials to other cells
3. Do not contribute significantly to contractile forces
4. Starts at the superior wall of the right atrium
5. Continues through the apex of the heart and myocardium of the ventricles
6. Structures include:
  - a. Sinoatrial (SA) node
  - b. Atrioventricular (AV) node
  - c. Atrioventricular (AV) bundle (Bundle of HIS)
  - d. Right and left bundle branches
  - e. Purkinje fibers



**D. Contractile cells – constitute the great majority of cells in the functional syncytium**

1. Produce forces, but do not spontaneously depolarize
2. Produce action potentials in response to signals from the nodal cells
3. Excitation contraction coupling – has similarity to both skeletal and smooth muscle
4. Cardiac muscle has a long refractory period

**E. The autorhythmic fibers of the heart have two important functions:**

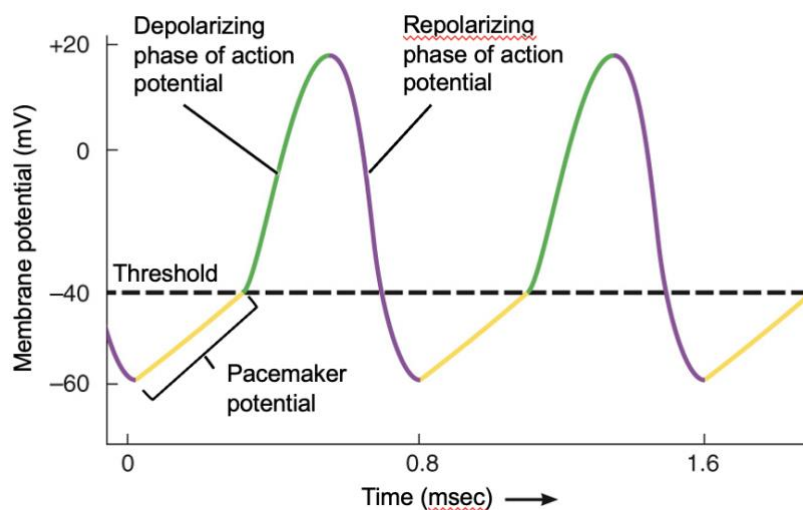
1. They act as a pacemaker, setting the rhythm of electrical excitation that causes contraction of the heart.
2. They form the conduction system, the pathway that rapidly delivers action potentials throughout the heart muscle. Action potentials are able to be conducted throughout the heart by the conduction system because gap junctions connect the components of the conduction system to each other and to the contractile fibers of the heart. The conduction system ensures that cardiac chambers become stimulated to contract in a coordinated manner, which makes the heart an effective pump. As you will see later in the chapter, problems with the conduction system can result in arrhythmias (abnormal rhythms) in which the heart beats irregularly, too fast, or too slowly.

Cardiac action potentials propagate through the conduction system in the following sequence:

- I. Cardiac excitation normally begins in the SA node, when SA node cells spontaneously depolarize to threshold by producing a pacemaker potential (described shortly). Once threshold is reached, an action potential is generated and then propagates throughout both atria. Following the action potential, the atria contract.
- II. The action potential propagates from the atria to the atrioventricular (AV) node.
- III. From the AV node, the action potential enters the AV bundle (bundle of His). This bundle is the only site where action potentials can conduct from the atria to the ventricles. Recall that elsewhere the fibrous skeleton of the heart electrically insulates the atria from the ventricles.
- IV. After propagating along the AV bundle, the action potential enters both the right and left bundle branches.
- V. From the bundle branches, the action potential propagates to the Purkinje fibers, which in turn conduct the action potential beginning at the apex of the heart to the remainder of the ventricular myocardium. Then the ventricles contract, pushing the blood upward toward the semilunar valves.

Autorhythmic fibers can initiate their own action potentials because they have unstable resting membrane potentials. The membrane potential starts at about  $-60$  mV and then spontaneously depolarizes to threshold ( $-40$  mV), at which point an action potential is generated. After repolarization, the membrane potential again starts to depolarize and the cycle repeats. The spontaneous depolarization to threshold that occurs in an autorhythmic fiber of cardiac muscle is known as a pacemaker potential. The first half of the pacemaker potential is caused by (1) the closure of voltage-gated  $K^+$  channels that were open during the repolarizing phase of the previous action potential and (2) the opening of F-type channels (so-named because they have funny or unusual properties), which are mainly permeable to  $Na^+$  ions. Closure of the voltage-gated  $K^+$  channels decreases movement of  $K^+$  out of the cell ( $K^+$  has a higher concentration in the sarcoplasm than in extracellular fluid); opening of the F-type

channels increases movement of  $\text{Na}^+$  from extracellular fluid (which has a higher  $\text{Na}^+$  concentration) into the sarcoplasm. The combined effects of these channel activities cause the membrane potential to start drifting slowly above  $-60$  mV. Before the membrane potential reaches threshold, however, the F-type channels close and a new set of channels open: T-type voltage-gated  $\text{Ca}^{2+}$  channels (T for transient because they remain open for only a relatively short period of time). Opening of the T-type voltage-gated  $\text{Ca}^{2+}$  channels causes the second half of the pacemaker potential. When these channels open,  $\text{Ca}^{2+}$  enters the cell because the  $\text{Ca}^{2+}$  concentration is higher in extracellular fluid than in the sarcoplasm. The influx of  $\text{Ca}^{2+}$  depolarizes the membrane even further, eventually bringing it to threshold. Once threshold is reached, an action potential occurs.



Membrane channels involved	
<span style="display: inline-block; width: 15px; height: 15px; background-color: yellow; border: 1px solid black;"></span>	Pacemaker potential: During first half of pacemaker potential, voltage-gated $\text{K}^+$ channels close and F-type $\text{Na}^+$ channels open; during second half of pacemaker potential, T-type voltage-gated $\text{Ca}^{2+}$ channels open
<span style="display: inline-block; width: 15px; height: 15px; background-color: green; border: 1px solid black;"></span>	Depolarizing phase: L-type voltage-gated $\text{Ca}^{2+}$ channels open
<span style="display: inline-block; width: 15px; height: 15px; background-color: purple; border: 1px solid black;"></span>	Repolarizing phase: L-type voltage-gated $\text{Ca}^{2+}$ channels close; voltage-gated $\text{K}^+$ channels open

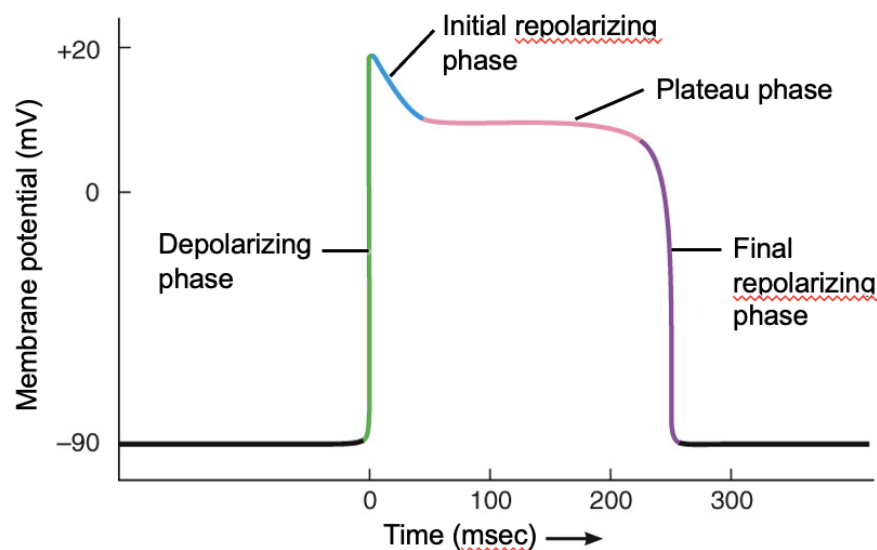
Pacemaker potentials and action potentials in an autorhythmic cardiac fiber.

In an autorhythmic cardiac muscle fiber, an action potential consists of a depolarizing phase and a repolarizing phase. The depolarizing phase of the action potential is caused by the opening of L-type voltage-gated  $\text{Ca}^{2+}$  channels (L for long-lasting because they open for a relatively long period of time). When these channels open, additional  $\text{Ca}^{2+}$  enters the cell, and the membrane potential rises above threshold to a positive value. (Recall that in neurons and skeletal muscle fibers, the depolarizing phase of the action potential is due to the influx of  $\text{Na}^{+}$  through voltage-gated  $\text{Na}^{+}$  channels.) The repolarizing phase of the action potential in an autorhythmic cardiac muscle fiber is caused by (1) the closure of L-type voltage-gated  $\text{Ca}^{2+}$  channels and (2) the opening of voltage-gated  $\text{K}^{+}$  channels. Opening the voltage-gated  $\text{K}^{+}$  channels allows  $\text{K}^{+}$  ions to leave the cell, which decreases the membrane potential back to around  $-60 \text{ mV}$ . Once an action potential is generated in an autorhythmic fiber, it spreads to the contractile fibers of cardiac muscle via gap junctions.

On their own, autorhythmic fibers in the SA node would initiate an action potential about every 0.6 second, or 100 times per minute. This rate is faster than that of any other autorhythmic fibers. Because action potentials from the SA node spread through the conduction system and stimulate other areas before the other areas can generate an action potential at their own, slower rate, the SA node acts as the natural pacemaker of the heart. Action potentials from the autonomic nervous system (ANS) and blood-borne hormones (such as epinephrine) modify the timing and strength of each heartbeat, but they do not establish the fundamental rhythm. In a person at rest, for example, acetylcholine released by the parasympathetic division of the ANS slows SA node pacing to about every 0.8 second or 75 action potentials per minute. Hence, the resting heart rate is about 75 beats per minute. If the SA node becomes damaged or diseased, the AV node can pick up the pacemaking task. With pacing by the AV node, however, heart rate is slower, only 40 to 60 beats per minute. If activity of both nodes is suppressed, the heartbeat may still be maintained by the AV bundle, a bundle branch, or Purkinje fibers. These fibers generate action potentials very slowly, about 20 to 35 times per minute. At such a low heart rate, blood flow to the brain is inadequate.



Unlike autorhythmic fibers, contractile cardiac muscle fibers have a stable resting membrane potential of about  $-90$  mV. This value is a result of the fact that resting contractile fibers are highly permeable to  $K^+$  ions and not very permeable to other ions. So the resting membrane potential stabilizes around the  $K^+$  equilibrium potential of  $-90$  mV. When a contractile cardiac muscle fiber is depolarized to threshold by an action potential initiated by an autorhythmic fiber, it produces its own action potential. The action potentials that occur in contractile cardiac muscle fibers consist of four phases: a depolarizing phase, initial repolarizing phase, plateau phase, and final repolarizing phase.



#### Membrane channels involved

- Depolarizing phase: Fast voltage-gated  $Na^+$  channels open
- Initial repolarizing phase: Fast voltage-gated  $Na^+$  channels close and fast voltage-gated  $K^+$  channels open
- Plateau phase: L-type voltage-gated  $Ca^{2+}$  channels open, fast voltage-gated  $K^+$  channels close, and slow voltage-gated  $K^+$  channels partially open
- Final repolarizing phase: L-type voltage-gated  $Ca^{2+}$  channels close and slow voltage-gated  $K^+$  channels fully open

An action potential in a contractile cardiac muscle fiber.

**Depolarizing Phase**

During the depolarizing phase, fast voltage-gated  $\text{Na}^+$  channels open. These channels are referred to as fast because they open very rapidly in response to a threshold-level depolarization. Opening of these channels increases the membrane permeability to  $\text{Na}^+$  ions, allowing  $\text{Na}^+$  to flow into the cell. This produces a rapid depolarization that increases the membrane potential to about +20 mV.

**Initial Repolarizing Phase**

Within a few milliseconds, the fast  $\text{Na}^+$  channels automatically inactivate, reducing the membrane permeability to  $\text{Na}^+$ . As a result,  $\text{Na}^+$  inflow decreases. Of the several different types of voltage-gated  $\text{K}^+$  channels present in a contractile cardiac muscle fiber, a subset known as fast voltage-gated  $\text{K}^+$  channels\* opens at this time, allowing  $\text{K}^+$  ions to leave the cell. The closure of fast voltage-gated  $\text{Na}^+$  channels and the opening of fast voltage-gated  $\text{K}^+$  channels cause the initial repolarizing phase of the action potential. During this phase, the membrane potential begins to decrease.

**Plateau Phase**

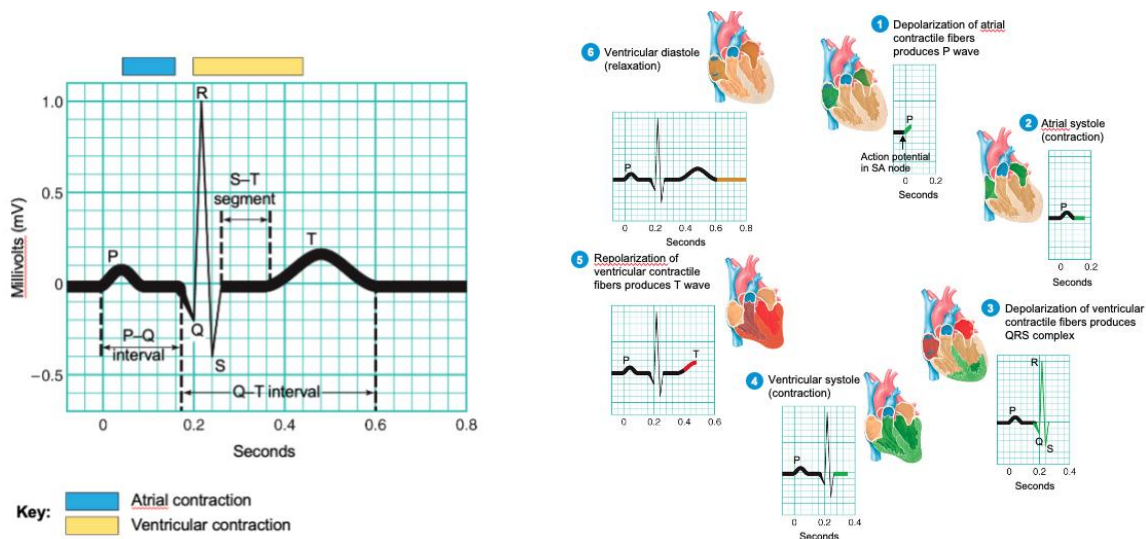
The next phase of the action potential is the plateau, a period of sustained depolarization. It is due in part to the opening of L-type voltage-gated  $\text{Ca}^{2+}$  channels. When these channels open, calcium ions move from extracellular fluid into the cell. While this is occurring, fast voltage-gated  $\text{K}^+$  channels close and slow voltage-gated  $\text{K}^+$  channels begin to open. The slow voltage-gated  $\text{K}^+$  channels† are so-named because they are activated when the membrane initially depolarizes but are slow to open. They are the same type of voltage-gated  $\text{K}^+$  channels found in neurons and skeletal muscle fibers. Because the fast voltage-gated  $\text{K}^+$  channels are completely closed and the slow voltage-gated  $\text{K}^+$  channels are only partially open, the membrane permeability to  $\text{K}^+$  is relatively low at this time. However, there is just enough efflux of  $\text{K}^+$  through the slow voltage-gated  $\text{K}^+$  channels to balance the  $\text{Ca}^{2+}$  influx through the L-type voltage-gated  $\text{Ca}^{2+}$  channels, causing the action potential curve to flatten out like a plateau. The plateau phase lasts for about 0.2 sec, and the membrane potential of the contractile fiber is close to 0 mV. By comparison, depolarization in a neuron or skeletal muscle fiber is much briefer, about 1 msec, because it lacks a plateau phase.

**Final Repolarizing Phase**

During the final repolarizing phase of the action potential, the slow voltage-gated  $\text{K}^+$  channels fully open. This increases the membrane permeability to  $\text{K}^+$ , accelerating  $\text{K}^+$  outflow. At the same time, the L-type voltage-gated  $\text{Ca}^{2+}$  channels close. This decreases the membrane permeability to  $\text{Ca}^{2+}$ , reducing  $\text{Ca}^{2+}$  inflow. The increase in  $\text{K}^+$  outflow and decrease in  $\text{Ca}^{2+}$  inflow rapidly restore the membrane potential to -90 mV. Once the membrane potential reaches the resting level, the slow voltage-gated  $\text{K}^+$  channels close.

D. Electrocardiogram – As action potentials propagate through the heart, they generate electrical currents that can be detected at the surface of the body. An electrocardiogram, abbreviated either ECG or EKG (from the German word elektrokardiogram), is a recording of these electrical signals. The ECG is a composite record of action potentials produced by all of the heart muscle fibers during each heartbeat.

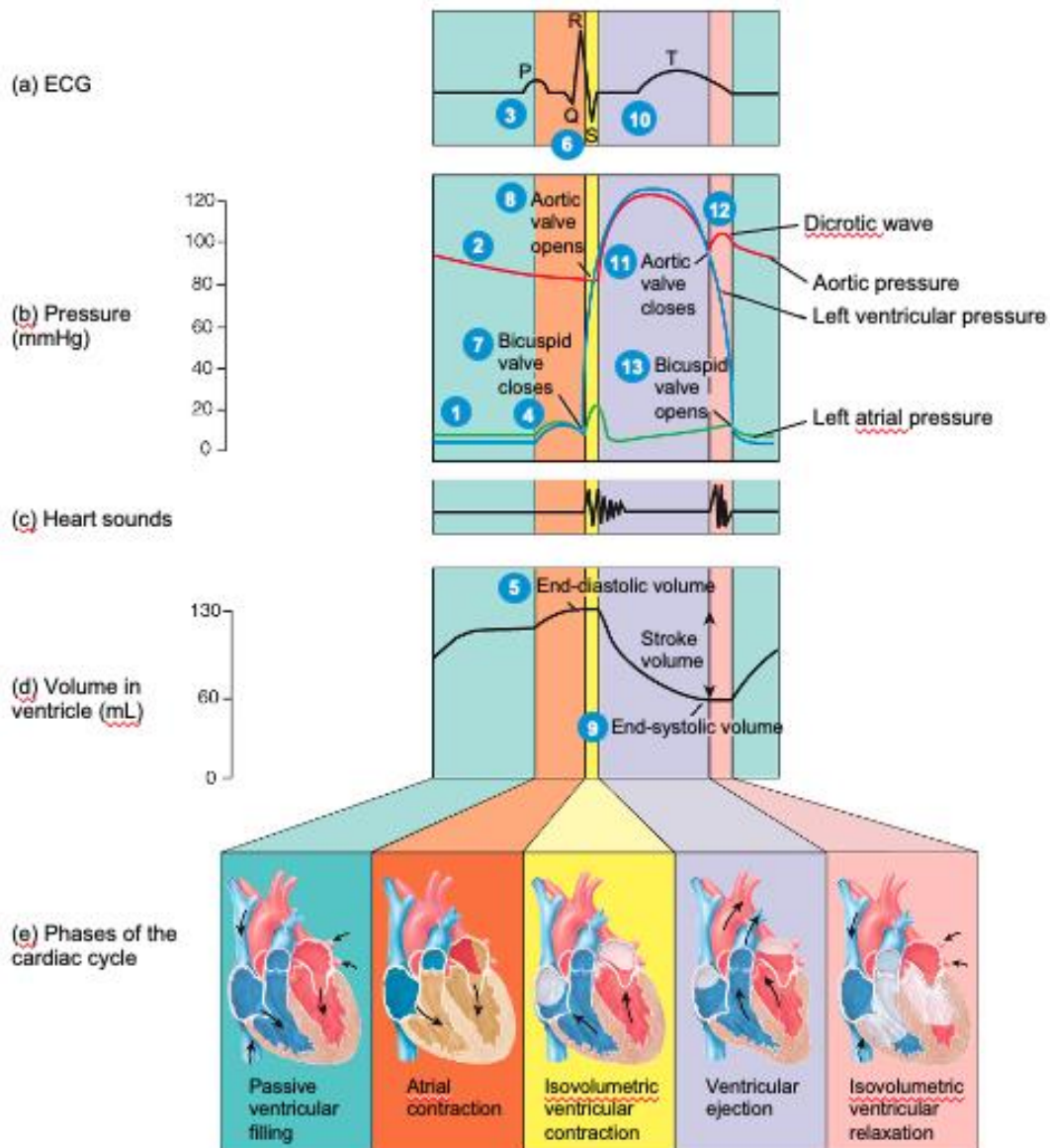
1. Records electrical signals of the heart
2. Consists of waves, intervals and segments
3. Can be read to provide clues for abnormalities
4. Composed of:
  - a. P wave
    - 1) Represents depolarization of the atria
  - b. P-R interval
    - 1) Represents the AV node delay
  - c. QRS complex
    - 1) Represents ventricular depolarization
  - d. S-T segment
    - 1) Depolarized state of the ventricular muscle
  - e. T wave
    - 1) Represents ventricular repolarization



- The Cardiac Cycle

- A. Has 5 phases

1. Passive ventricular filling
2. Atrial contraction
3. Isovolumetric ventricular contraction
4. Ventricular ejection
5. Isovolumetric ventricular relaxation



- I. **Passive Ventricular Filling** – Our discussion of the cardiac cycle begins during the period when both the atria and ventricles are in diastole. Atrial pressure is higher than ventricular pressure (step 1) because the atria are filling with blood returning to the heart by veins. As a result of the pressure difference, the atrioventricular (AV) valves open, and blood flows from the atria into the ventricles. This phase of the cardiac cycle is known as passive ventricular filling. The term passive is used because no muscle contractions are involved. About 80% of ventricular filling occurs during this phase; the remaining 20% of ventricular filling occurs during atrial contraction. It is worth mentioning that the semilunar (SL) valves are closed at this time because aortic pressure is higher than left ventricular pressure (step 2) and pulmonary trunk pressure is higher than right ventricular pressure. At the end of atrial diastole, an action potential arises in the SA node and then propagates throughout the atria, causing the atria to depolarize. Atrial depolarization is indicated by the P wave on the ECG (step 3).
- II. **Atrial Contraction** – Atrial depolarization causes atrial systole. While the atria are in systole, the ventricles remain in diastole. As the atria contract, atrial pressure increases (step 4) and more blood is forced through the open AV valves into the ventricles. Atrial contraction contributes a final 25 mL of blood to the volume already in each ventricle (about 105 mL). The end of atrial systole is also the end of ventricular diastole (relaxation). Thus, each ventricle contains about 130 mL at the end of its relaxation period (diastole). This blood volume is called the end-diastolic volume (EDV) (step 5). Toward the end of atria systole, the QRS complex appears on the ECG, marking the onset of ventricular depolarization (step 6).
- III. **Isovolumetric Ventricular Contraction** – Ventricular depolarization causes ventricular systole. While the ventricles are in systole, the atria are in diastole. As ventricular systole begins, pressure rises inside the ventricles and pushes blood up against the AV valves, forcing them shut (step 7). For a brief moment, both the AV and SL valves are closed. This phase of the cardiac cycle is referred to as isovolumetric ventricular contraction (iso- = same). During this interval, cardiac muscle fibers are contracting and exerting force but are not yet shortening. Thus,

the muscle contraction is isometric (same length). Moreover, because all four valves are closed, ventricular volume remains the same (isovolumic).

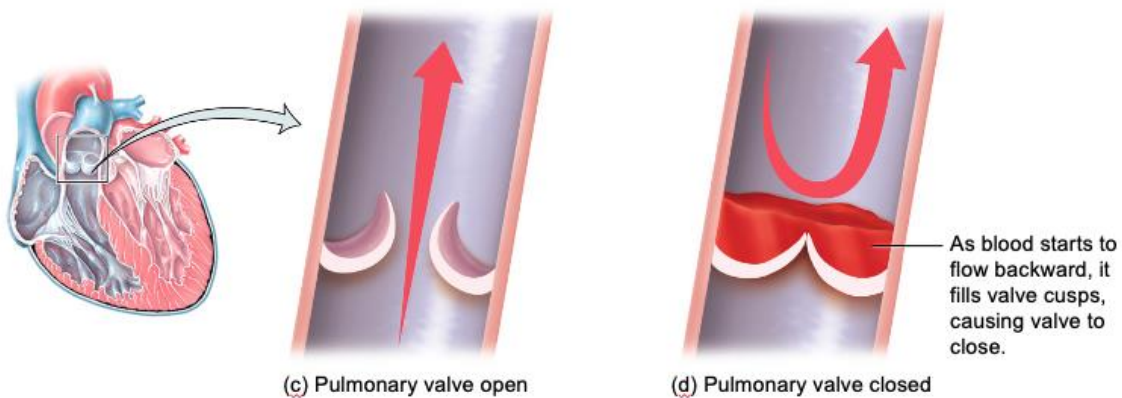
- IV. **Ventricular Ejection** – Continued contraction of the ventricles causes pressure inside the chambers to rise sharply. When left ventricular pressure surpasses aortic pressure at about 80 mmHg and right ventricular pressure rises above pulmonary trunk pressure (about 20 mmHg), both SL valves open (step 8). At this point, the ventricular ejection phase of the cardiac cycle begins. During this phase, blood is pumped out of the heart. The left ventricle ejects about 70 mL of blood into the aorta, and the right ventricle ejects the same volume of blood into the pulmonary trunk. The volume remaining in each ventricle at the end of systole, about 60 mL, is the end-systolic volume (ESV) (step 9). Stroke volume, the volume ejected per beat from each ventricle, equals end-diastolic volume minus end-systolic volume:  $SV = EDV - ESV$ . At rest, the stroke volume is about  $130\text{ mL} - 60\text{ mL} = 70\text{ mL}$  (a little more than 2 oz). The percentage of the end-diastolic volume that is ejected with each stroke volume is called the ejection fraction (EF):  $EF = SV/EDV \times 100$ . Under normal resting conditions, EF is about 54% ( $70\text{ mL}/130\text{ mL} \times 100$ ). Changes in stroke volume alter the ejection fraction. Near the end of ventricular systole, the T wave appears on the ECG, marking the onset of ventricular repolarization (step 10).
- V. **Isovolumetric Ventricular Relaxation** – Ventricular repolarization causes ventricular diastole. As the ventricles relax, pressure within the chambers falls, and blood in the aorta and pulmonary trunk begins to flow backward toward the regions of lower pressure in the ventricles. Backflowing blood catches in the valve cusps and closes the SL valves (step 11). Rebound of blood off the closed cusps of the aortic valve produces the dicrotic wave on the aortic pressure curve (step 12). After the SL valves close, there is a brief interval when ventricular blood volume does not change because all four valves are closed. This phase is known as isovolumetric ventricular relaxation. As the ventricles continue to relax, the pressure falls quickly. When ventricular pressure drops below atrial pressure, the AV valves open (step 13), and another cardiac cycle repeats as passive ventricular filling begins.

**A. Heart sounds****6. First sound (S1)**

- a. Lub
- b. Louder and a bit longer
- c. Caused by vibrations associated with the closure of the AV valves

**7. Second sound (S2)**

- a. Dupp
- b. shorter and not as loud
- c. Caused by vibrations associated with the closure of the AV valves

**• Cardiac Output**

A. The volume of blood ejected per minute

B. Autonomic regulation – heart rate

**1. Sympathetic effects**

- a. Release E and NE
  - 1) Increase force of contraction
  - 2) Increase heart rate

**2. Parasympathetic effects**

- a. Release Ach
  - 1) Decrease heart rate