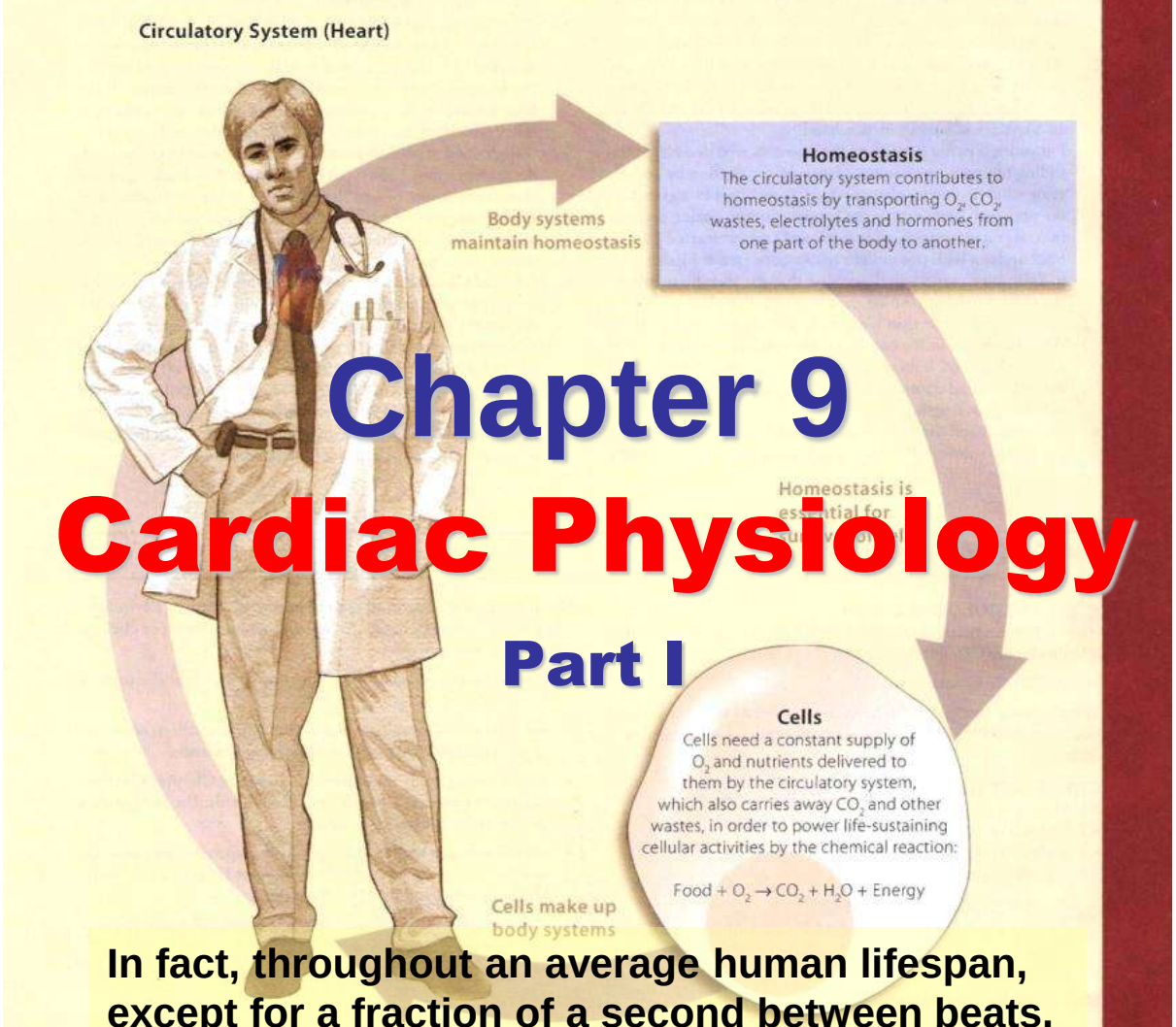



# Chapter 9
# Cardiac Physiology
## Part I

**In fact, throughout an average human lifespan, except for a fraction of a second between beats, which start to function within about three weeks after conception, and it is believed to be the first organ to become functional, because the circulatory system is the transport system of the body.**

# Introduction

- The circulatory system consists of three basic components:

1. **The heart:** serves as the pump that imparts تعطي /تمنح pressure to the blood. **(Ch. 9)**
2. **The blood vessels:** serves as the passage ways through which blood is directed and distributed. **(Ch. 10)**
3. **The blood:** serves as the transport medium within which materials being transported are dissolved or suspended. **(Ch 11)**

Travels to and from the heart through two separate vascular loops:

- **The pulmonary circulation.**
- **The systemic circulation.**

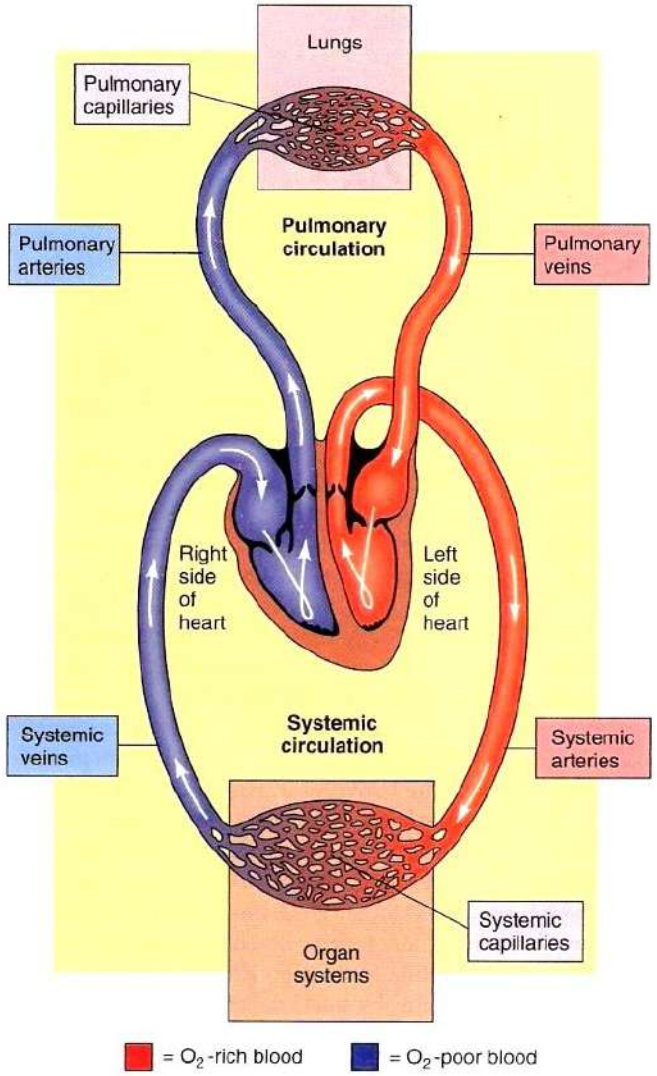



FIGURE 9-1

**Pulmonary and systemic circulation in relation to the heart**
The circulatory system consists of two separate vascular loops: the pulmonary circulation, which carries blood between the heart and lungs; and the systemic circulation, which carries blood between the heart and organ systems.

# Anatomy of the heart

- The midline location of the heart brings up a potentially confusing point.
- Where did you place your hand?
- the heart has a broad **base** at the top and tapers to a pointed tip known as the **apex** at the bottom.

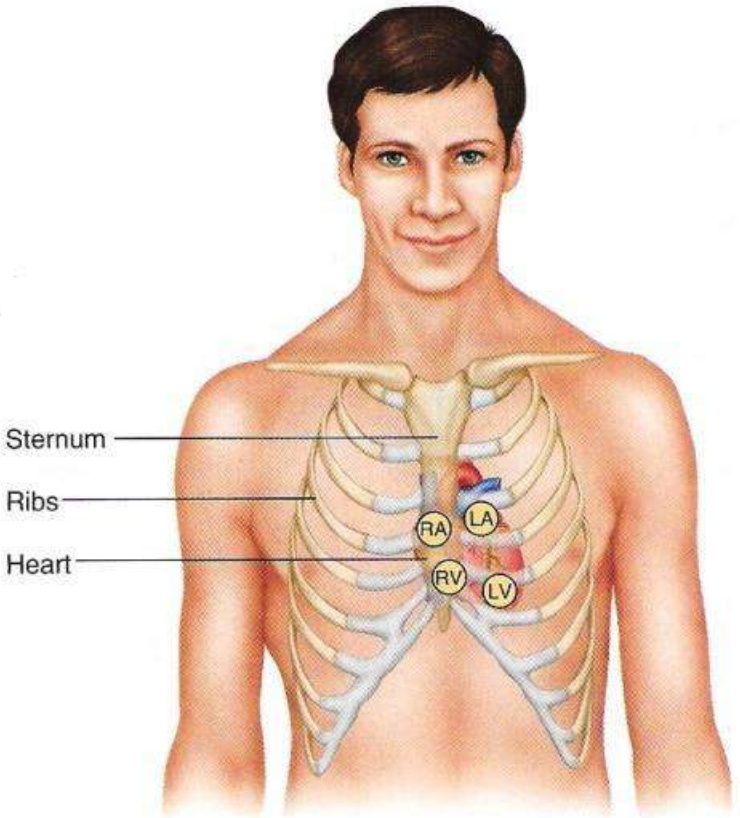
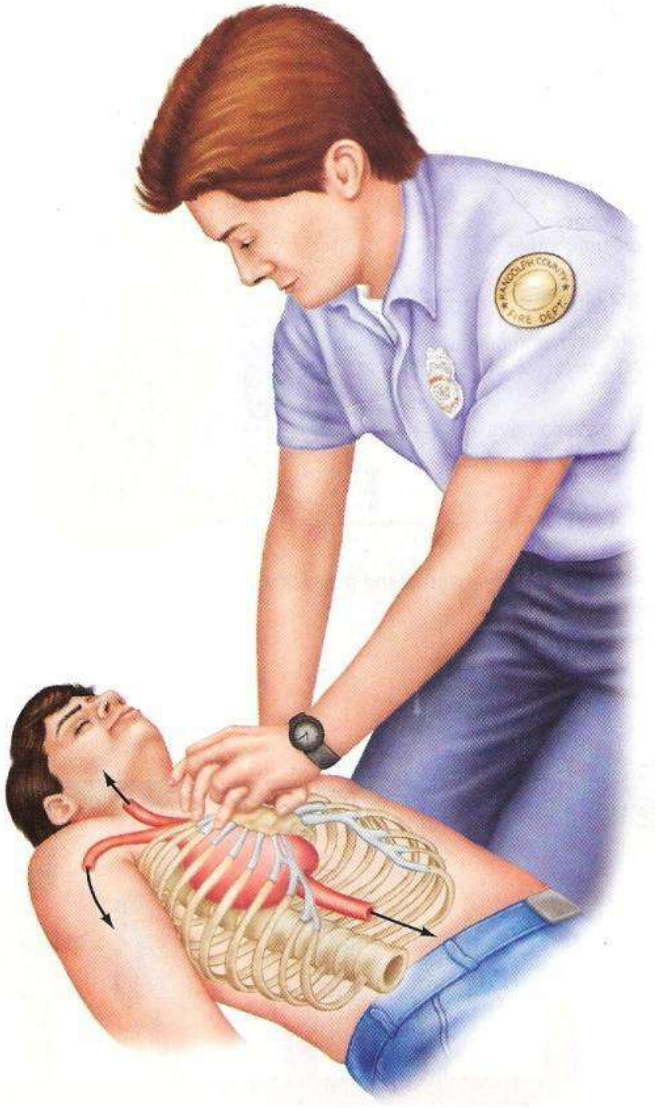



FIGURE 9-2

**Location and external compression of the heart within the thoracic cavity**
(a) Location of the heart within the thoracic cavity. (b) External cardiac compression during cardiopulmonary resuscitation. Manual compression of the heart between the sternum anteriorly and the vertebrae posteriorly forces blood out of a nonfunctioning heart.

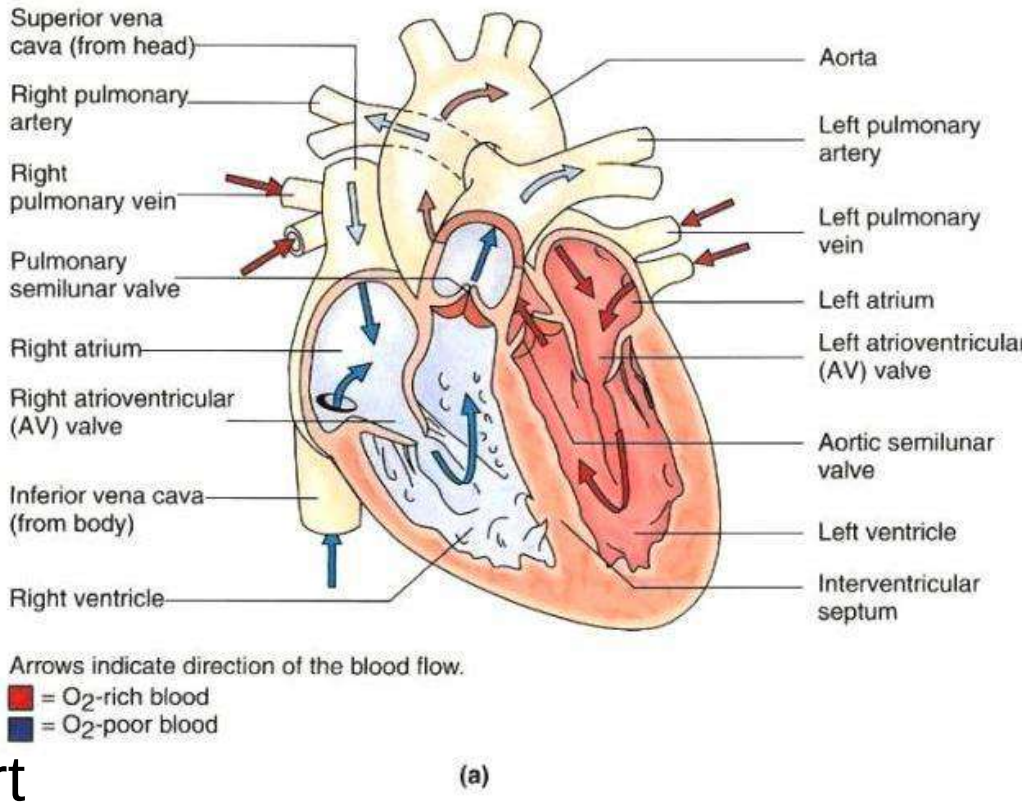
# Anatomy of the heart

- The fact that the heart is positioned between two bony structures, the sternum and vertebrae, makes it possible to manually drive blood out of the heart when it is not pumping effectively, by rhythmically depressing the sternum as part of **cardiopulmonary resuscitation** (**CPR**).



# The heart is "a dual pump"

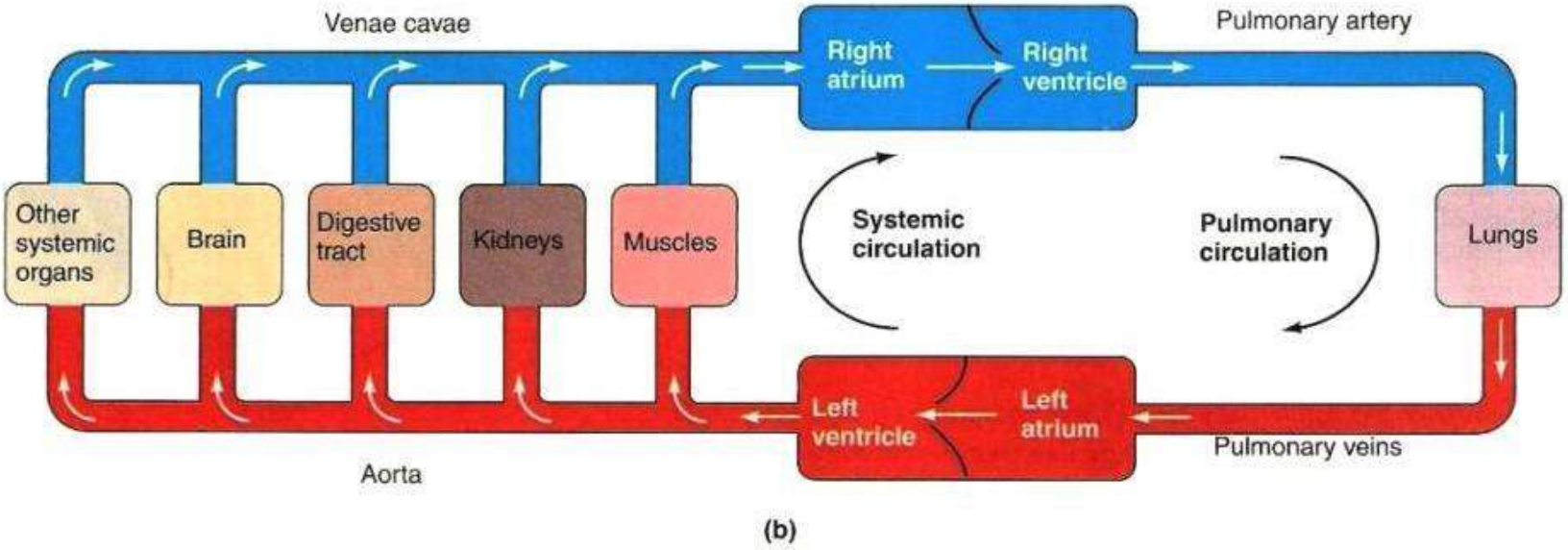
- Even though anatomically the heart is a single organ, the right and left sides of the heart function as two separate pumps.
- The two halves of the heart are separated by the **septum**, so the right half of the heart is receiving and pumping **$O_2$-poor blood** while the left side of the heart receives and pumps **$O_2$-rich blood**.



# The complete circuit of blood flow

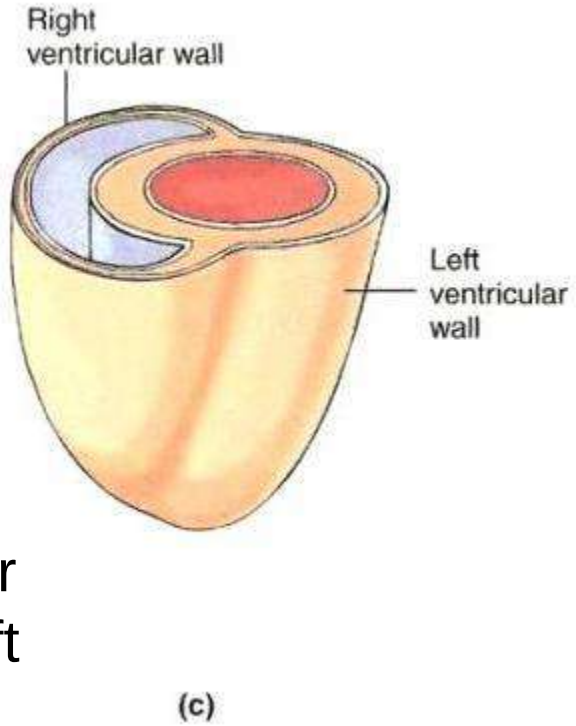
- **Let us examine how the heart functions as a dual pump, by tracing a drop of blood through one complete circuit (fig. 9-3a and b).**

**Thus,** ***the right side of the heart receives blood from the systemic circulation and pumps it into the pulmonary circulation*****, and** ***the left side of the heart receives blood from the pulmonary circulation and pumps it into the systemic circulation*****.**



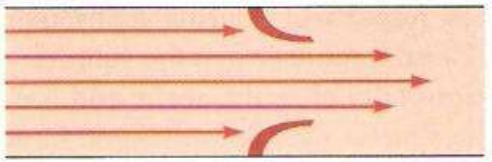
# Comparison of the right and left pumps

- Both sides of the heart simultaneously pump equal amounts of blood.
- The pulmonary circulation is a **low-pressure**, **low-resistance** system, whereas the systemic circulation is a high-pressure, high-resistance system.
- Resistance is the opposition to blood flow, largely caused by friction between the flowing blood and the vessel wall.
- The left side performs more work, because it pumped an equal volume of blood at a higher pressure into a higher-resistance system.
- The heart muscle on the left side is much thicker than the muscle on the right side, making the left side a stronger pump.



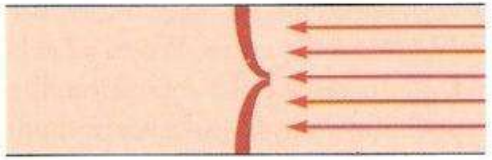
# Heart valves ensure that the blood flows in the proper direction through the heart

- The presence of 4 one-way heart valves ensures this unidirectional flow of blood.
- The valves are positioned so that they open and close passively because of pressure differences, similar to a one-way door.
- ***Note***, that a backward gradient can force the valve closed.



When pressure is greater behind the valve, it opens.

Valve opened



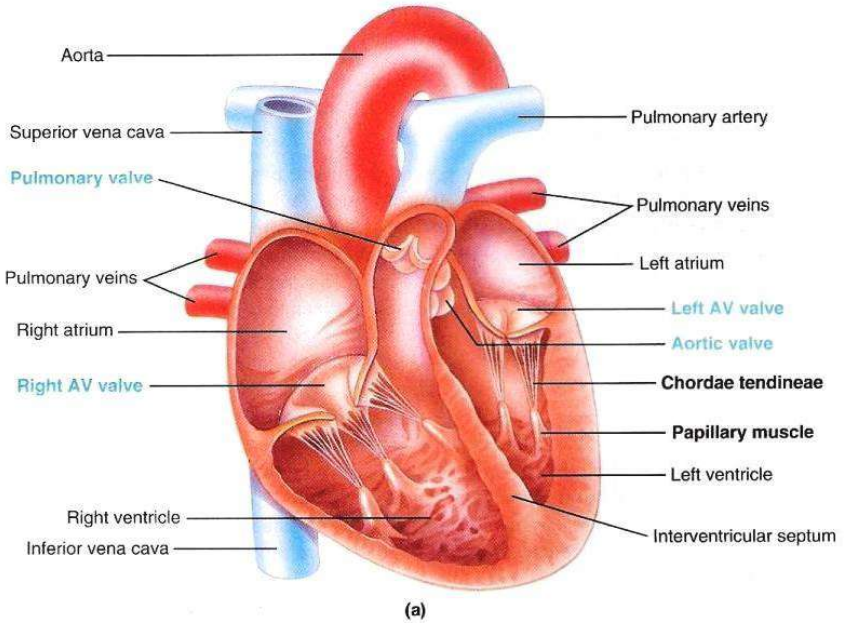
When pressure is greater in front of the valve, it closes. Note that when pressure is greater in front of the valve, it does not open in the opposite direction; that is, it is a one-way valve.

Valve closed; does not open in opposite direction

FIGURE 9-4
Mechanism of valve action

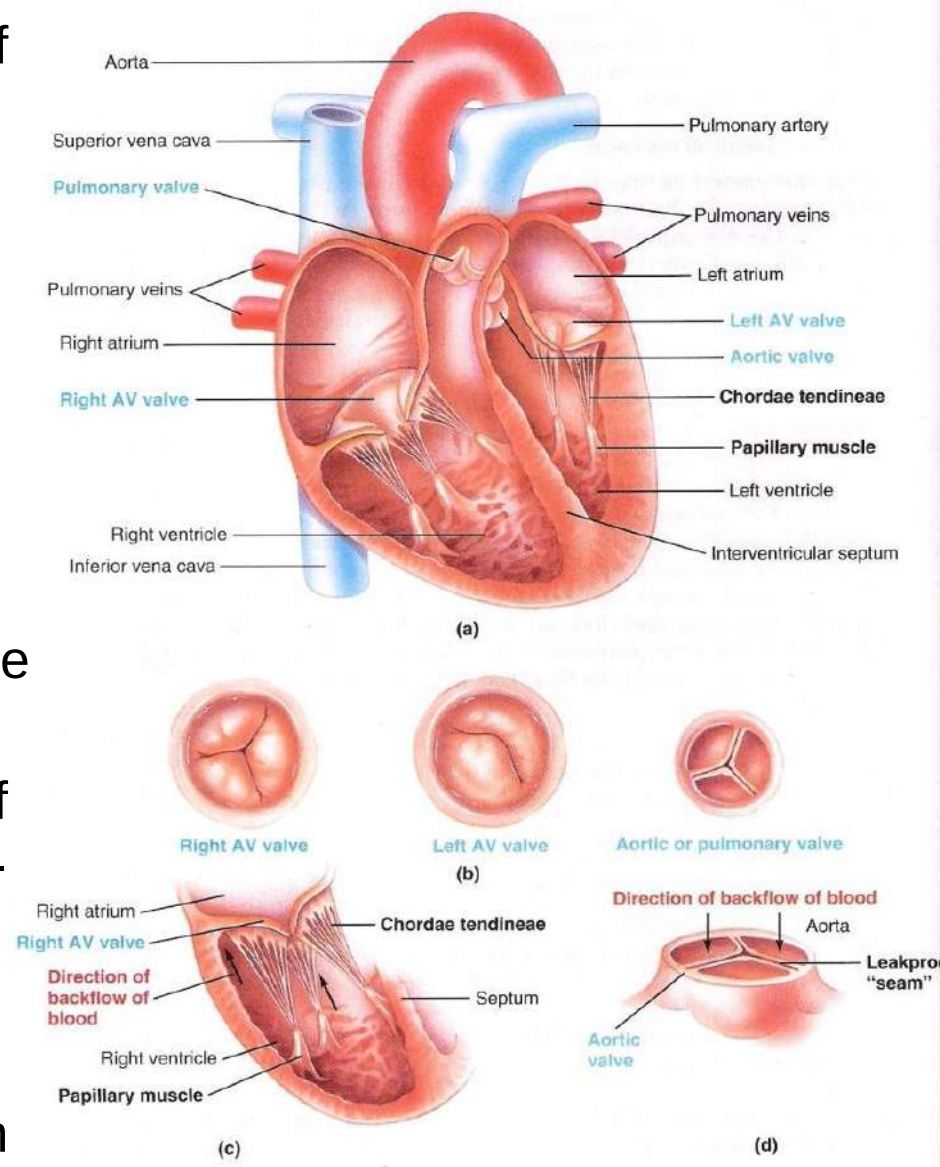
# AV valves between the atria and ventricles

- **Animation**.
- These valves allow blood to flow from the atria into the ventricles during ventricular filling ( ***when atrial pressure exceeds ventricular pressure***) but prevent the backflow of blood from the ventricles into the atria during ventricular emptying (***when ventricular pressure greatly exceeds atrial pressure***).
- If the rising ventricular pressure did not force the AV valves to close as the ventricles contracted to empty, much of the blood would inefficiently be forced back into the atria and veins instead of arteries.



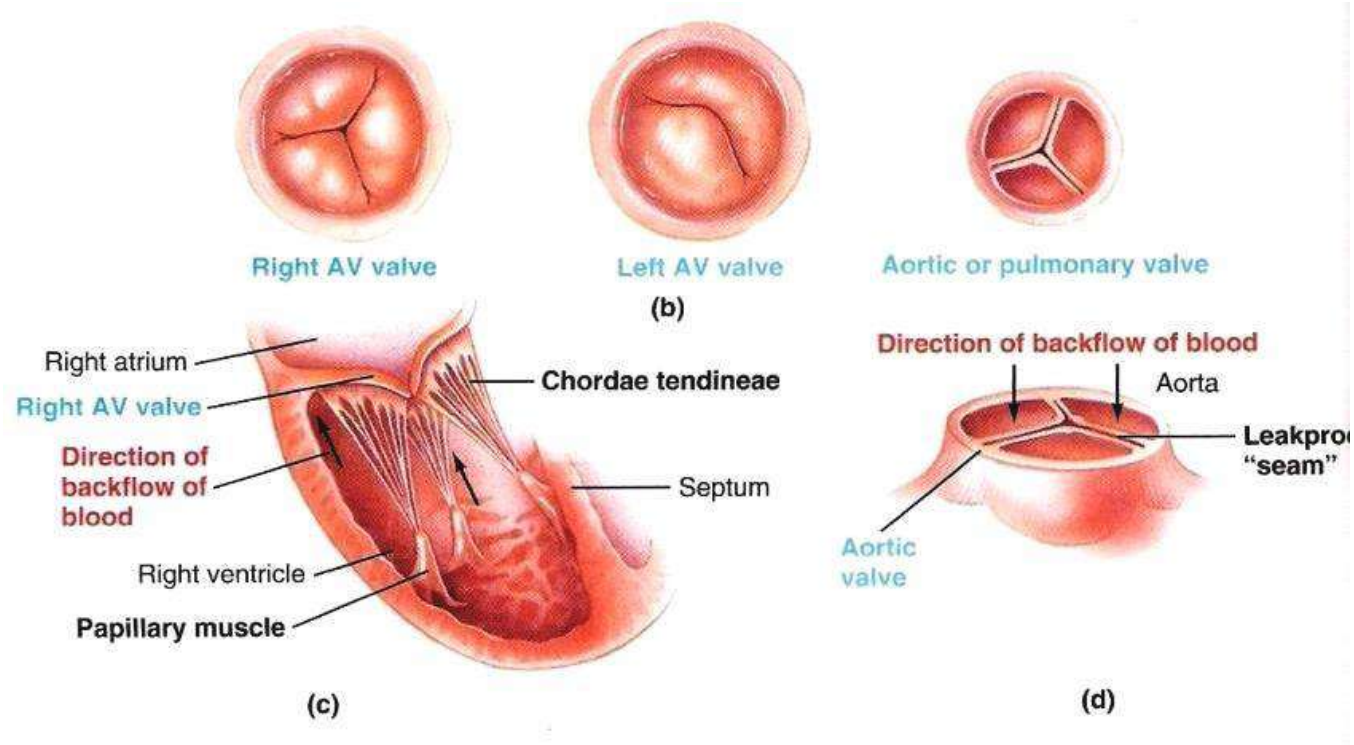
- The right AV valve is also called the **tricuspid valve** because it consists of three cusps or leaflets.
- Likewise, the left AV valves, which consists of two cusps, is often called the **bicuspid valve**, or **mitral valve**.

- The edges of the AV valves leaflets are fastened by tough, thin, fibrous cords of tendinous-type tissue, the **chordae tendineae**, which prevent the valves from being everted تنقلب.
- These cords extend from the edges of each cusp and attach to small, nipple-shaped **papillary muscles.**
- When the ventricles contract, pulling downward that exerts tension on the closed AV valve cusps to hold them in position.



# Semilunar valves between the ventricles and major arteries

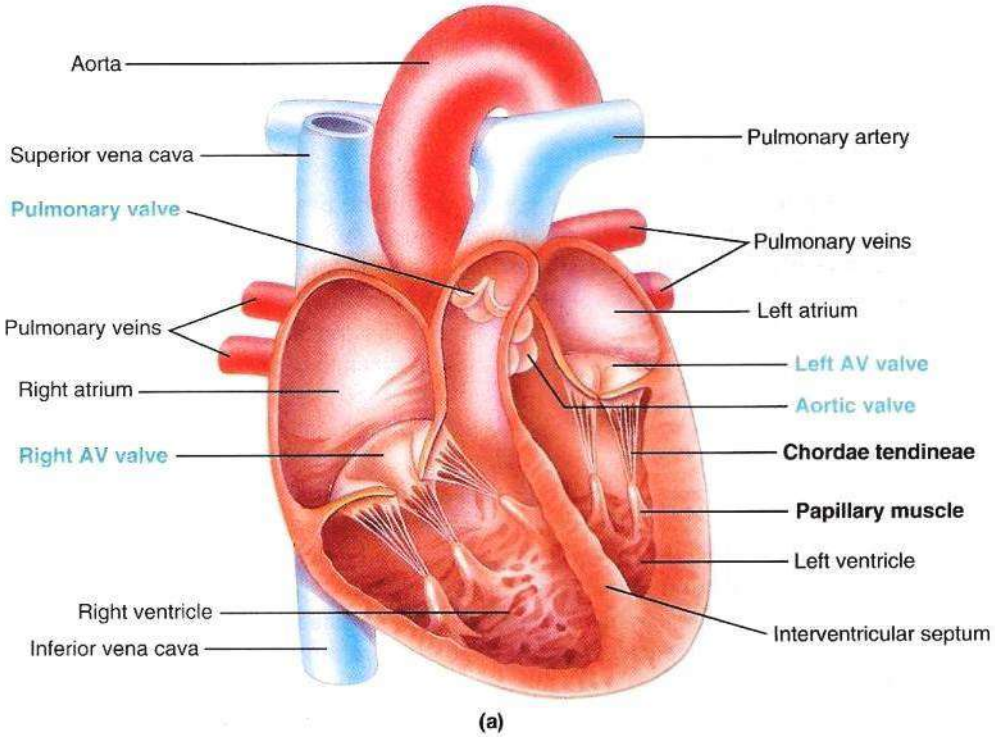
- The two remaining heart valves, **the aortic** and **pulmonary valves**, are located at the juncture where the major arteries leave the ventricles.
- These valves are forced open when the left and right ventricular pressures exceed the pressure in the aorta and pulmonary arteries during ventricular contraction and emptying.
- The Semilunar valves are prevented from everting by the anatomical structure and positioning of the cusps.



# NO valves between the atria and veins

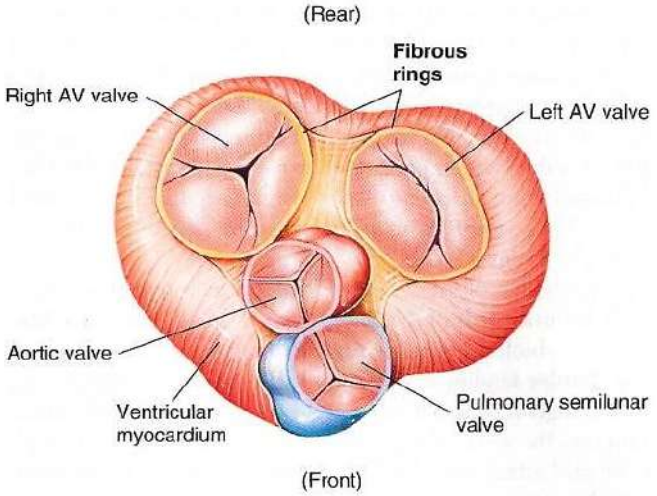
- **Even though there are no valves between atrea and veins it is not a significant problem for two reasons:**

1. Atrial pressures usually are not much higher than venous pressures, and
2. The sites where the venae cavae enter the atria are partially compressed during atrial contraction.

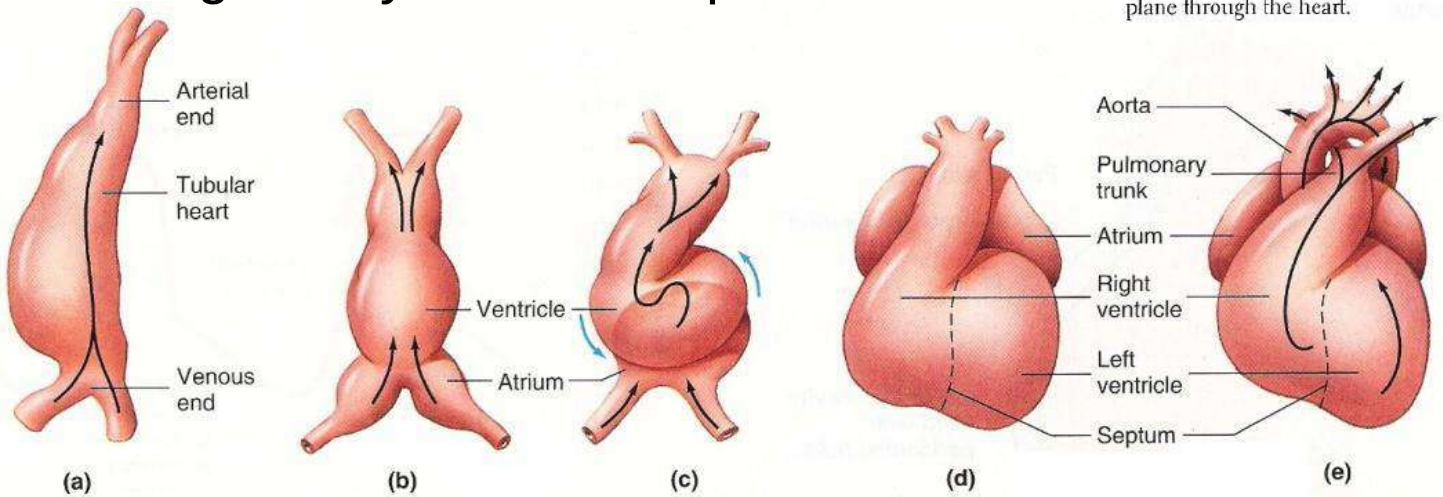


# Fibrous skeleton of the valves

- Four interconnecting rings of dense connective tissue provide a firm vase for attachment of the four heart valves.
- The inlet and outlet valves all lie on the same plane through the heart, as delineated by the fibrous skeleton, <u>because</u> the heart forms from a single tube that bends on itself and twists on its axis during embryonic development.




● FIGURE 9-6
**Fibrous skeleton of the heart**
A view of the heart from above, with the atria and major vessels removed to show the heart valves and fibrous rings. Note that the inlet and outlet valves to the ventricle all lie on the same plane through the heart.




● FIGURE 9-7
**Twisting of the embryonic heart on its axis during development**
The black arrows within the heart indicate the direction of blood flow. The blue arrows outside the heart depict the direction the embryonic heart twists during development.

# The heart walls are composed primarily of spirally arranged cardiac muscle fibers

- The heart wall consists of three distinct layers:
- The **endocardium** is a thin inner layer of **endothelium**.
- The **myocardium**, the middle layer, composed of cardiac muscle.
- The **epicardium** is a thin external membrane covering the heart.

The myocardium consists of interlacing bundles of cardiac muscle fibers arranged spirally around the circumference of the heart, due to the heart's complex twisting during development.

As a result of this arrangement, when the ventricular muscle contracts and shortens, the diameter of the ventricular chambers is reduced while the apex is simultaneously pulled upward toward the top of the heart in rotating manner.

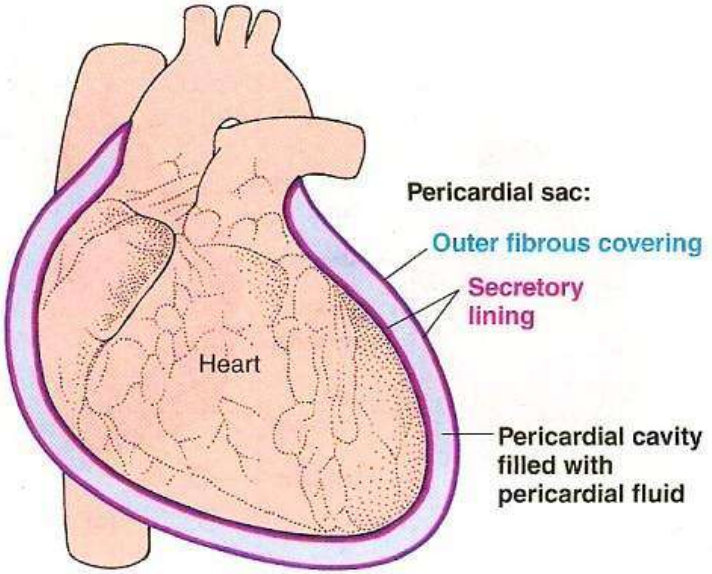
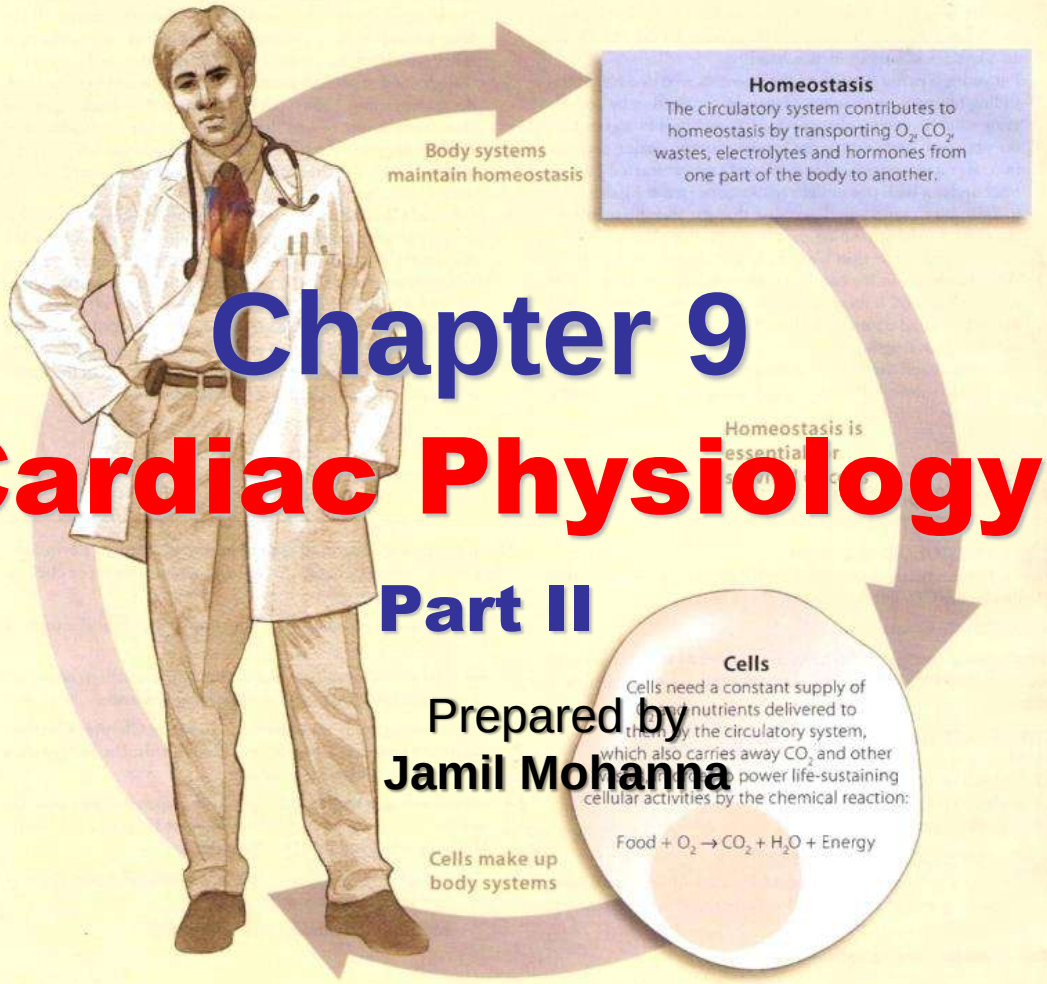



FIGURE 9-9
Pericardial sac

# الحمد لله رب العالمين

Circulatory System (Heart)




# Chapter 9
# Cardiac Physiology
## Part II

Prepared by
**Jamil Mohanna**

The maintenance of homeostasis depends on essential materials such as $O_2$ and nutrients being continually picked up from the external environment and delivered to the cells and on waste products being continually removed. Homeostasis also depends on the transfer of hormones, which are important regulatory chemical messengers, from their site of production to their site of action. The circulatory system, which contributes to homeostasis by serving as the body's transport system, consists of the heart, blood vessels, and blood.

All body tissues constantly depend on the life-supporting blood flow provided to them by the contraction or beating of the heart. The heart drives the blood through the blood vessels for delivery to the tissues in sufficient amounts, whether the body is at rest or engaging in vigorous exercise.

# Electrical Activity of The Heart

- The heart contracts, or beats, rhythmically as a result of action potentials that it generates by itself, a property known as **autorhythmicity**.

1. 99% of the cardiac muscle cells are **contractile cells**.
2. The **autorhythmic cells**, are specialized for initiating and conducting the action potentials responsible for contraction of the working cells.

# Cardiac autorhythmic cells display pacemaker activity

- The cardiac artorhythmic cells do not have a resting potential.
- They display **pacemaker activity**; that is, their membrane potential slowly depolarizes between action potentials until threshold is reached at which time the membrane fires or has a cyclically initiate action potential, without any nervous stimulation.

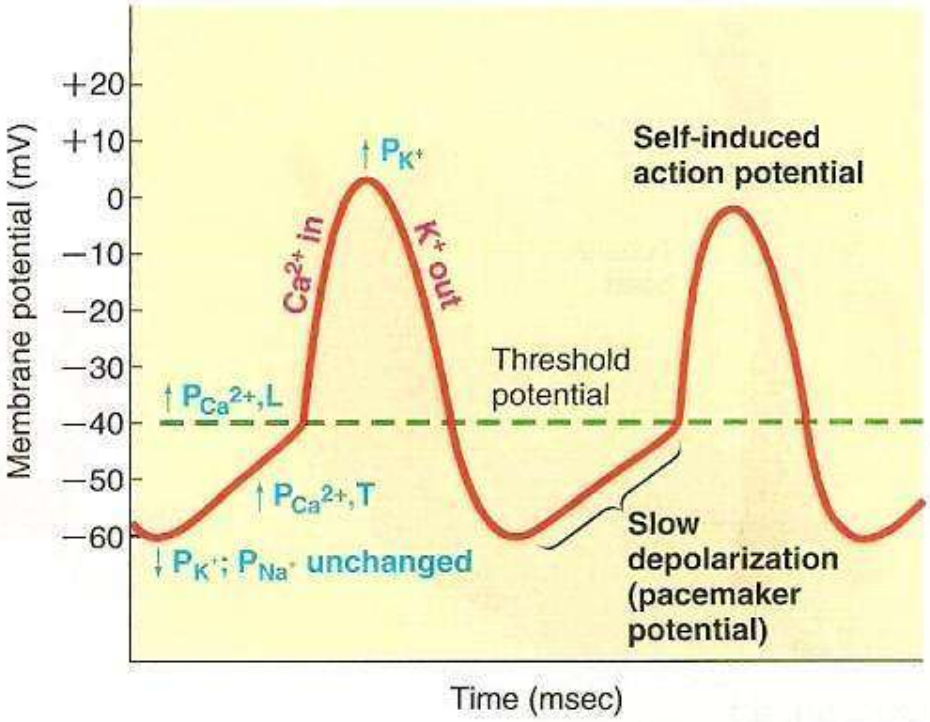



FIGURE 9-10
Pacemaker activity of cardiac autorhythmic cells

# Pacemaker potential and action potential in autorhythmic cells

* Complex interaction of several different ionic mechanisms are responsible for the **pacemaker potential**.
* The most important changes are:

1. A decreased outward $K^+$ current coupled with a constant inward $Na^+$ current.
2. An increased inward $Ca^{2+}$ current.

* To elaborate, the initial phase of the slow depolarization to threshold is caused by a cyclical decrease in the passive outward flux of $K^+$ superimposed on a slow, unchanging inward lead of $Na^+$.
* Membrane permeability to $K^+$ decreases between action potentials, because $K^+$ channels slowly close at negative potentials, gradually diminishes the outflow of positive potassium ions down their concentration gradient.
* Cardiac autorhythmic cells do not have voltage-gated $Na^+$ channels.
* They have channels that are always open and thus permeable to $Na^+$ at negative potentials.
* At the same time the rate of $K^+$ efflux slowly declines.
* Thus the inside gradually becomes less negative; that is, the membrane gradually depolarizes and drifts toward threshold.
* A transient $Ca^{2+}$ channels ($Ca^{2+}$, *T*), one of tow types of voltage-gated $Ca^{2+}$ cannels, opens, before the membrane reaches threshold.

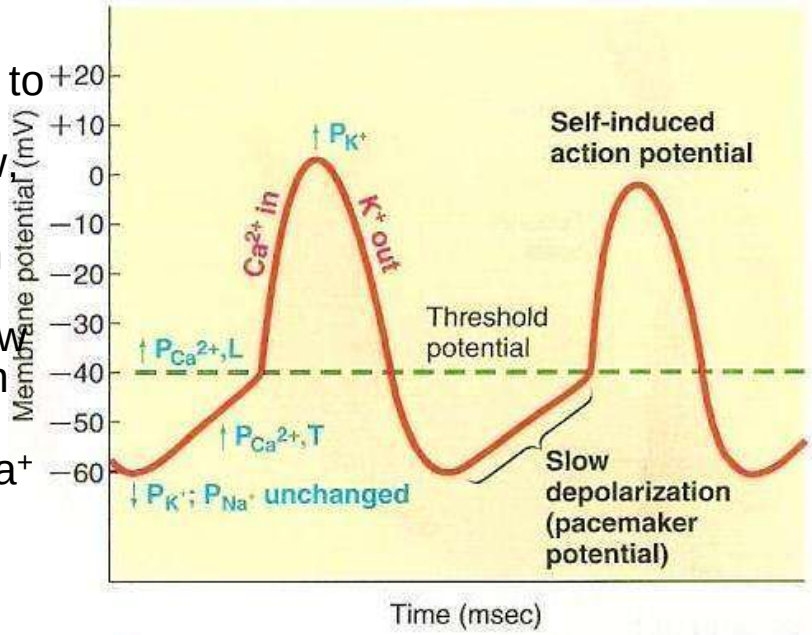



FIGURE 9-10
Pacemaker activity of cardiac autorhythmic cells

- Once threshold is reached, activation of a longer-lasting, voltage-gated $Ca^{2+}$ channel ($Ca^{2+}$, L) where $Na^{+}$ influx rather than $Ca^{2+}$ influx swings the potential in the positive direction.
- The falling phase is due to the $K^{+}$ efflux that occurs when $K^{+}$ permeability increases as a result of activation of voltage-gated $K^{+}$ channels.
- After the action potential is over, slow closure of there $K^{+}$ channels initiates the next slow depolarization to threshold.

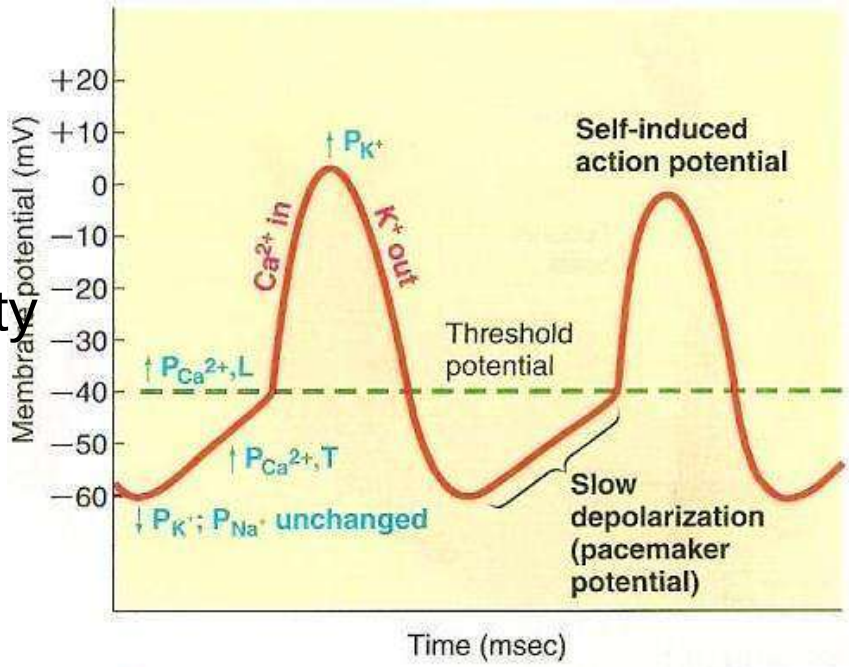
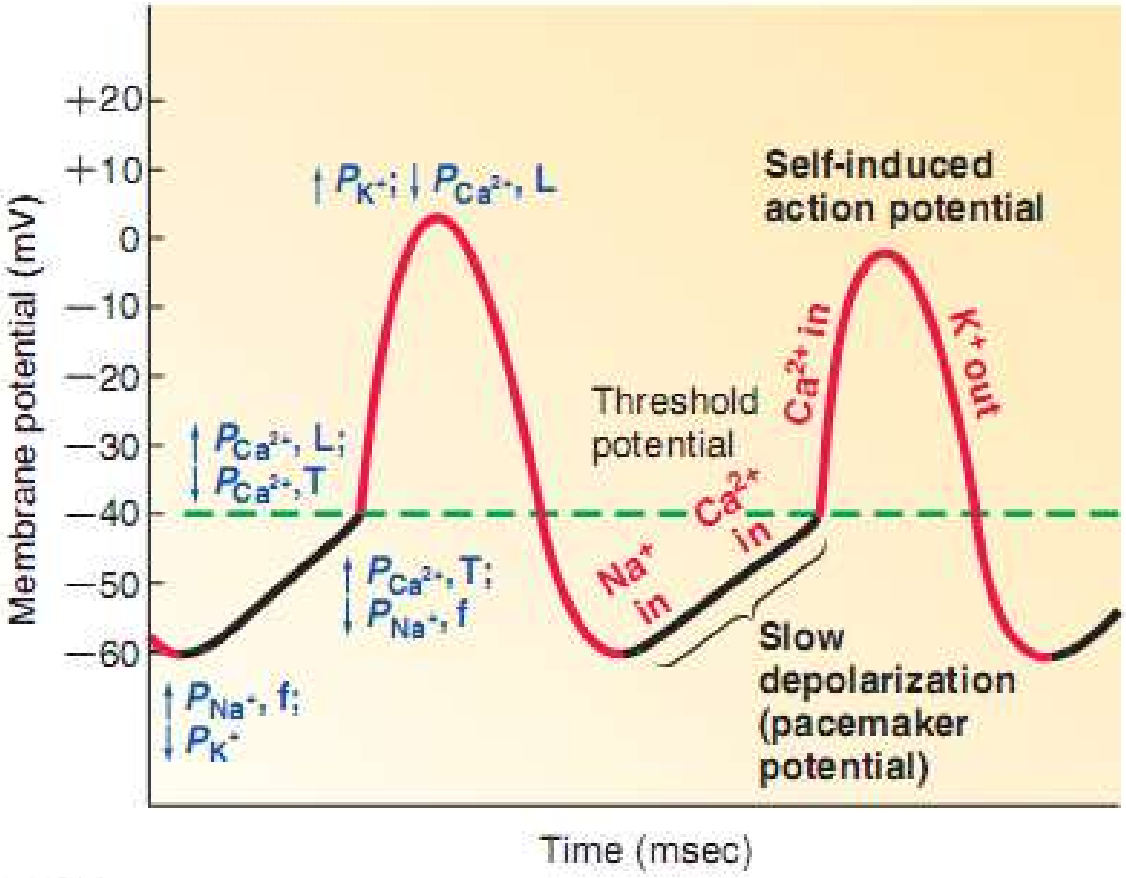



FIGURE 9-10
Pacemaker activity of cardiac autorhythmic cells



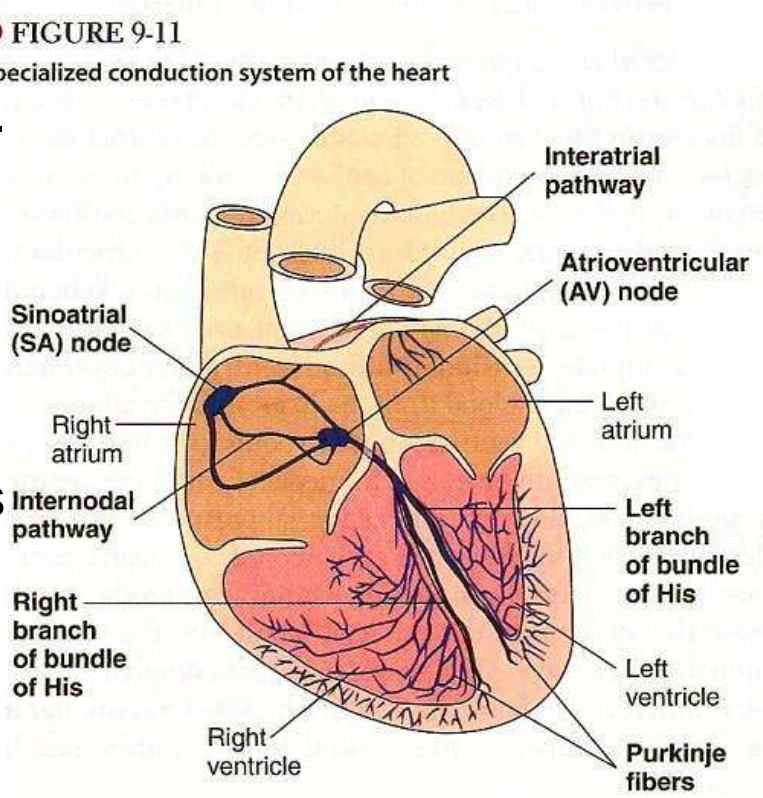

**KEY**

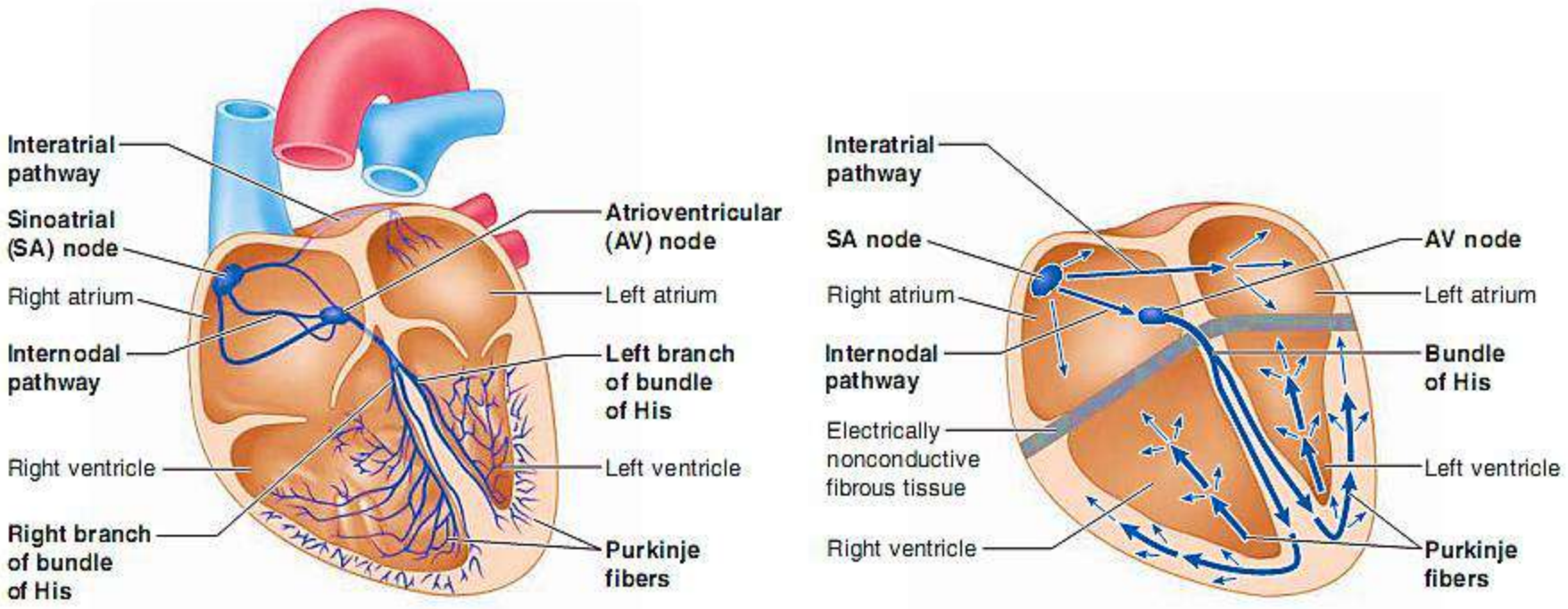
**f** = Funny channels
**T** = Transient-type channels
**L** = Long-lasting channels

# The sinoatrial node is the normal pacemaker of the heart

- The specialized noncontractile cardiac cells capable of autorhythmicity are:

1. The **sinoatrial node (SA node)**, a specialized region in the right atrial wall near the opening of the superior vena cava.
2. The **atrioventricular node ( AV node)**, located at the base of the right atrium near the septum, just above the junction of the atria and ventricles.
3. The **bundle of His ( atrioventricular bundle)**, originates at the AV node and enters the interventricular septum, it divides to form the right and left bundle branches that travel down the septum, curve around the tip of the ventricular chambers, and travel back toward the atria along the outer walls.
4. **Purkinje fibers**, that extend from the bundle of His and spread throughout the ventricular myocardium.






● **FIGURE 9-8 Specialized conduction system of the heart and spread of cardiac excitation.** An action potential initiated at the SA node first spreads throughout both atria. Its spread is facilitated by two specialized atrial conduction pathways, the interatrial and internodal pathways. The AV node is the only point where an action potential can spread from the atria to the ventricles. From the AV node, the action potential spreads rapidly throughout the ventricles, hastened by a specialized ventricular conduction system consisting of the bundle of His and Purkinje fibers.

# Normal pacemaker activity

- Because these various autorhythmic cells have different rates of slow depolarization to threshold, *the rates* at which they are normally capable of generating action potentials also differ .
- The heart cells with the fastest rate of action potential initiation are localized in the SA node( known as the **pacemaker** ).
- That is, the entire heart becomes excited, triggering the contractile cells to contract and the heart to beat at the pace or rate set by SA node autorhythmicity, normally at 70-80 beats per minute.
- The others are unable to assume their own naturally slower rates, because they are activated by SA node action potentials before they are able to reach threshold at their own, slower rhythm.

**TABLE 9-1** Normal Rate of Action Potential Discharge in Autorhythmic Tissues of the Heart

| Tissue | Action Potentials per Minute* |
|---|---|
| SA node (normal pacemaker) | 70–80 |
| AV node | 40–60 |
| Bundle of His and Purkinje fibers | 20–40 |

*In the presence of parasympathetic tone; see p. 240 and p. 327.

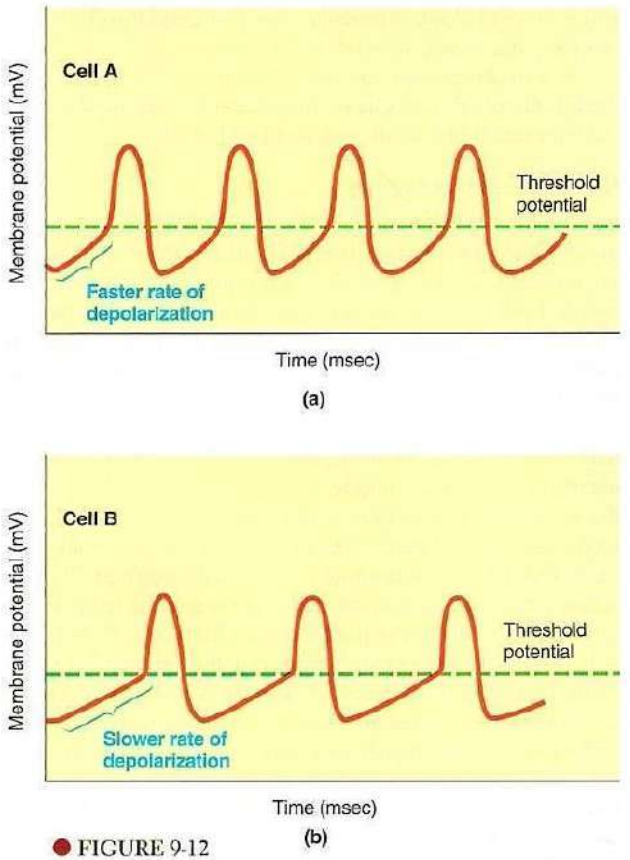
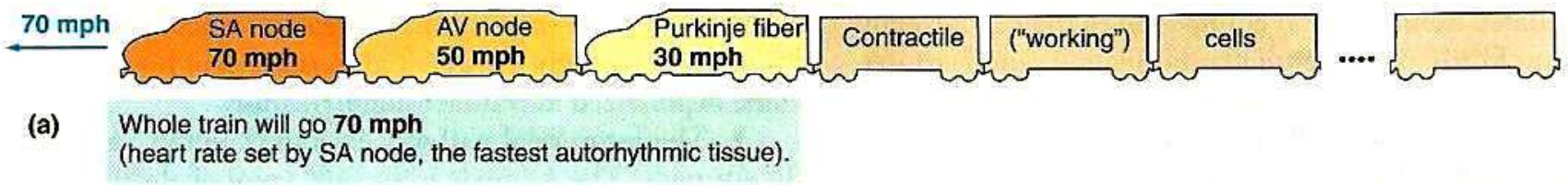



FIGURE 9-12

- The following analogy demonstrates how the SA node drives the remainder of the heart at its own pace.




(a) Whole train will go **70 mph**
(heart rate set by SA node, the fastest autorhythmic tissue).

## Abnormal pacemaker activity

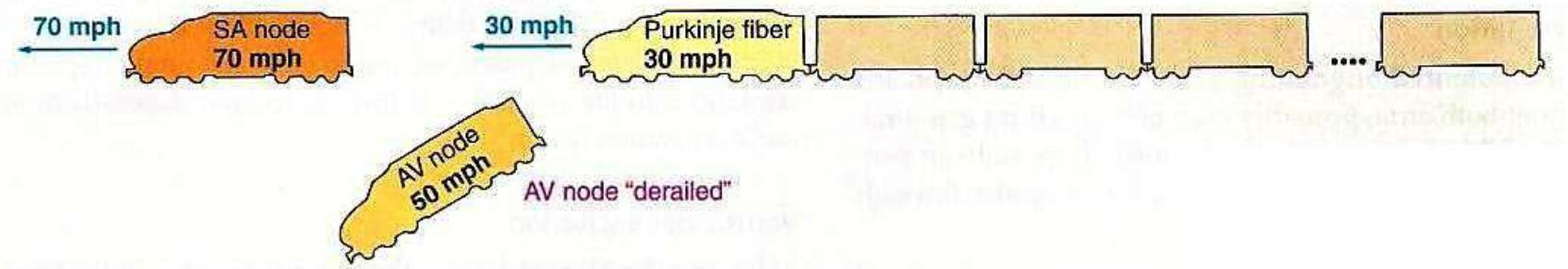
If for some reason the fastest engine breaks down ( SA node damage), the next fastest engine ( AV node ) takes over, known as **latent pacemakers**.


(b) Train will go **50 mph**
(the next fastest autorhythmic tissue, the AV node, will set the heart rate).

If conduction of the impulse becomes blocked between the atria and the ventricles,??, a phenomenon known as **complete heart block**.

A ventricular rate of 30 beats per minute will support only a very sedentary existence, in fact, the patient usually becomes comatose.

In circumstances of abnormally low heart rate, as in SA node failure or heart block, an **artificial pacemaker** can be used.

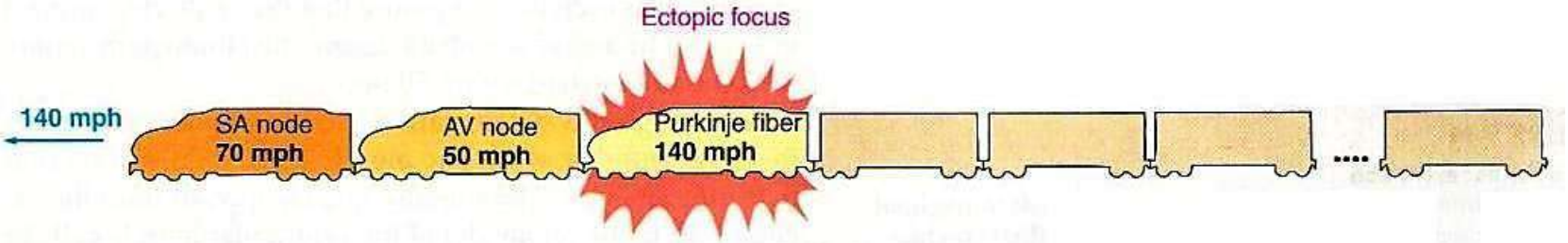



(c) First part of train will go **70 mph**; last part will go **30 mph** (atria will be driven by SA node; ventricles will assume own, much slower rhythm).

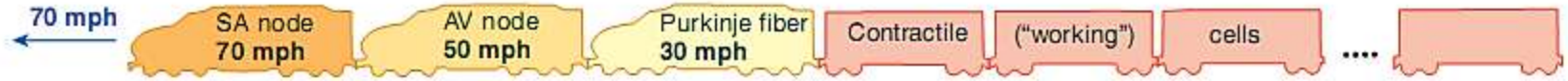
Occasionally an area of the heart, such as a Purkinje fiber, becomes overly excitable and depolarizes more rapidly than lead engine, **ectopic focus**.

An occasional abnormal impulse from an ectopic focus produces a **premature beat**, or **extrasystole**.

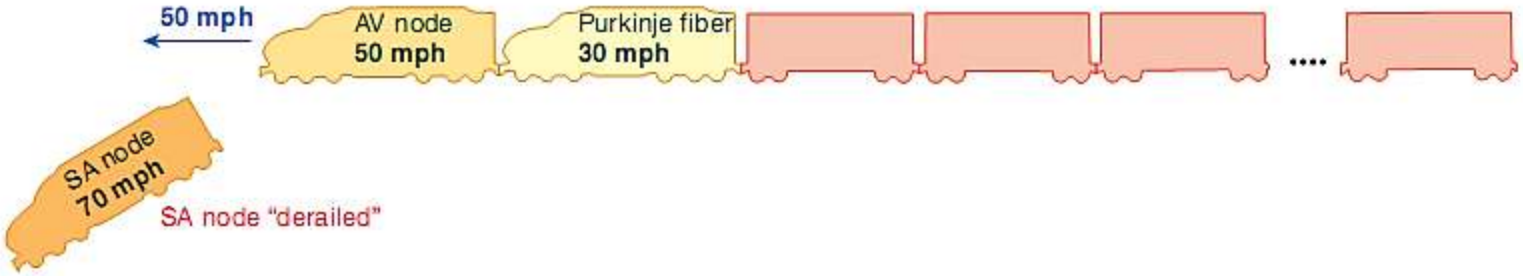
Such overly irritable areas may be associated with organic heart disease, byt more frequently they occur in response to anxiety, lack of sleep, or excess caffeine, nicotine, or alcohol consumption.



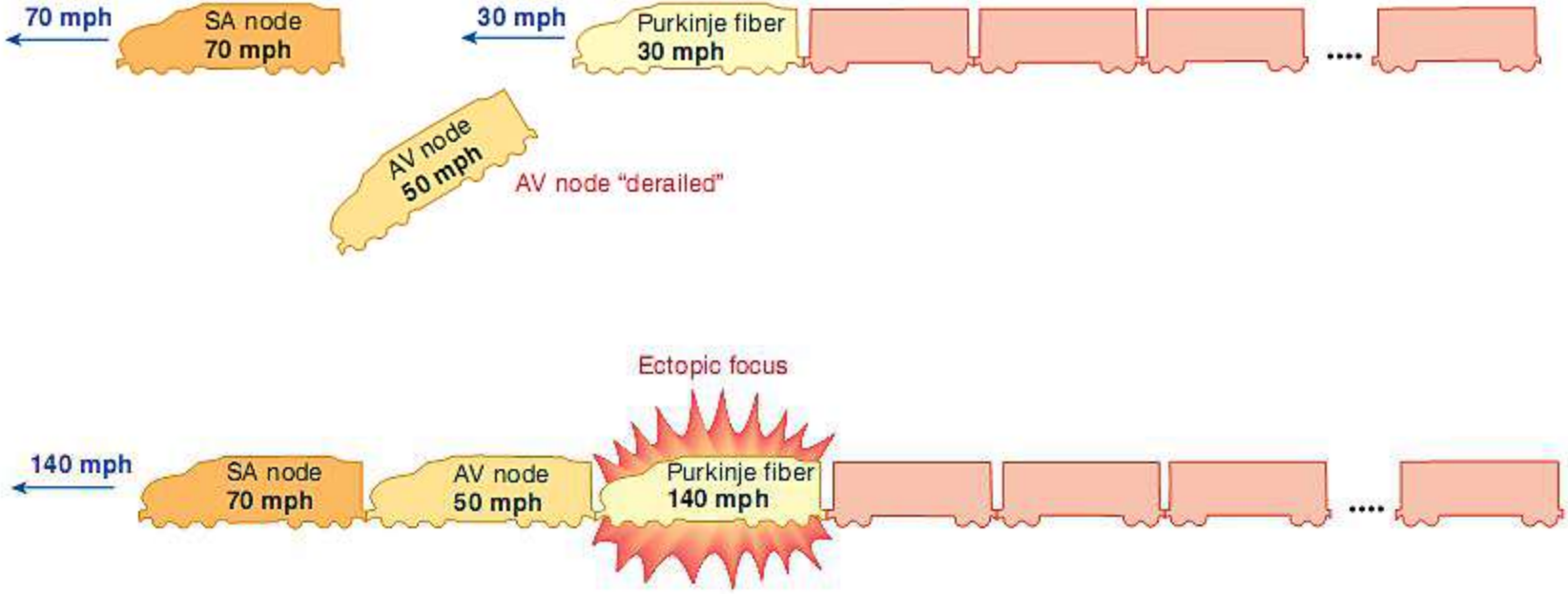

(d) Train will be driven by ectopic focus, which is now going faster than the SA node (the whole heart will be driven more rapidly by an abnormal pacemaker).




**(a)** Normal pacemaker activity: Whole train will go **70 mph** (heart rate set by SA node, the fastest autorhythmic tissue).




**(b)** Takeover of pacemaker activity by AV node when the SA node is nonfunctional: Train will go **50 mph** (the next fastest autorhythmic tissue, the AV node, will set the heart rate).



# The spread of cardiac excitation is coordinated to ensure efficient pumping

- For efficient cardiac function, the spread of excitation should satisfy three criteria:

**1.** ***Atrial excitation and contraction should be complete before the onset of ventricular contraction.***

Almost 80% of ventricular filling occurs by this means before atrial contraction. When the atria do contract, to complete ventricular filling (the remaining 20%).During a normal heartbeat, atrial contraction occurs about 160 msec. before ventricular contraction.

**2.** ***Excitation of cardiac muscle fibers should be coordinated to ensure that each heart chamber contracts as a unit to accomplish efficient pumping.*** example: basting syringe

Contraction of isolated cardiac muscle fibers is not successful in pumping blood. Such random, un coordinated excitation and contraction of the cardiac cells is known as ***fibrillation***.

# The spread of cardiac excitation is coordinated to ensure efficient pumping

- ventricular fibrillation rapidly causes death, because the heart is not able to pump blood into the arteries, often corrected by **electrical defibrillation**, in which a very strong electrical current is applied on the chest wall. Stimulates (depolarizes) all parts of the heart simultaneously, to recover is the SA node takes over pacemaker activity.

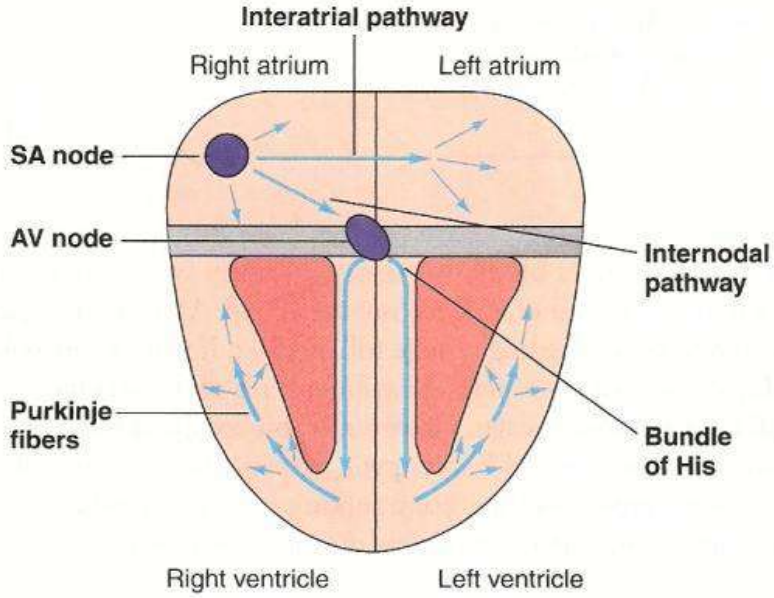
**3.** ***The pair of atria and pair of ventricles should be functionally coordinated so that both members of the pair contract simultaneously.***

- The normal spread of cardiac excitation is carefully orchestrated to ensure that these criteria are met and the heart functions efficiently as follows.

FIGURE 9-14

**Spread of cardiac excitation**

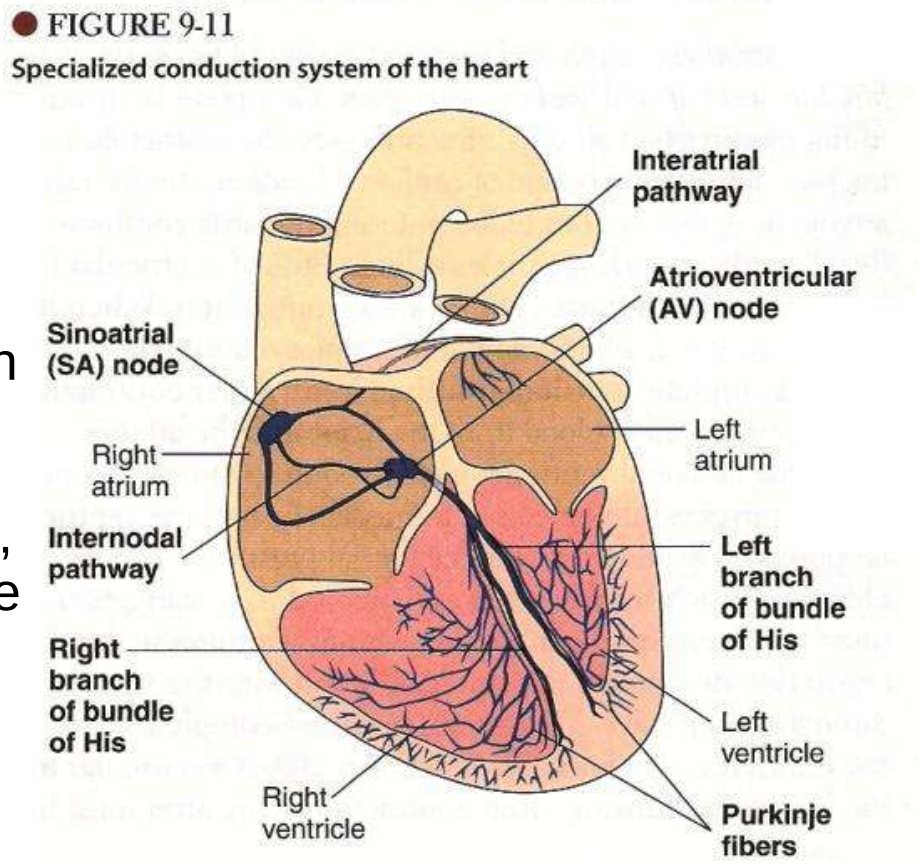
An action potential initiated at the SA node first spreads throughout both atria. Its spread is facilitated by two specialized atrial conduction pathways, the interatrial and internodal pathways. The AV node is the only point where an action potential can spread from the atria to the ventricles. From the AV node, the action potential spreads rapidly throughout the ventricles, hastened by a specialized ventricular conduction system consisting of the bundle of His and Purkinje fibers.



## Atrial excitation:

SA node action potential spreads in both atria via gap junctions, specialized conduction pathways hasten يسرع conduction of the impulse through the atria( fig. 9-11).

- The **interatrial pathway** extends from the SA node within the right atrium to the left atrium. A wave of excitation can spread across the gap junctions, ensures that both atria become depolarized to contract simultaneously, to ensures sequential contraction of the ventricles following atrial contraction.
- Hastened by this pathway, the action potential arrives at the AV node within 30 msec of SA node firing.

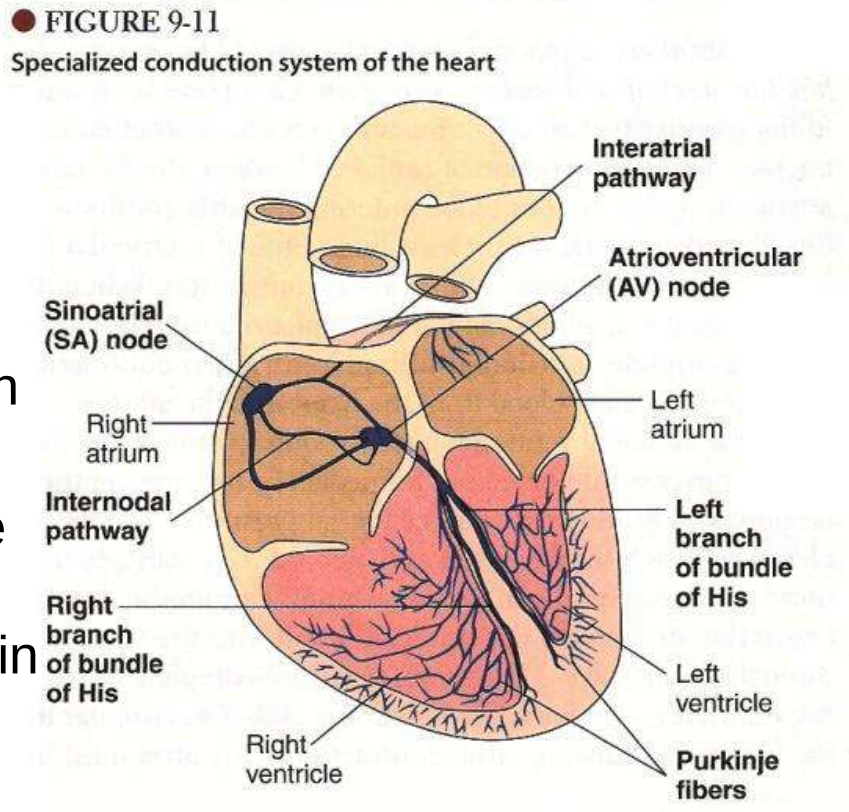


# Transmission between the atria and the ventricles

- The action potential is conducted relatively slowly through the AV node, because it allows time for complete ventricular filling by 100 msec ( the **AV nodal delay**).

## Ventricular excitation

- The impulse travels rapidly down the bundle of His and Purkinje fibers , specialized for rapid propagation of action potentials.
- Its presence hastens and coordinates the spread of ventricular excitation to ensure that the ventricles contract as a unit (within 30 msec).
- Because the ventricular mass is so much larger than the atrial mass, Purkinje fibers are six times faster than the ventricular syncytium of contractile cells could.



# The action potential of cardiac contractile cells shows a characteristic plateau

- The action potential in cardiac contractile cells, although initiated by the nodal pacemaker cells, varies considerably in ionic mechanisms and shape from the SA node potential (compare fig. 9-10 and 9-15).
- Action potential interplay of permeability changes and membrane potential changes as follows:

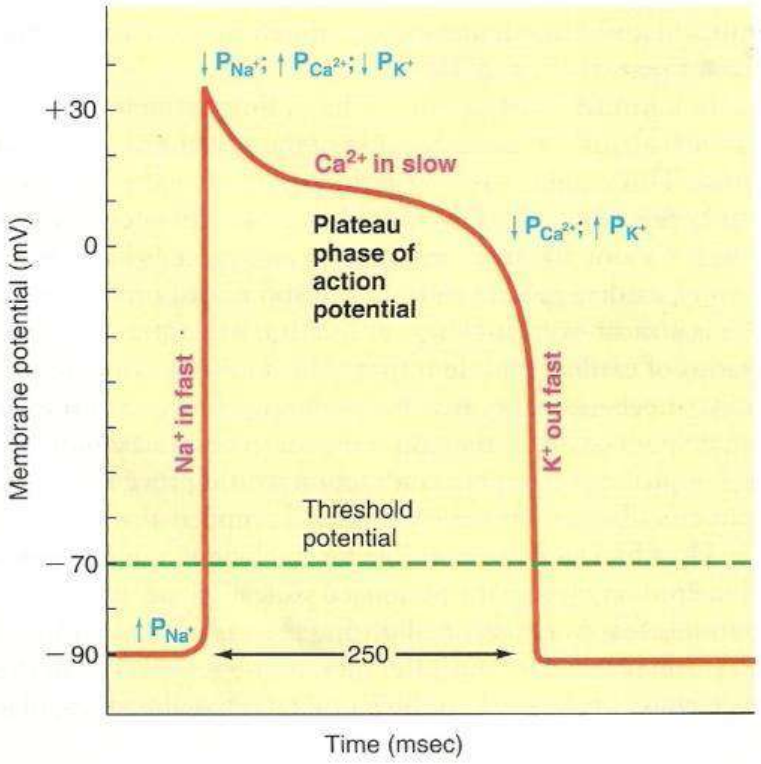
1. The **rising phase**, the membrane potential rapidly becomes reversed to a positive value of +30 mV as a result of an explosive increase in membrane permeability to $Na^+$ and a subsequent massive $Na^+$ influx.

- The membrane potential is maintained at this positive level for several hundred milliseconds, producing ***a plateau phase***.

FIGURE 9-15

**Action potential in contractile cardiac muscle cells**

The action potential in cardiac contractile cells differs considerably from the action potential in cardiac autorhythmic cells (compare with Figure 9-10).



# The action potential of cardiac contractile cells shows a characteristic plateau

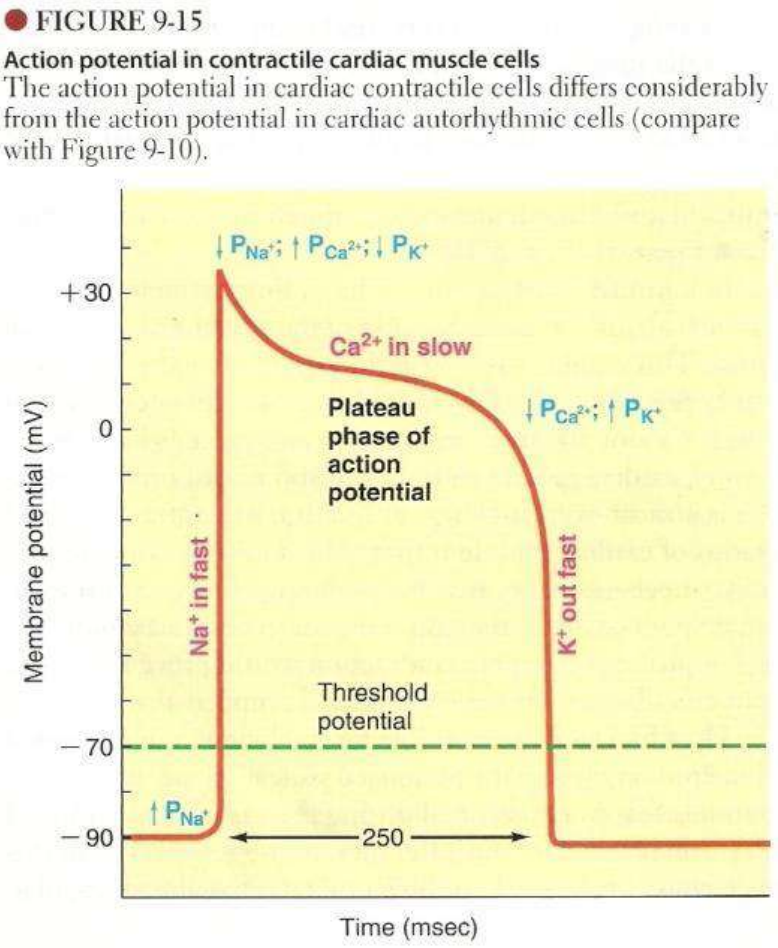
2. Two voltage-dependent permeability changes that are responsible for maintaining this ***plateau***:

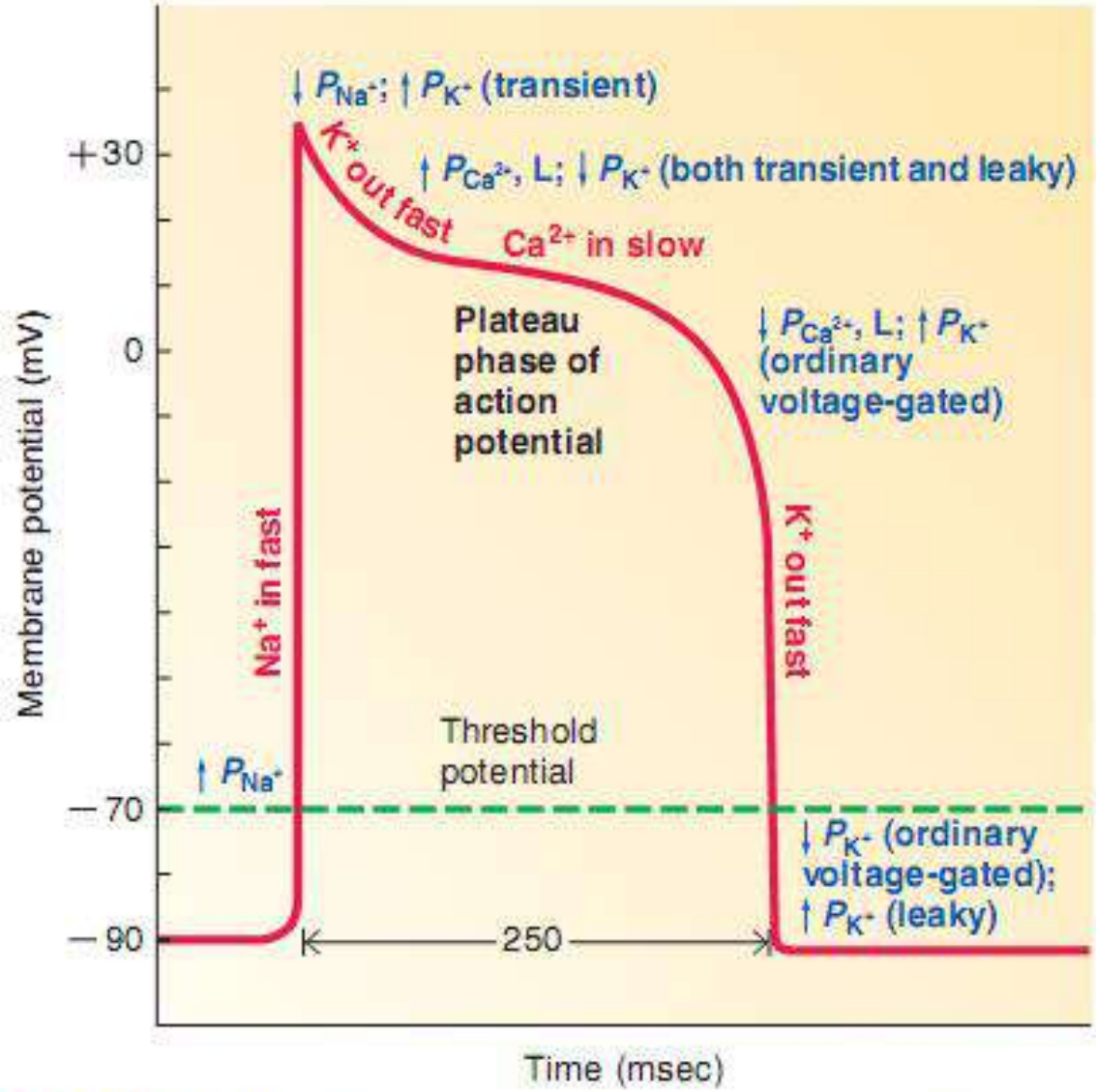
   ❶activation of slow L-type $Ca^{2+}$ channels, and

   ❷a marked decrease in $K^+$ permeability.

- Continued influx of positively charged $Ca^{2+}$ prolongs the positivity inside the cell and the resultant reduction in out flux of positively charged $K^+$ primarily responsible for the plateau portion.

3. The rapid ***falling phase*** results from inactivation of the $Ca^{2+}$ channels and activation of $K^+$ channels.






● **FIGURE 9-10 Action potential in contractile cardiac muscle cells.** The action potential in cardiac contractile cells differs

# $Ca^{2+}$ entry from the ECF induces a much larger $Ca^{2+}$ release from the sarcoplasmic reticulum

- The extra supply of $Ca^{2+}$ from the sarcoplasmic reticulum is responsible for the long period of cardiac contraction, (300 msec compared to 100 msec for a single skeletal muscle).
- This increased contractile time ensures adequate time to eject the blood.

➢ **Role of cytosolic $Ca^{2+}$ in cardiac excitation-contraction coupling**

- $Ca^{2+}$ within the cytosol bind with the troponin-tropomysin complex and physically pull it aside so that cross-bridge cycling and contraction can take place.
- Unlike skeletal muscle, in which sufficient $Ca^{2+}$ is always released to turn on all of the cross bridges, in cardiac muscle the extent of cross-bridge activity varies with the amount of cytosolic $Ca^{2+}$, various regulatory factors can alter the amount of cytosolic $Ca^{2+}$.

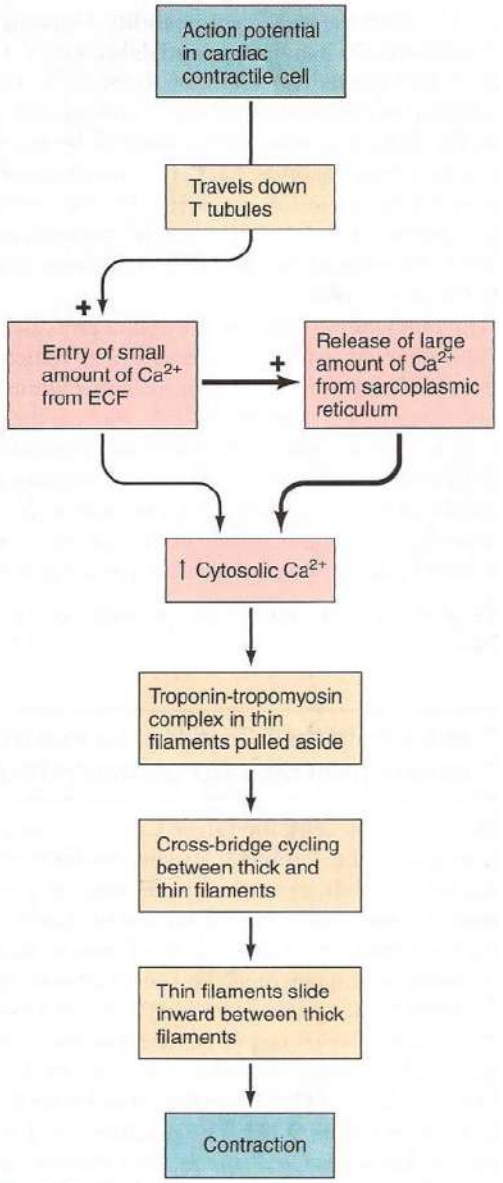
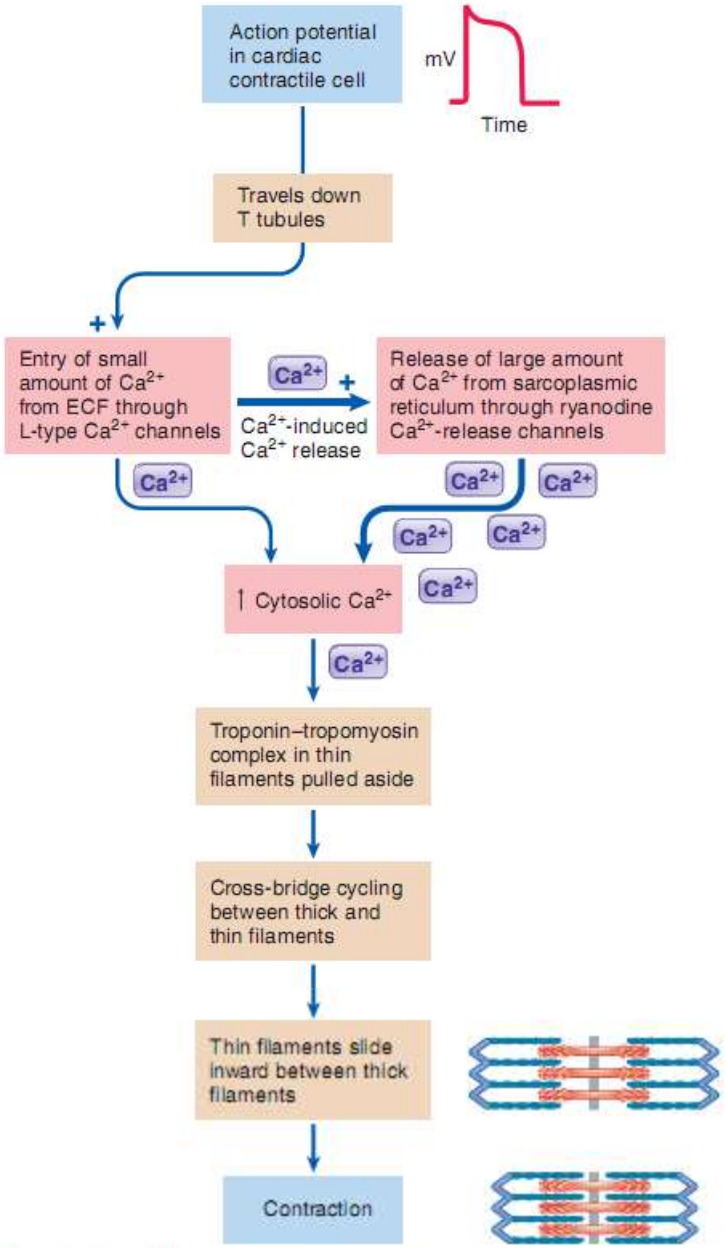



FIGURE 9-16
Excitation–contraction coupling in cardiac contractile cells




● **FIGURE 9-11** Excitation–contraction coupling in cardiac contractile cells.

# $Ca^{2+}$ entry from the ECF induces a much larger $Ca^{2+}$ release from the sarcoplasmic reticulum

➢ **Influence of altered ECF $K^+$ and $Ca^{2+}$ concentrations:**

- Changes in $K^+$ concentration in the ECF alter the $K^+$ concentration gradient between the ICF and ECF. Normally, there is substantially more $K^+$ inside the cells than in the ECF, but with *elevated ECF $K^+$ levels this gradient is reduced*.
- Among the consequences is a tendency to develop *ectopic foci* as well as cardiac arrhythmias. Also, the resultant diminution of the action potentials' intensity causes the heart to become weak, flaccid and dilated. At the extreme, with $K^+$ levels elevated *two to three times* the normal value, the weakened heart may actually stop pumping.
- A rise in ECF $Ca^{2+}$ concentration, augments the strength of cardiac concentration by prolonging the plateau phase. The heart tends to contract spastically, with little time to rest between contractions.

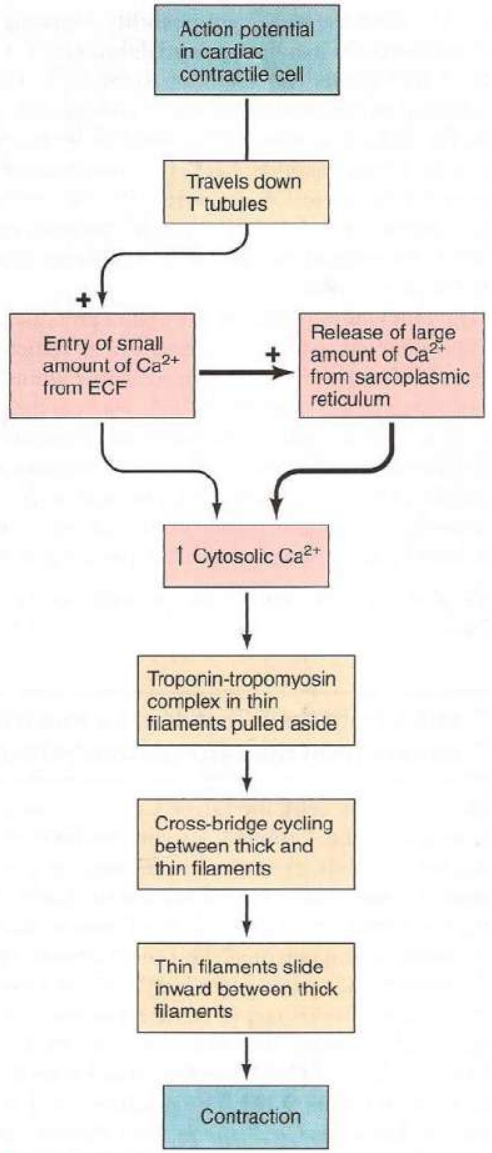



FIGURE 9-16
Excitation–contraction coupling in cardiac contractile cells

# $Ca^{2+}$ entry from the ECF induces a much larger $Ca^{2+}$ release from the sarcoplasmic reticulum

- **Some drugs that alter cardiac function do so by influencing $Ca^{2+}$ mevement;**

For example, $Ca^{2+}$ blocking agents, such as ***verapamil***, block $Ca^{2+}$ influx during contraction.

Other drugs, such as ***digitalis***, increase cardiac contractility by inducing an accumulation of cytosolic $Ca^{2+}$.

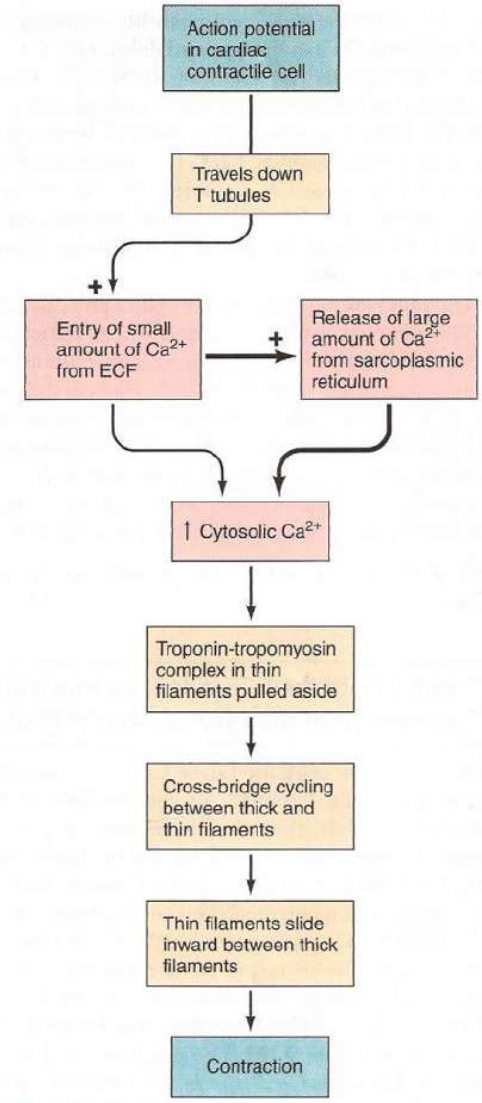



FIGURE 9-16
Excitation–contraction coupling in cardiac contractile cells

# Tetanus of cardiac muscle is prevented by a long refractory period

- Rapidly repetitive stimulation that does not allow the muscle fiber to relax between stimulations results in a sustained, maximal contraction known as ***tetanus***.
- Cardiac muscle has a long refractory period that lasts about 250 msec because of the prolonged action potential.
- A cardiac muscle fiber contraction averages about 300 msec in duration. Consequently, cardiac muscle cannot be restimulated until contraction is almost over, making summation of contraction and tetanus of cardiac muscle impossible.
- This is a valuable protective mechanism, because, ..??
- The chief factor is inactivation of $Na^+$ channels that were activated during the initial $Na^+$ influx of the rising phase, which can be activated once again to begin another action potential.
- (review page 107 fig. 4-9)

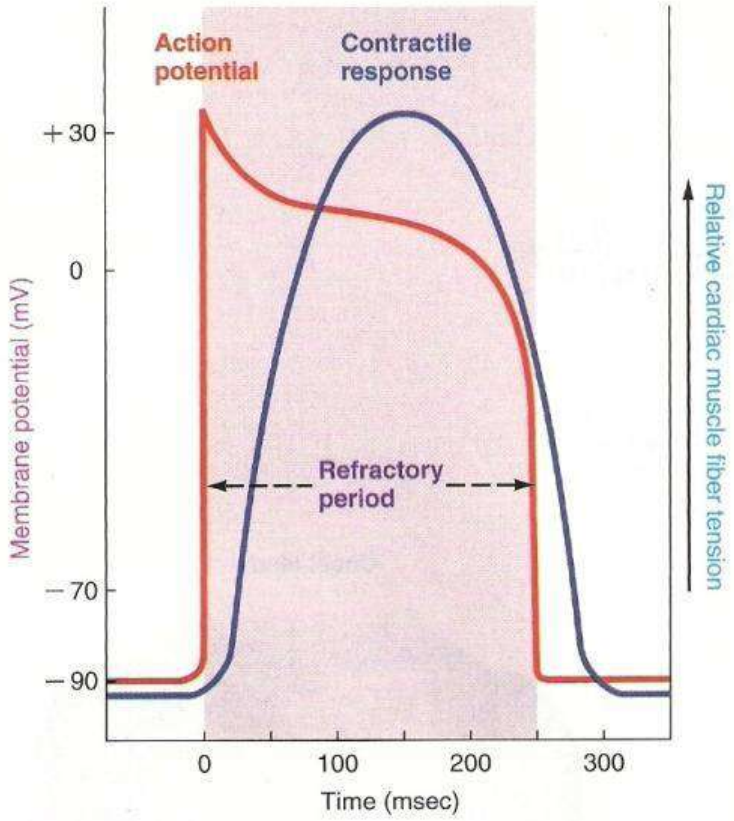
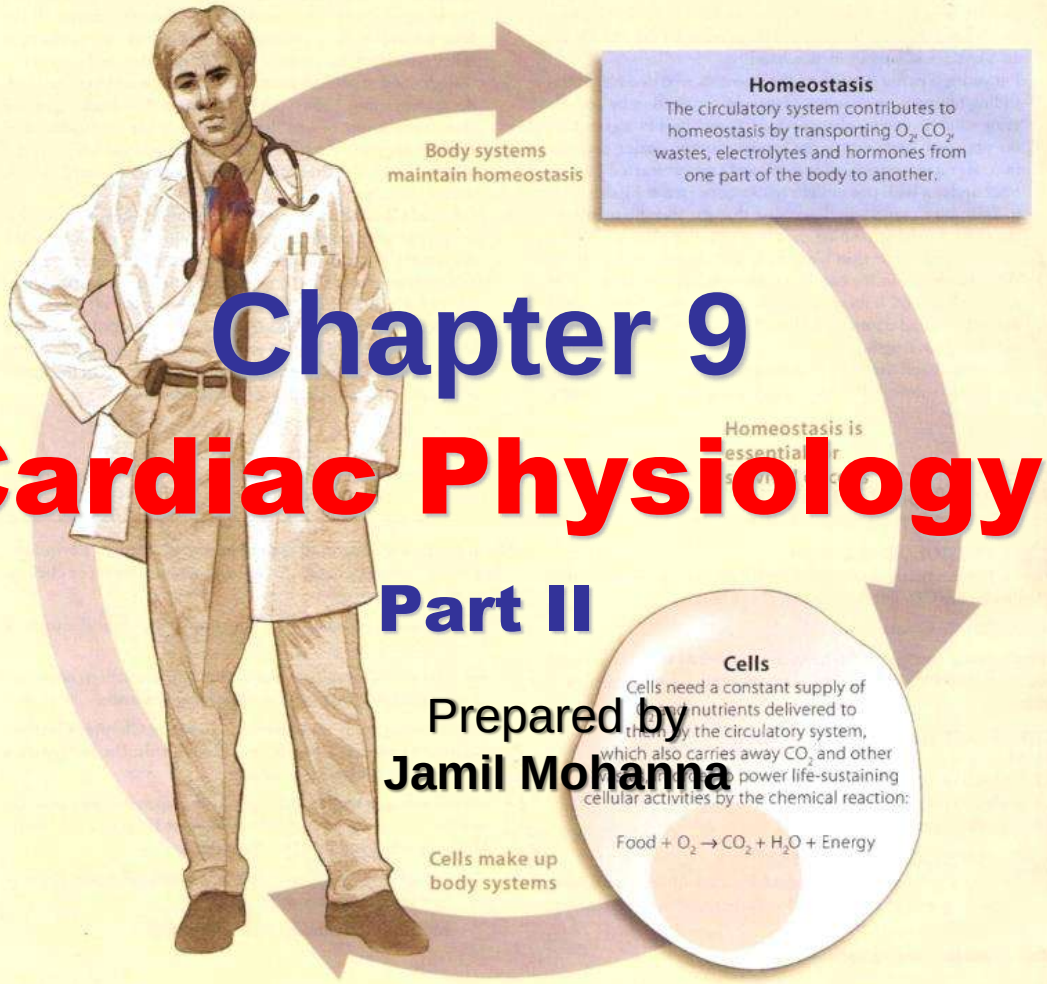



FIGURE 9-17
Relationship of an action potential and the refractory period to the duration of the contractile response in cardiac muscle

Circulatory System (Heart)




# Chapter 9
# Cardiac Physiology
## Part II

Prepared by
**Jamil Mohanna**

The maintenance of homeostasis depends on essential materials such as $O_2$ and nutrients being continually picked up from the external environment and delivered to the cells and on waste products being continually removed. Homeostasis also depends on the transfer of hormones, which are important regulatory chemical messengers, from their site of production to their site of action. The circulatory system, which contributes to homeostasis by serving as the body's transport system, consists of the heart, blood vessels, and blood.

All body tissues constantly depend on the life-supporting blood flow provided to them by the contraction or beating of the heart. The heart drives the blood through the blood vessels for delivery to the tissues in sufficient amounts, whether the body is at rest or engaging in vigorous exercise.

# The ECG is a record of the overall spread of electrical activity through the heart

- The electrical currents generated by cardiac muscle spread into the body fluids. A small portion reaches the body surface, where it can be detected using recording electrodes of **Electrocardiogram**, or **ECG**.

- Three important points should be remembered:

1- An ECG is not a direct recording of actual electrical activity of the heart.

2- The ECG is a complex recording representing the overall spread of activity throughout the heart during depolarization and repolarization.

* the record at any given time represents the sum of electrical activity in all the cardiac muscle cells, some of which may be undergoing action potentials while others may not yet be activated.

3- The recording represents comparisons in voltage detected by electrodes at two different points on the body surface, not the actual potential.

- The exact pattern of electrical activity recorded from the body surface depends on the orientation of the recording electrodes.
- Even though the same electrical events are occurring in the heart, different waveforms representing the same electrical activity result when this activity is recorded by electrodes at different points of the body.

# The ECG is a record of the overall spread of electrical activity through the heart

- To provide standard comparisons, ECG records routinely consist of 12 conventional electrode systems, or **leads**.
- The 12 different leads each record electrical activity in the heart from different locations-six different electrical arrangements from the limbs and six chest leads at various sites around the heart.

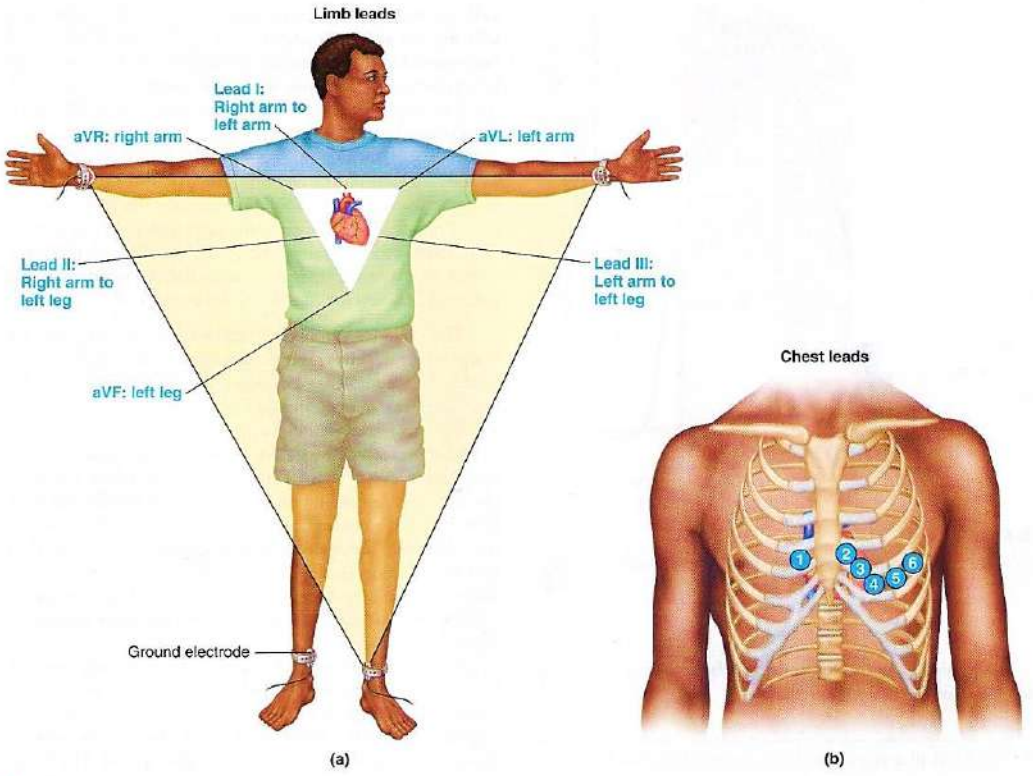



FIGURE 9-18

**Electrocardiogram leads**

(a) Limb leads. The six limb leads include leads I, II, III, aVR, aVL, and aVF. Leads I, II, and III are bipolar leads because two recording electrodes are used. The tracing records the *difference* in potential between the two electrodes. For example, lead I records the difference in potential detected at the right arm and left arm. The electrode placed on the right leg serves as a ground and is not a recording electrode. The aVR, aVL, and aVF leads are unipolar leads. Even though two electrodes are used, only the actual potential under one electrode, the exploring electrode, is recorded. The other electrode is set at zero potential and serves as a neutral reference point. For example, the aVR lead records the potential reaching the right arm in comparison to the rest of the body. (b) Chest leads. The six chest leads, $V_1$ through $V_6$, are also unipolar leads. The exploring electrode mainly records the electrical potential of the cardiac musculature immediately beneath the electrode in six different locations surrounding the heart.

# Various components of the ECG record can be correlated to specific cardiac events

- **Interpretation of ECG:**

A normal ECG exhibits three distinct waveforms: P wave, the QRS complex, and the T wave (Fig. 9-19).

The following important points about the ECG record should also be noted:

1. Firing of the SA node does not generate sufficient electrical activity , therefore, the first recorded wave, the **P wave**, occurs when the impulse spreads across the atria.
2. Atrial repolarization normally occurs simultaneously with ventricular depolarization and is masked by the **QRS complex**.
3. The P wave is much smaller than the QRS complex because the atria have a much smaller muscle mass than ventricles.

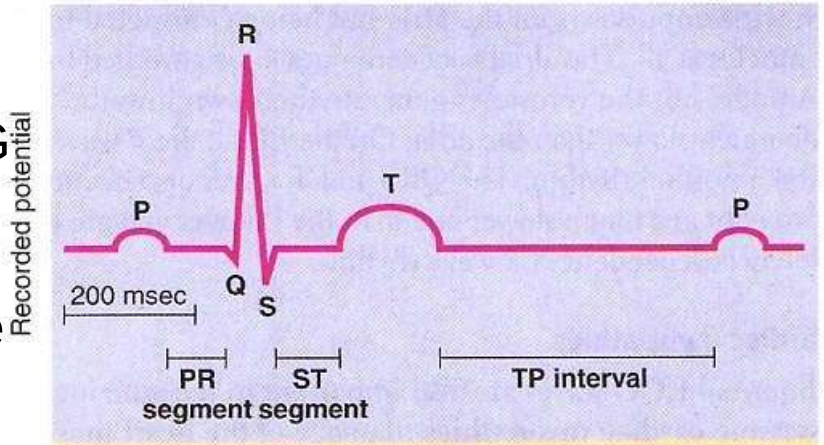
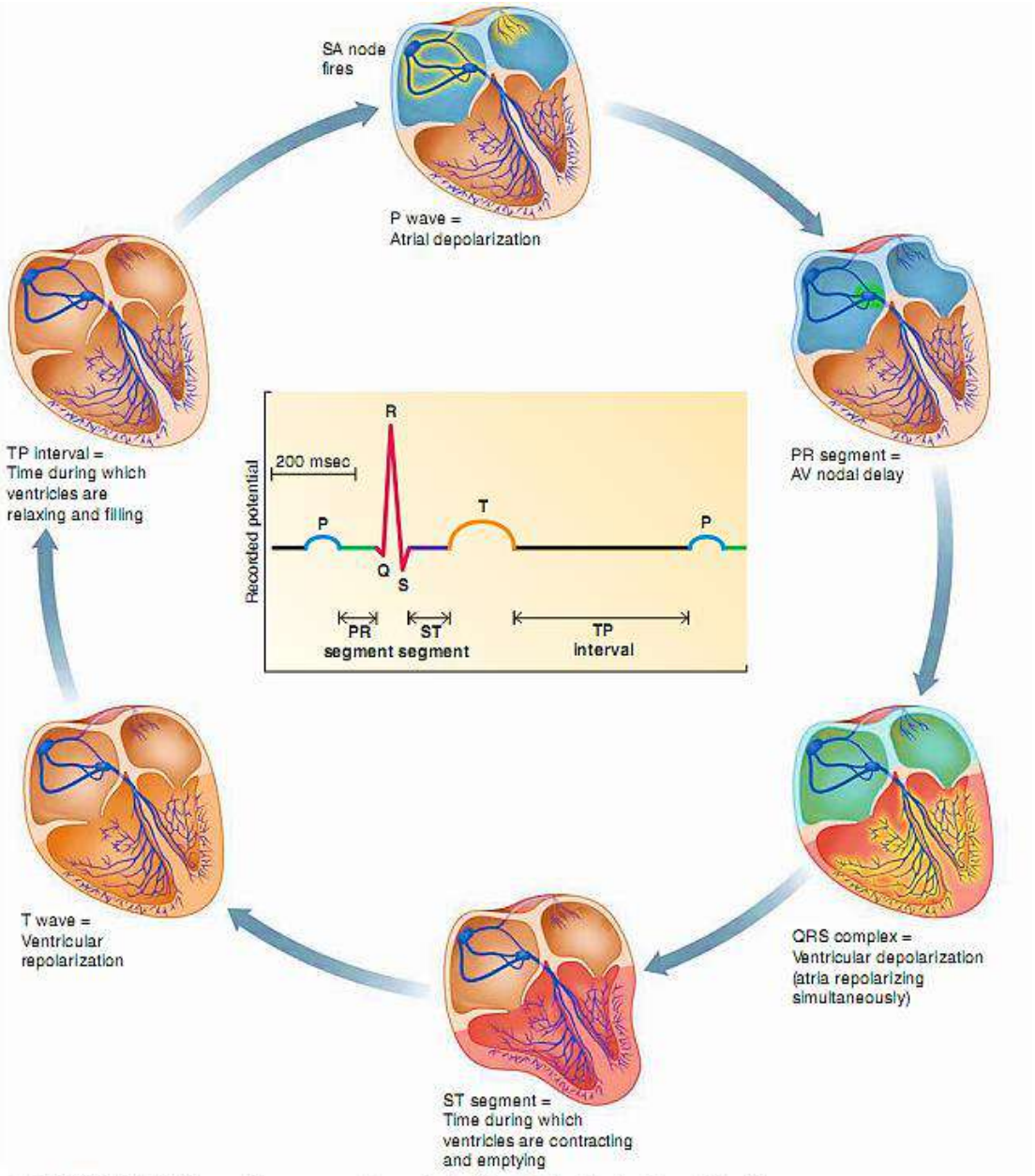



FIGURE 9-19
Electrocardiogram waveforms in lead II




● **FIGURE 9-14** Electrocardiogram waveforms in lead II and electrical status of heart

# Various components of the ECG record can be correlated to specific cardiac events

4. At three times no current is flowing in the heart musculature and the ECG remains at baseline:
   a. During the AV nodal delay ( the **PR segment**).
   b. When the ventricles are completely depolarized and the cardiac contractile cells are undergoing the plateau phase (**ST segment**).
   c. When the heart muscle is completely at rest and ventricular filling is taking place ( the **TP interval**)

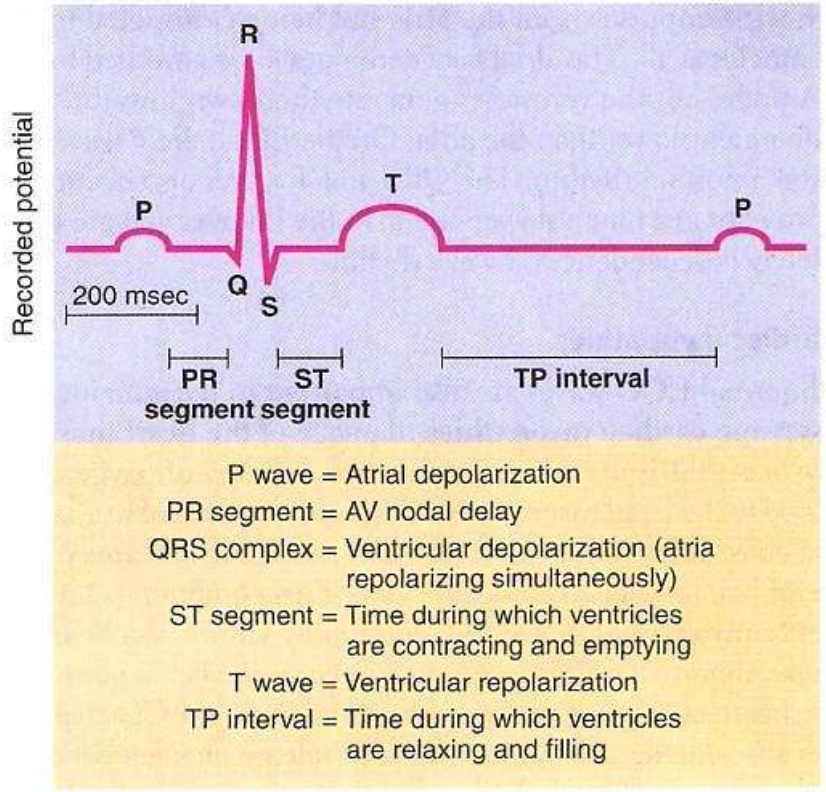



FIGURE 9-19
Electrocardiogram waveforms in lead II

# The ECG can be used to diagnose abnormal heart rates, arrhythmias, and damage of heart muscle

- Because electrical activity triggers mechanical activity, the evaluation of ECG patterns can provide useful information about the status of the heart.

- The principal deviations from normal that can be ascertained through electrocardiography are:
  **(1) Abnormalities in rate.**
  **(2) Abnormalities in rhythm.**
  **(3) Cardiac myopathies.**

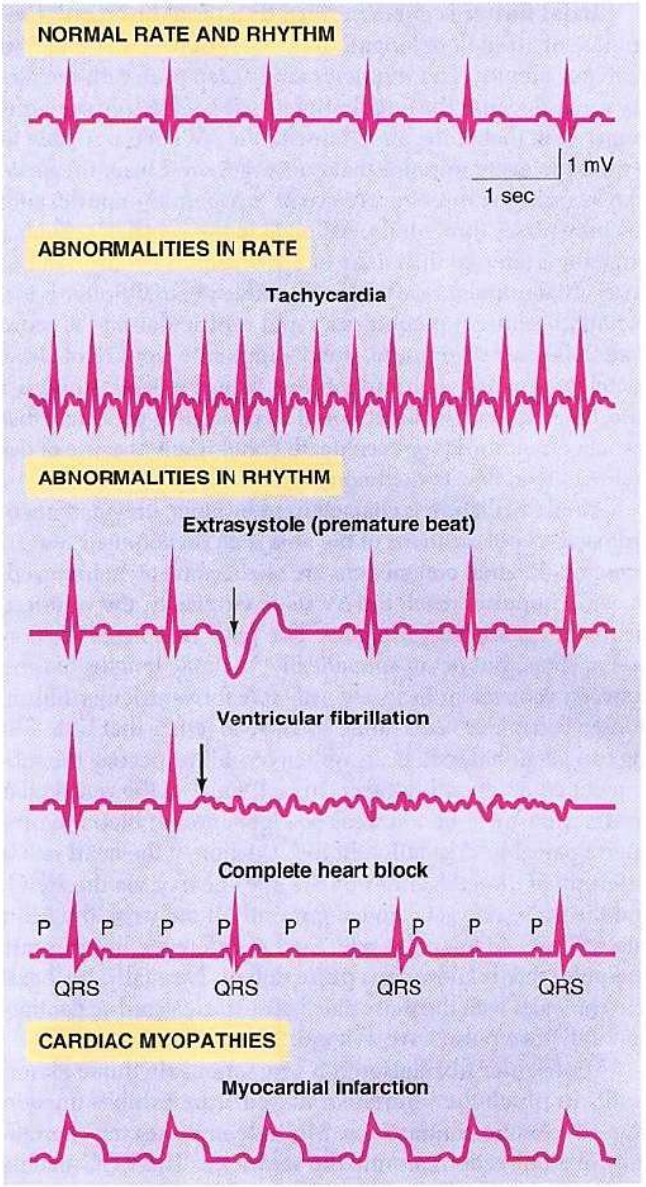



FIGURE 9-20
Representative heart conditions detectable through electrocardiography

# The ECG can be used to diagnose abnormal heart rates, arrhythmias, and damage of heart muscle

## (1) Abnormalities in rate.

The distance between two consecutive QRS complexes on an ECG record is calibrated to the beat-to-beat heart rate.

A rapid heart rate of more than 100 beats per minute is known as **tachycardia**, whereas a slow heart rate of fewer than 60 beats per minutes is referred to as **bradycardia**.

## (2) Abnormalities in rhythm.

The term *rhythm* is refers to the regularity of the ECG waves, while any variation termed an *arrhythmia*.

It may result from the ectopic foci, alterations in SA node pacemaker activity or interference with conduction. Heart rate is also often altered( *Extrasystoles* or *premature beats*).

Other abnormalities in rhythm easily detected on an ECG include atrial flutter, atrial fibrillation, ventricular fibrillation, and heart block.

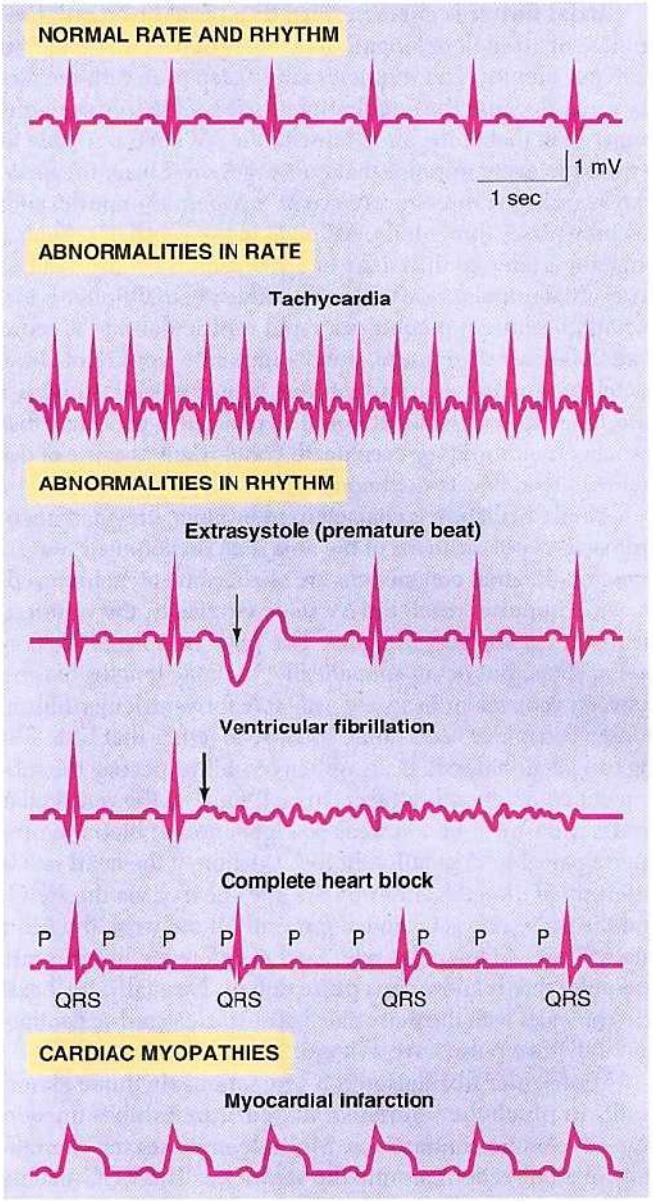



FIGURE 9-20
Representative heart conditions detectable through electrocardiography

# The ECG can be used to diagnose abnormal heart rates, arrhythmias, and damage of heart muscle

**Atrial flutter**; a rapid but regular sequence of atrial depolarizations at rates between 200 to 380 b/m, because the conducting tissue's refractory period is longer than that of the atrial muscle, the AV node is unable to respond to every impulse (2:1 or 3:1 rhythm)

Not every atrial impulse reaches the ventricle is important, or a rapid ventricular rate of more than 200 b/m would not allow adequate time for ventricular filling between beats, loss of consciousness or even death could result.

**Atrial fibrillation**, rapid, irregular, uncoordinated depolarizations of the atria with no definite P waves, the ventricular rhythm is also very irregular. The QRS complex is normal in shape but occur sporadically متفرق.

In fact, some of the ventricular contractions may be too weak to eject enough blood to produce a palpable wrist pulse.

If the heart rate is determined directly, the heart rate will exceed the pulse rate, such a difference known as a **pulse deficit**.

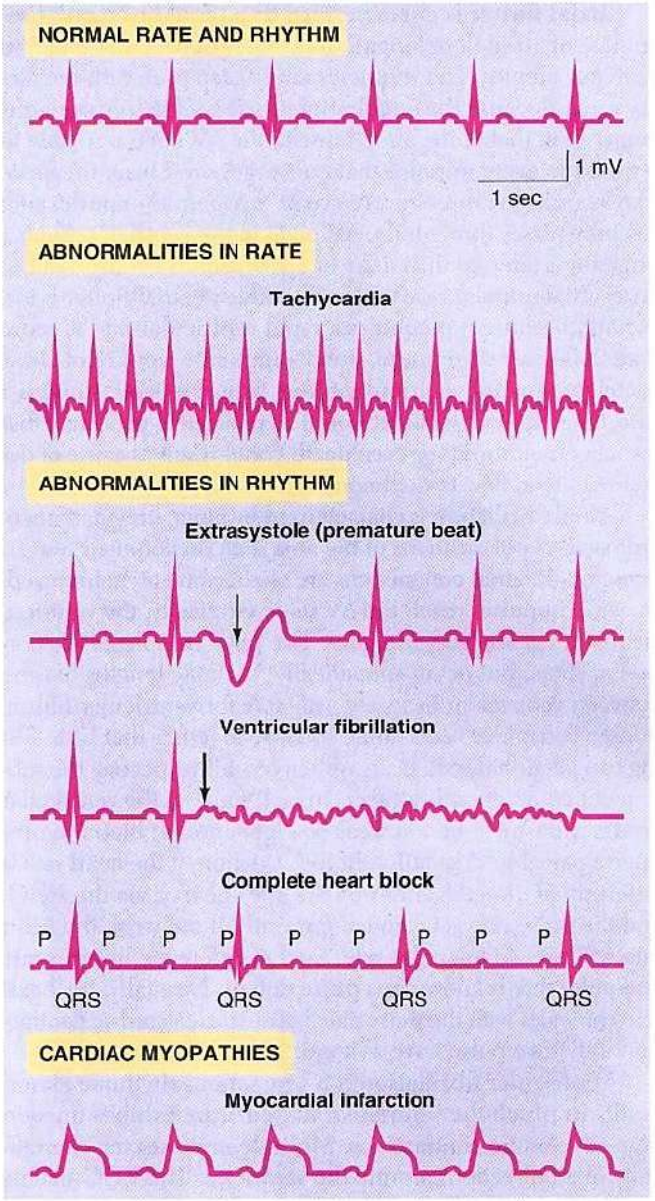



FIGURE 9-20
Representative heart conditions detectable through electrocardiography

# The ECG can be used to diagnose abnormal heart rates, arrhythmias, and damage of heart muscle

**Ventricular fibrillation**, in which the ventricular musculature exhibits uncoordinated, chaotic contractionsمشوشة.

If circulation is not restored in less than four minutes through external cardiac compression or electrical defibrillation, irreversible brain damage occurs, and death is imminent.

**Heart block**, arises from defects in the cardiac conducting system. In some forms of heart block shows 2:1 or 3:1 block.

In heart block, the atrial rate is normal but the ventricular rate is considerably below normal, whereas in atrial flutter the atrial rate is very high, in accompaniment with a normal or above normal ventricular rate.

On the ECG of ***complete heart block***, the P waves exhibit a normal rhythm. The QRS and T waves also occur regularly but at a much slower rate than the P waves.

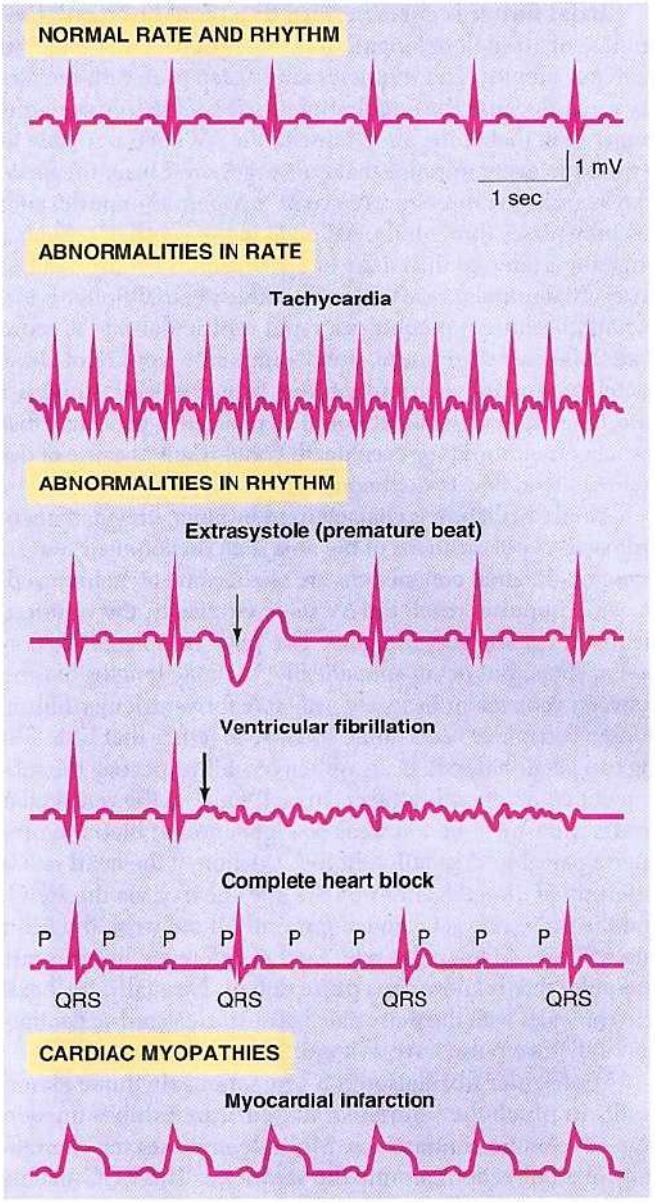



FIGURE 9-20
Representative heart conditions detectable through electrocardiography

# The ECG can be used to diagnose abnormal heart rates, arrhythmias, and damage of heart muscle

**(3) Cardiac myopathies**, a damage of the heart muscle.

**Myocardial ischemia** is inadequate delivery of oxygenate blood to the heart tissue. Actual death, or **necrosis**, of heart muscle cells occurs and termed **Acute myocardial infarction** (commonly a **heart attack**).

Damaged heart muscle cells release characteristic enzymes into the blood that provides a further index of the extent of myocardial damage.

- The foregoing discussion is not by any means intended to make you an ECG expert but seeks to give you an appreciation of the ways in which the ECG can be used as a diagnostic tool.

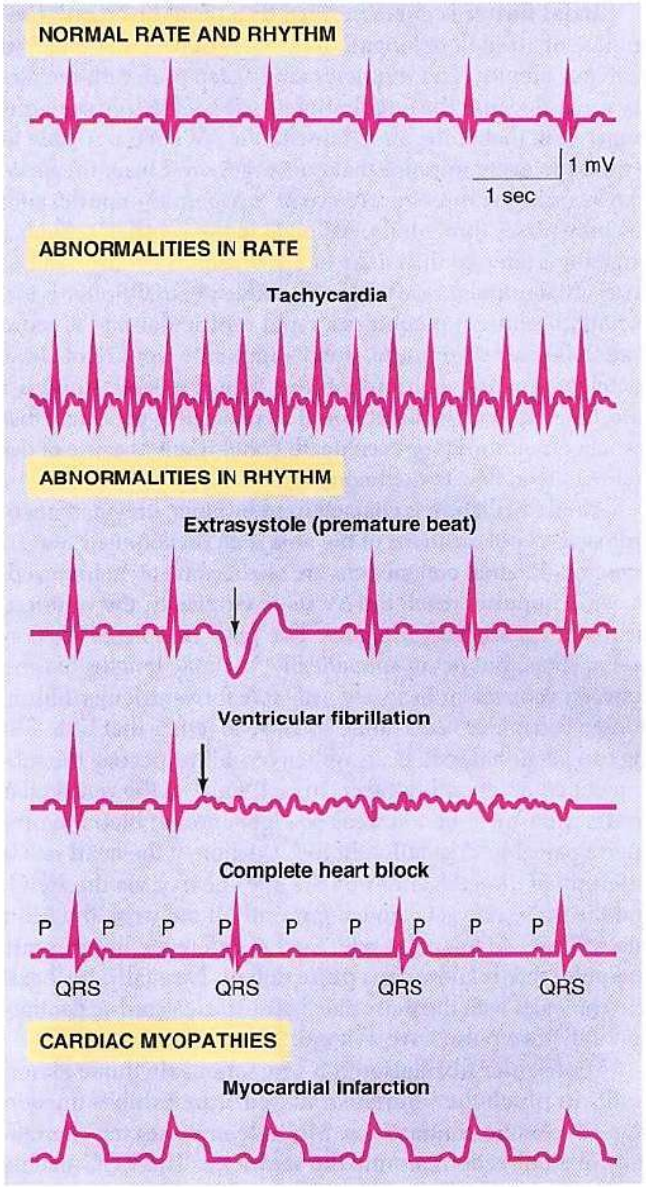
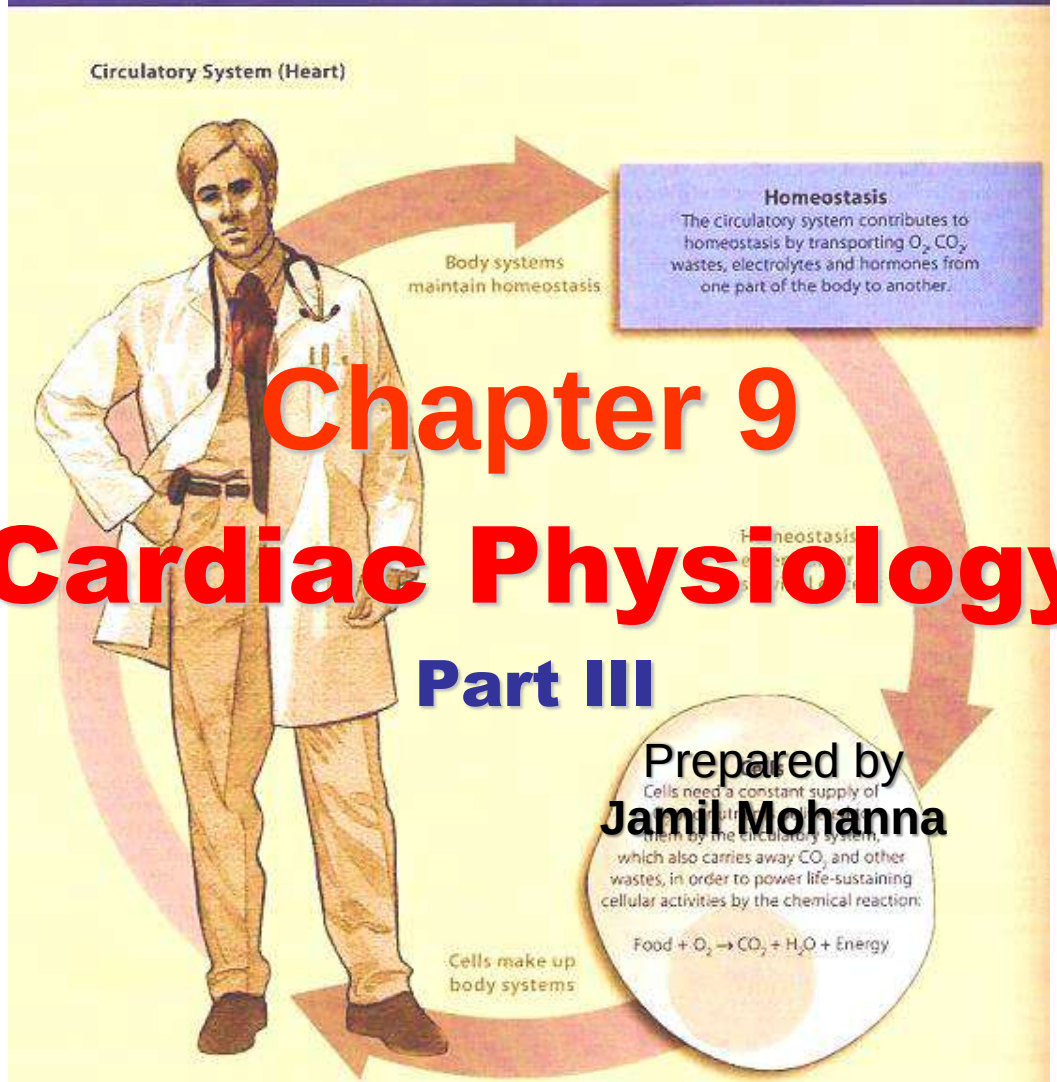



FIGURE 9-20
Representative heart conditions detectable through electrocardiography

# الحمد لله رب العالمين




# Chapter 9
# Cardiac Physiology
## Part III

Prepared by
**Jamil Mohanna**

The maintenance of homeostasis depends on essential materials such as $O_2$ and nutrients being continually picked up from the external environment and delivered to the cells and on waste products being continually removed. Homeostasis also depends on the transfer of hormones, which are important regulatory chemical messengers, from their site of production to their site of action. The circulatory system, which contributes to homeostasis by serving as the body's transport system, consists of the heart, blood vessels, and blood.

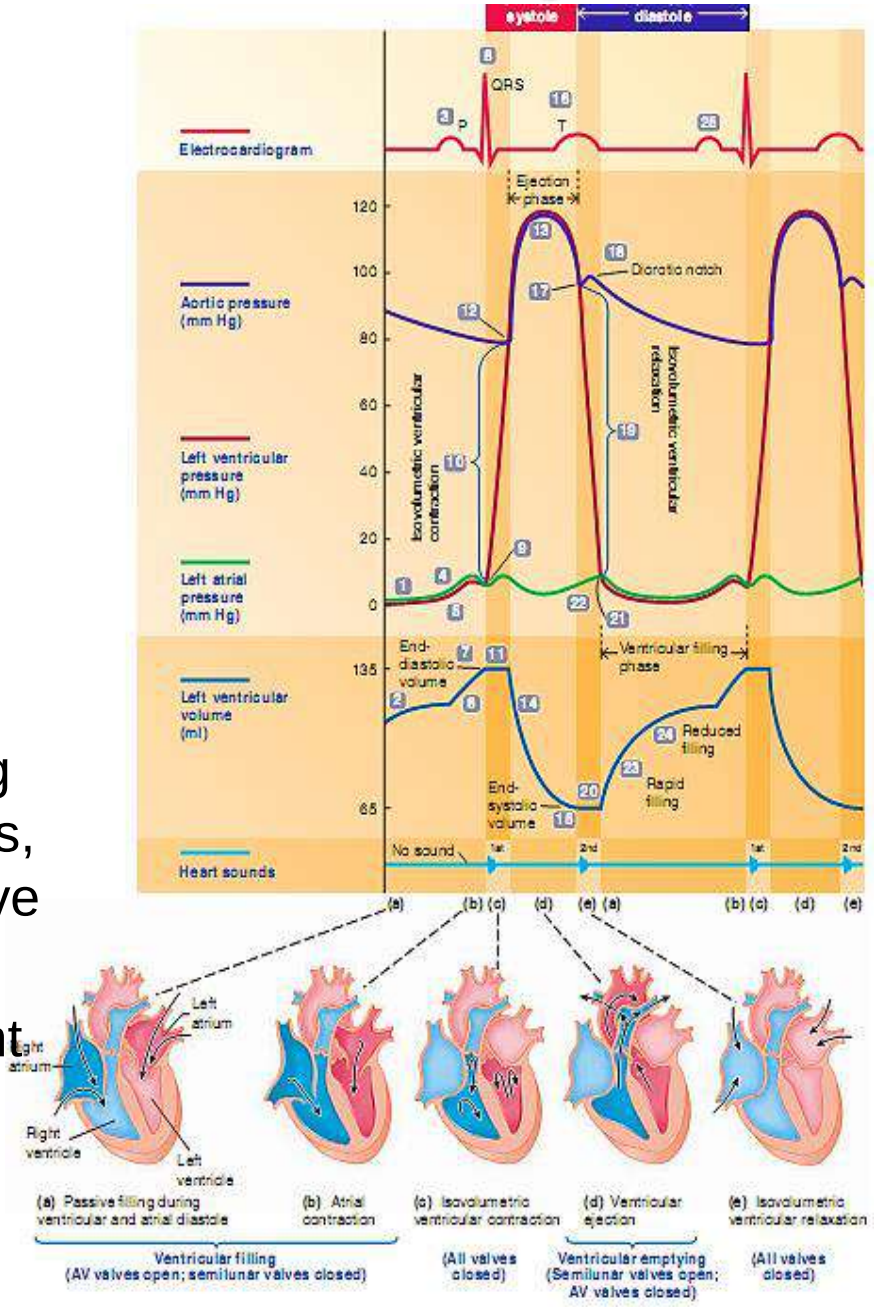
All body tissues constantly depend on the life-supporting blood flow provided to them by the contraction or beating of the heart. The heart drives the blood through the blood vessels for delivery to the tissues in sufficient amounts, whether the body is at rest or engaging in vigorous exercise.

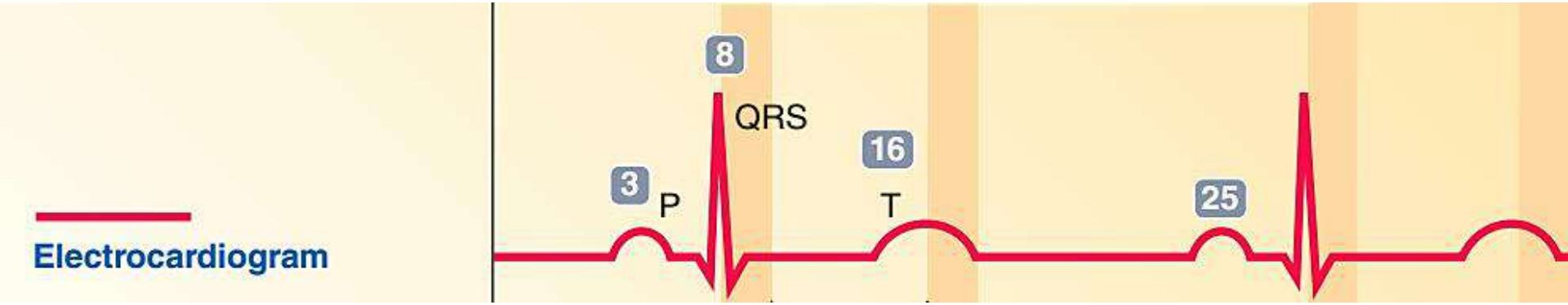
# Mechanical events of the cardiac cycle

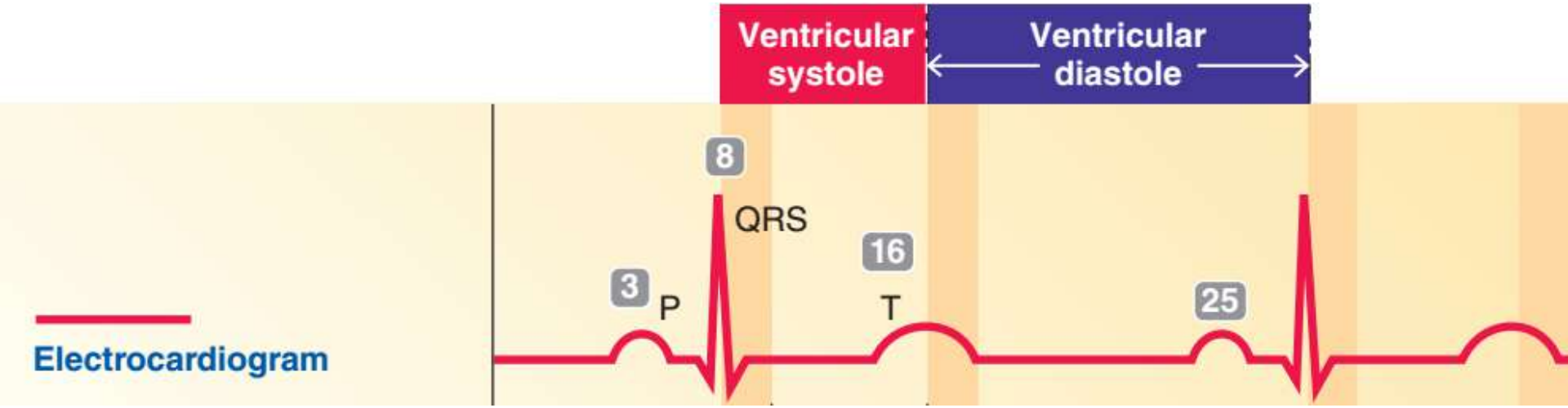
- The mechanical events of the cardiac cycle are brought about by the rhythmic changes in cardiac electrical activity.

**The heart alternately contracts to empty and relaxes to fill**

- The cardiac cycle consists of alternate periods of **systole** (contraction and emptying) and **diastole** (relaxation and filling).
- Various events occur concurrently during the cardiac cycle, including ECG features, pressure changes, volume changes, valve activity and heart sounds.
- Identical events are occurring on the right side of the heart, except that the pressures are lower.




8
QRS
16
3
P
T
25
Electrocardiogram


Ventricular systole
Ventricular diastole
8
QRS
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P
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25
Electrocardiogram

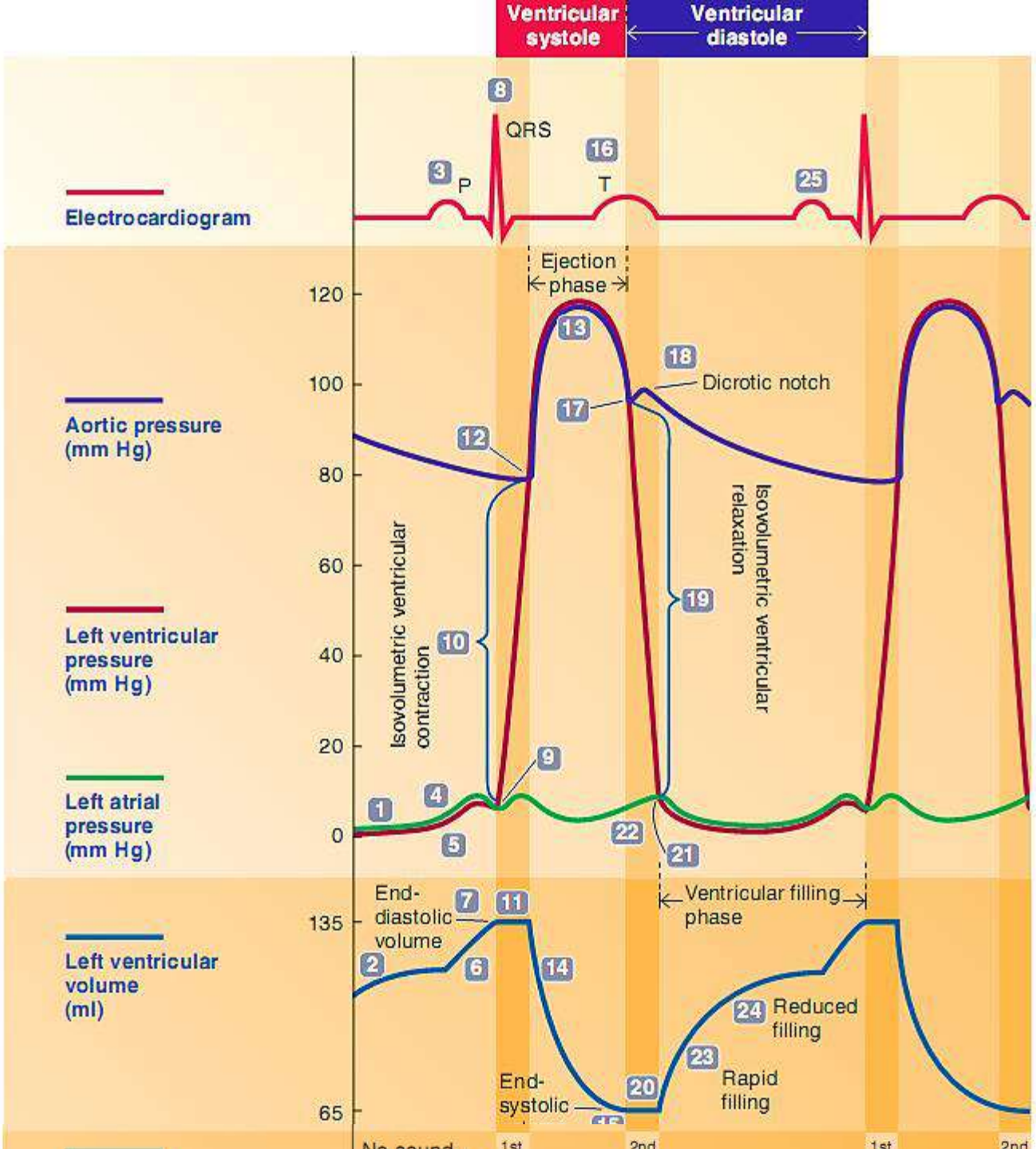
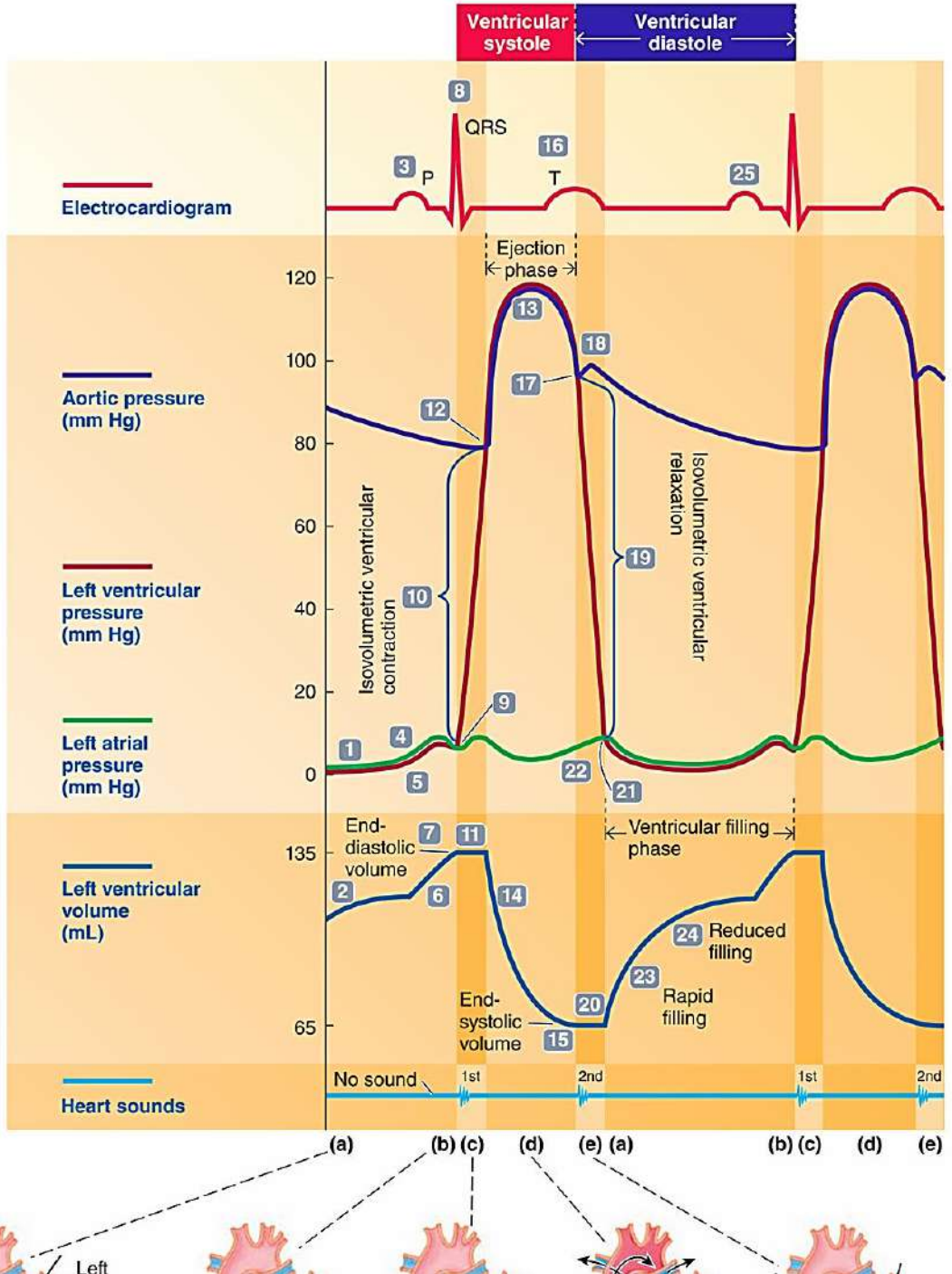

Ventricular systole
Ventricular diastole
Electrocardiogram
8
QRS
3
P
16
T
25
Ejection phase
120
100
80
60
40
20
0
Aortic pressure (mm Hg)
Left ventricular pressure (mm Hg)
Left atrial pressure (mm Hg)
13
18
Dicrotic notch
17
12
Isovolumetric ventricular contraction
Isovolumetric ventricular relaxation
10
19
9
4
1
5
22
21
Ventricular filling phase
End-diastolic volume
7
11
135
65
Left ventricular volume (ml)
2
6
14
24
Reduced filling
23
Rapid filling
End-systolic
20
1st
2nd
1st
2nd

**Figure 9-16 Cardiac cycle.** This diagram depicts various events that occur concurrently during the cardiac cycle. Follow each horizontal strip across to see the changes that take place in the electrocardiogram; aortic, ventricular, and atrial pressures; ventricular volume; and heart sounds throughout the cycle. The last half of diastole, one full systole and diastole (one full cardiac cycle), and another systole are shown for the left side of the heart. Follow each vertical strip downward to see what happens simultaneously with each of these factors during each phase of the cardiac cycle. See the text (pp. 315 and 317) for a detailed explanation of the numbered points. The sketches of the heart illustrate the flow of $O_2$-poor (*dark blue*) and $O_2$-rich (*dark pink*) blood in and out of the ventricles during the cardiac cycle.

**FIGURE FOCUS:** ***If the length of the diastolic filling phase is reduced by one half because the heart rate increases, would only half as much blood enter the ventricles? Use this figure to defend your answer.***



**Early ventricular diastole**

(1) The atrium is still also in diastole (TP interval), atrial pressure slightly exceeds ventricular pressure. This pressure differential open the AV valves.

(A) Blood flows directly from the atrium into the ventricle.

(2) The ventricular volume slowly continues to rise even before atrial contraction takes place.

**late ventricular diastole**

(3) The SA node reaches threshold and fires. The impulse spreads throughout the atria( P wave).

(4) Atrial contraction which squeezes more blood into the ventricle, causing a rise in the atrial pressure curve.

(5) Rise in ventricular pressure.

(6,B) Additional volume of blood added to the ventricle by atrial contraction.

**End of ventricular diastole**

(7) Ventricular diastole ends at the onset of ventricular contraction. Atrial contraction and ventricular filling are completed at the **end-diastolic volume(EDV)**, which averages about 135ml. The EDV is the maximum amount of blood that the ventricle will contain during cardiac cycle.

(8) By the time ventricular activation is complete, atrial contraction is already accomplished( QRS complex).

(9) Inducing ventricular contraction, and ventricular pressure curve sharply increases shortly after the QRS complex, signaling the onset of ventricular systole.

The slight delay between the QRS complex and the actual onset of ventricular systole is the time required for the excitation-contraction coupling process to occur.

Ventricular pressure immediately exceeds atrial pressure, this backward pressure differential forces the AV valve closed.

**Isovolumetric ventricular contraction**

(10) The ventricular pressure must continue to increase before it exceeds aortic pressure to open the aortic valve.

Between closure of the AV valve and opening of the aortic valve, there is a brief period of time when the ventricle remains a closed chamber.

(C) Because all valves are closed, this period termed **isovolumetric ventricular contraction**

(11) Because no blood enters or leaves the ventricle, constant ventricular volume, and the muscle fibers remain at constant length, ventricular pressure continues to increase as the volume remains constant.

**Ventricular ejection**

**(12)** When ventricular pressure exceeds aortic pressure,

**(D)** The aortic valve is forced open and ejection of blood begins.

(13) The aortic pressure curve rises as blood is forced into the aorta from the ventricle faster than blood is draining off into the smaller vessels at the other end.

(14) The ventricular volume decreases substantially as blood is rapidly pumped out. Ventricular systole includes both the period of isovolumetric contraction and the ventricular ejection phase.

**End of ventricular systole**

(15) Only about half the blood contained within the ventricle at the end of diastole is pumped out, and known as the **end-systolic volume (ESV)**, which averages about 65 ml.

the amount of blood pumped out of each contraction is known as the **stroke volume (SV)**, so the end-diastolic volume is 135m, the end-systolic volume is 65 ml, and the stroke volume is 70 ml.

**Ventricular repolarization and onset of ventricular diastole**

(16) The T wave signifies ventricular repolarization occurring at the end of ventricular systole.

(17) Ventricular pressure falls below aortic pressure and the aortic valve closes.

(18) Closure of the aortic valve produces a disturbance or notch on the aortic pressure curve known as **dicrotic notch**.

**Isovolumetric ventricular relaxation**

(19), (E) All valves are once again closed for a brief period of time known as ***Isovolumetric ventricular relaxation*** .

(20) The muscle fiber length and chamber volume remain constant. No blood leaves or enters as the ventricle continues to relax and the pressure steadily falls.

**Ventricular filling**

(21) When the ventricular pressure falls below the atrial pressure, the AV valve opens, and ventricular filling occurs once again. Ventricular diastole includes both the period of isovolumetric ventricular relaxation and the ventricular filling phase.

(22) Atrial repolarization and ventricular depolarization occur simultaneously. Blood continues to flow from the pulmonary veins into the left atrium, pools in atrium, atrial pressure rises continuously.

(A) The AV valve opens at the end of ventricular systole, the blood in the atrium pours rapidly into the ventricle.

( 23) ventricular filling thus occurs rapidly at first because of the increased atrial pressure resulting from the accumulation of blood in the atria.

(24) Then ventricular filling slows down.

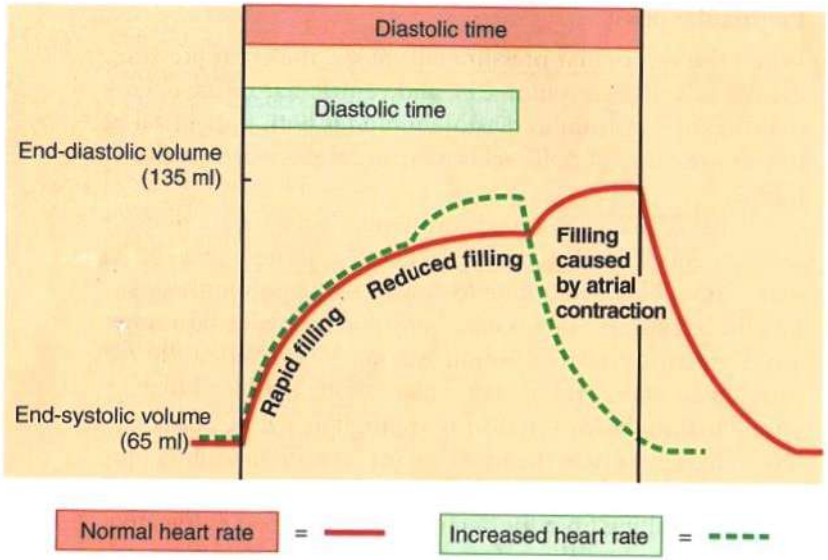
(During late ventricular diastole, when ventricular filling is proceeding slowly, the SA node fires again, and the cardiac cycle starts over.

- It is significant that much of ventricular filling occurs early in diastole during the rapid-filling phase. (Fig 9-22)

For example, if the heart rate increases from 75 to 180 beats per minute, the duration of diastole decreases about 75%, from 500 msec to 125 msec, such as during exercise.

At heart rates greater than 200 beats per minute, diastolic time is too short to allow adequate ventricular filling, the resultant cardiac output is deficient.

The relatively long refractory period of the AV node will not allow impulses to be conducted to the ventricles more frequently than 200 beats per minute.




● FIGURE 9-22

**Ventricular filling profiles during normal and rapid heart rates**
Because much of ventricular filling occurs early in diastole during the rapid-filling phase, filling is not seriously impaired when diastolic time is reduced as a result of an increase in heart rate.

# The two heart sounds are associated with valve closures

- With a stethoscope, the **first heart sound** is low-pitched, soft, and relatively long "**Lub**", associated with closure of the AV valves. Closure of the AV valves occurs at the onset of ventricular contraction, when ventricular pressure first exceeds atrial pressure, the first heart sound onset of ventricular systole.
- The **second heart sound** has a higher pitch and is shorter and sharper "**Dup**", associated with closure of the semilunar valves, that occurs at the onset of ventricular relaxation as the left and right ventricular pressures fall below the aortic and pulmonary artery pressures, therefore, the second heart sound signals the onset of ventricular diastole.
- The sounds are caused by vibrations set up within the walls of the ventricles and major arteries during valve closure, not by the valves snapping shut.

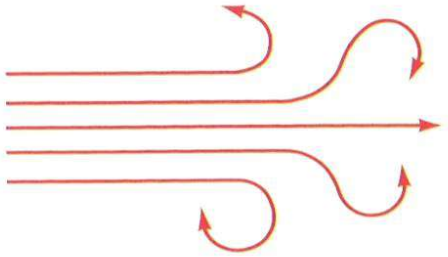
# Turbulent blood flow produces heart murmurs

- Abnormal heart sounds, or **murmurs** associated with cardiac diseases, **functional murmurs**, (not pathology) are more common in young people.
- Blood normally flows in a *laminar fashion,* not produce sound. When blood flow becomes turbulent, a sound can be heard due to vibrations created in the surrounding structures by the turbulent flow (fig. 9-23).

Laminar flow (does not create any sound)

**Stenotic and insufficient valves**, the most common cause of turbulence is valve malfunction, **a stenotic valve** is a stiff, narrowed valve that does not open completely, produces an abnormal whistling sound صفير .

An **insufficient valve ( leaky valve)** is one that cannot close completely, usually because the valve edges are scarred and do not fit together properly, so backward blood flows= **(regurgitation)** collides with blood moving in the opposite direction, creating a swishing or gurgling murmur.



Turbulent flow (can be heard)

Both cases caused by **rheumatic fever**, an autoimmune disease triggered by a streptococcus bacterial infection.

Large, hemorrhagic, fibrous lesions form along the inflamed edges of an affected heart valve, causing the valve to become thickened, stiff, and scarred. Some times the leaflet edges permanently adhere to each other.

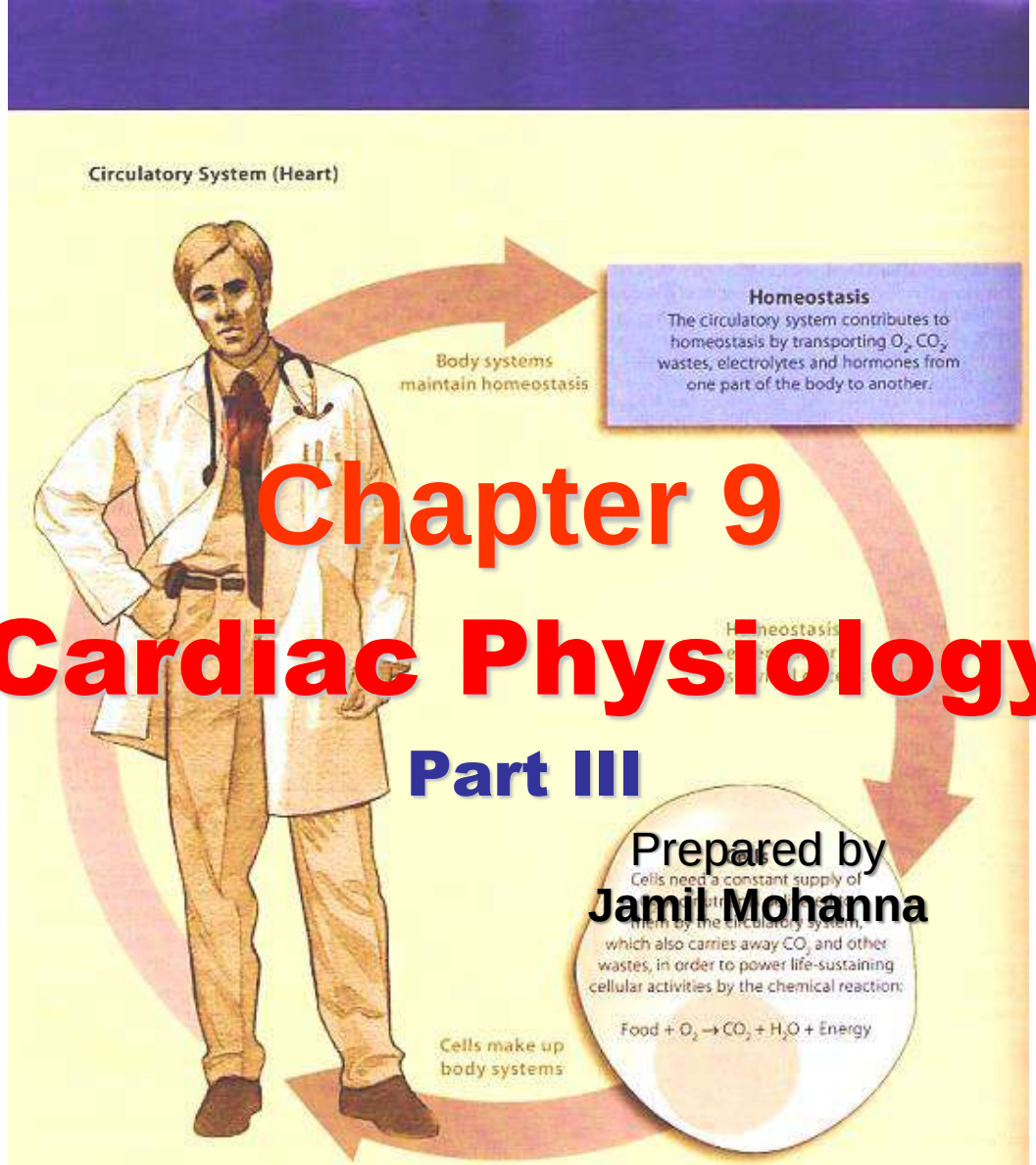
# Timing of murmurs

- The valve involved and the type of defect can usually be detected by the *location* and *timing* of the murmurs.
- The timing of the murmur refers to the part of the cardiac cycle during which the murmur is heard.
- Thus a murmur occurring between the first and second heart sounds ( lub-murmur-dup, lub-murmur-dup) signifies a **systolic murmur**. A **diastolic murmur**, in contrast, occurs between the second and first heart sound ( lub-dup-murmur, lub-dup-murmur)
- (Table 9-2).
- Identifying which of these valves is stenotic is accomplished by determining the location over which the murmur is best heard.
- The main concern with heart murmurs, is the accompanying detrimental circulatory consequences caused by the defect.

▲ TABLE 9-2
**Timing and Type of Murmur Associated with Various Heart Valve Disorders**

| Pattern Heard on Auscultation | Type of Valve Defect | Timing of Murmur | Valve Disorder | Comment |
|---|---|---|---|---|
| Lub-Whistle-Dup | Stenotic | Systolic | Stenotic semilunar valve | A whistling systolic murmur signifies that a valve that should be open during systole (a semilunar valve) does not open completely. |
| Lub-Dup-Whistle | Stenotic | Diastolic | Stenotic AV valve | A whistling diastolic murmur signifies that a valve that should be open during diastole (an AV valve) does not open completely. |
| Lub-Swish-Dup | Insufficient | Systolic | Insufficient AV valve | A swishy systolic murmur signifies that a valve that should be closed during systole (an AV valve) does not close completely. |
| Lub-Dup-Swish | Insufficient | Diastolic | Insufficient semilunar valve | A swishy diastolic murmur signifies that a valve that should be closed during diastole (a semilunar valve) does not close completely. |

# الحمد لله رب العالمين




# Chapter 9
# Cardiac Physiology
## Part III

Prepared by
**Jamil Mohanna**

The maintenance of homeostasis depends on essential materials such as $O_2$ and nutrients being continually picked up from the external environment and delivered to the cells and on waste products being continually removed. Homeostasis also depends on the transfer of hormones, which are important regulatory chemical messengers, from their site of production to their site of action. The circulatory system, which contributes to homeostasis by serving as the body's transport system, consists of the heart, blood vessels, and blood.

All body tissues constantly depend on the life-supporting blood flow provided to them by the contraction or beating of the heart. The heart drives the blood through the blood vessels for delivery to the tissues in sufficient amounts, whether the body is at rest or engaging in vigorous exercise.

# Cardiac output and its control

- **Cardiac output depends on the heart rate and the stroke volume**

**Cardiac out put (CO)** is the volume of blood pumped by each ventricle per minute.

**Cardiac output (CO) = heart rate * stroke volume**
**= 70 beats/min * 70 ml/beat**
**= 4900 ml/ min=5 liters/min**

Each half of the heart pumps the equivalent of the entire blood volume each minute. At this rate, each half of the heart would pump about 2.5 million liters of blood in just one year.

During exercise the cardiac output can increase to 20 to 25 liters per minute, and outputs as high as 40 liters per minute have been recorded in trained athletes during heavy exercise, the difference volume known as **cardiac reserve.**

# Heart rate is determined primarily by autonomic influences on the SA node

- The heart is innervated by both divisions of the autonomic nervous system, which can modify the rate ( as well as the strength) of contraction, even though nervous stimulation is not required to initiate contraction.
- The **parasympathetic nerve** to the heart, the **vagus nerve**, primarily supplies the atrium, especially the SA and AV nodes, while the ventricles is sparse. The cardiac **sympathetic nerves** supply the atria and richly innervate the ventricles as well.
- Both divisions affects the heart by altering the activity of the cyclic AMP second-messenger system in the innervated cardiac cells. Acetylcholine released from the vagus nerve binds to a muscarinic receptor and is coupled to an inhibitory G-protein that reduces activity of the cyclic AMP pathway.
- The sympathetic neurotransmitter **norepinephrine** binds with a **β1 adrenergic receptor** and is coupled to a stimulatory G protein that accelerates the cyclic AMP pathway in the target cells.

# The specific effects that parasympathetic and sympathetic stimulation have on the heart

**TABLE 9-3** Effects of the Autonomic Nervous System on the Heart and Structures That Influence the Heart

| Area Affected | Effect of Parasympathetic Stimulation | Effect of Sympathetic Stimulation |
|---|---|---|
| **SA Node** | Decreases the rate of depolarization to threshold; decreases the heart rate | Increases the rate of depolarization to threshold; increases the heart rate |
| **AV Node** | Decreases excitability; increases the AV nodal delay | Increases excitability; decreases the AV nodal delay |
| **Ventricular Conduction Pathway** | No effect | Increases excitability; hastens conduction through the bundle of His and Purkinje cells |
| **Atrial Muscle** | Decreases contractility; weakens contraction | Increases contractility; strengthens contraction |
| **Ventricular Muscle** | No effect | Increases contractility; strengthens contraction |
| **Adrenal Medulla (an Endocrine Gland)** | No effect | Promotes adrenomedullary secretion of epinephrine, a hormone that augments the sympathetic nervous system's actions on the heart |
| **Veins** | No effect | Increases venous return, which increases the strength of cardiac contraction through the Frank–Starling mechanism |

# Effect of parasympathetic stimulation on the heart

- **The parasympathetic** nervous system's acetylcholine decrease the heart rate **by slowing the closure of $K^+$** , the rate is reduced through:

1. Enhanced $K^+$ permeability hyperpolarizes the SA node membrane.
2. The enhanced $K^+$ permeability **opposes the gradual depolarization of the membrane to threshold**, decreases the rate of depolarization, prolonging the time required to drift to threshold.

- Parasympathetic influence on the AV node decreases the node's excitability**, prolonging the usual AV nodal delay**, by increasing $K^+$ permeability retarding the initiation of excitation in the AV node.
- Parasympathetic stimulation of the atrial contractile cells shortens the action potential, by a reduction in the slow inward current carried by $Ca^{2+}$ that is, the plateau phase is reduced; atrial contraction is weakened.
- Thus the heart is more 'leisurely' تمهلا under para-sympathetic influence it beats less rapidly, the time between atrial and ventricular contraction is stretched out and atrial contraction is weaker.

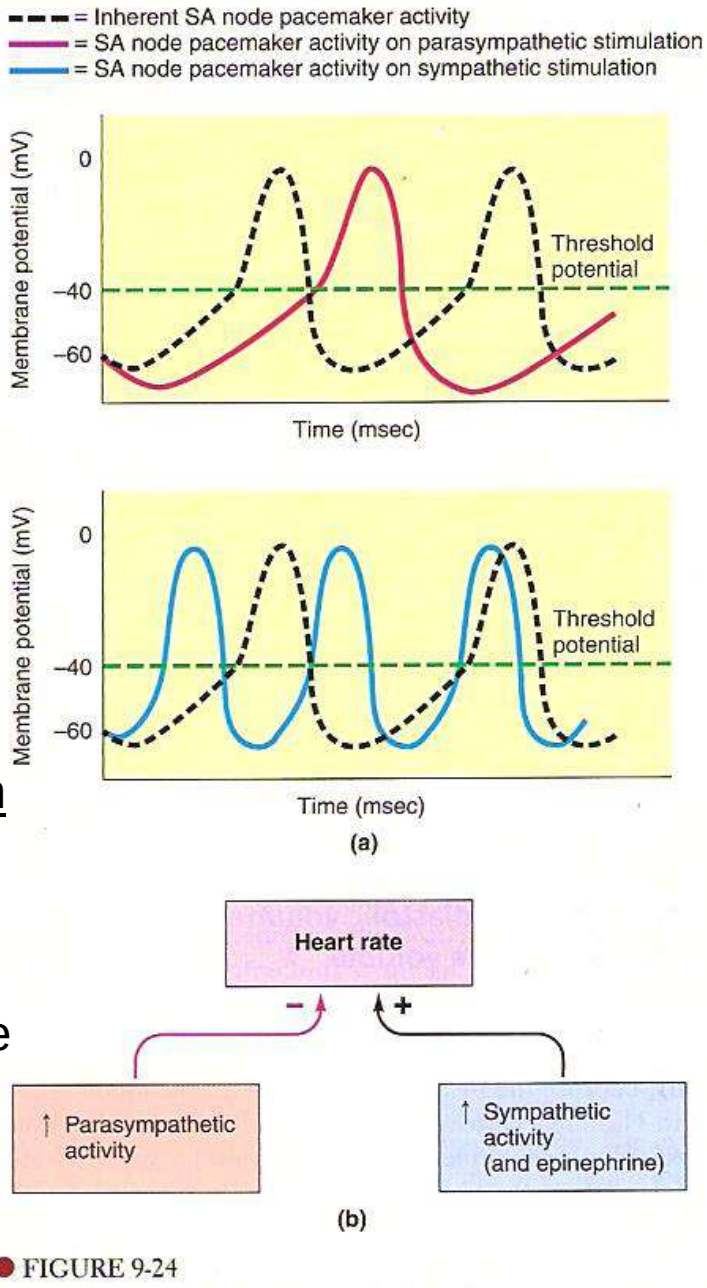



FIGURE 9-24

# Effect of sympathetic stimulation on the heart

- The main effect of sympathetic stimulation on the SA node is to increase its rate of depolarization so that threshold is reached more rapidly ( fig. 9-24) and (table 9-3). **Norepinephrine accelerating inactivation of the $K^+$ channels**, the inside of the cell becomes less negative, creating a depolarizing effect, permits a greater frequency of action potentials and a correspondingly more rapid heart rate.
- Sympathetic stimulation of the AV node reduces the AV nodal delay, by enhancing the slow, inward $Ca^{2+}$ current.
- Similarly, speeds up throughout the specialized conduction pathway.
- In the atrial and ventricular contractile cells, sympathetic stimulation **increases contractile strength** so that the heart beats more forcefully and squeezes out more blood, by increasing $Ca^{2+}$ permeability.

The overall effect of sympathetic stimulation on the heart, by increasing the heart rate, decreasing the AV delay , decreasing conduction time and increasing the force of contraction.

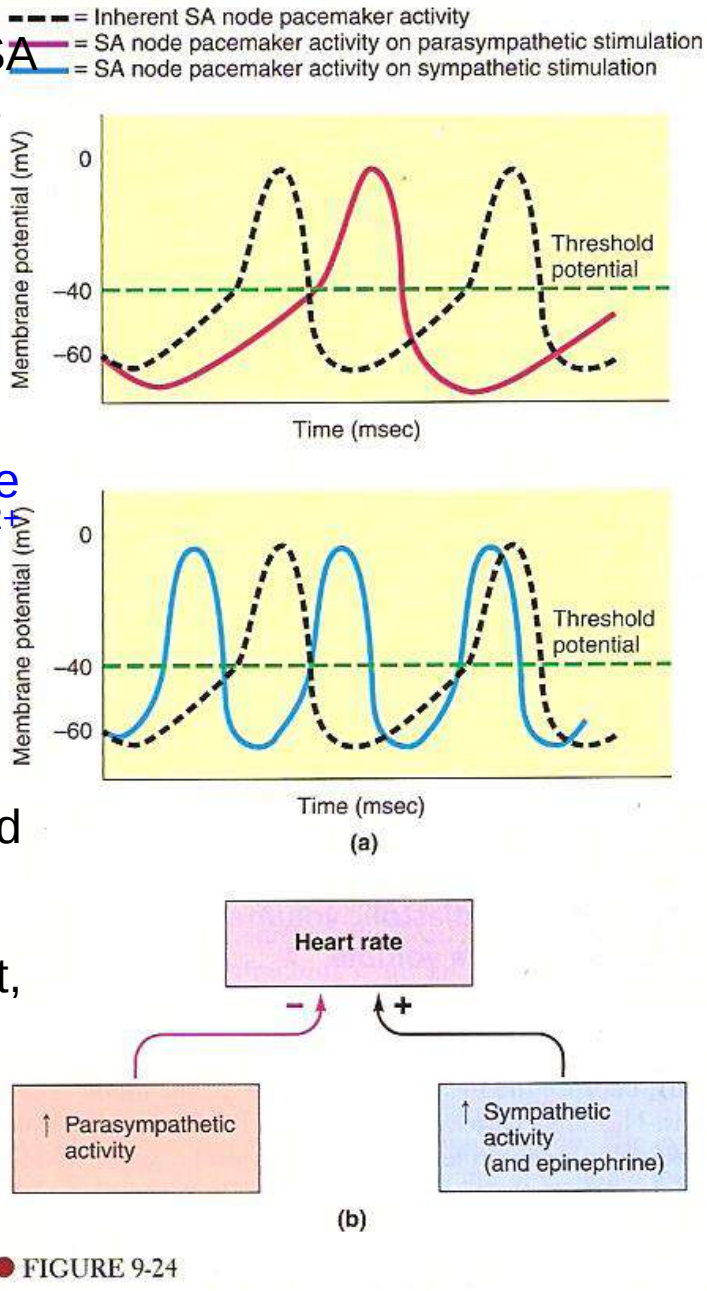



FIGURE 9-24

# Control of heart rate

- Both branches of ANS effect on heart rate are antagonistic.
- At any given moment, the heart rate is determined largely by the existing balance between the inhibitory effects of the vagus nerve and the stimulatory effects of the cardiac sympathetic nerves.
- In fact, if all autonomic nerves to the heart were blocked, the resting heart rate would increase to about 100 beats per minute.
- The relative level of activity in these two autonomic branches to the heart in turn is primarily coordinated by the ***cardiovascular control center*** located in the brain stem.
- The most important regulated factors affect heart
  is epinephrine, a hormone that is secreted into the blood from the adrenal medulla on sympathetic stimulation, to increase the heart rate, therefore reinforces the direct effect that the sympathetic nervous system has on the heart ( +ve feed back ).

**Stroke volume is determined by the extent of venous return and by sympathetic activity:**

Two types of controls influence stroke volume:

*(1) Intrinsic control* related to the extent of venous return

(2) *Extrinsic control* related to the extent of sympathetic stimulation of the heart.

Both factors increase stroke volume by increasing the strength of contraction of the heart (fig. 9-25).

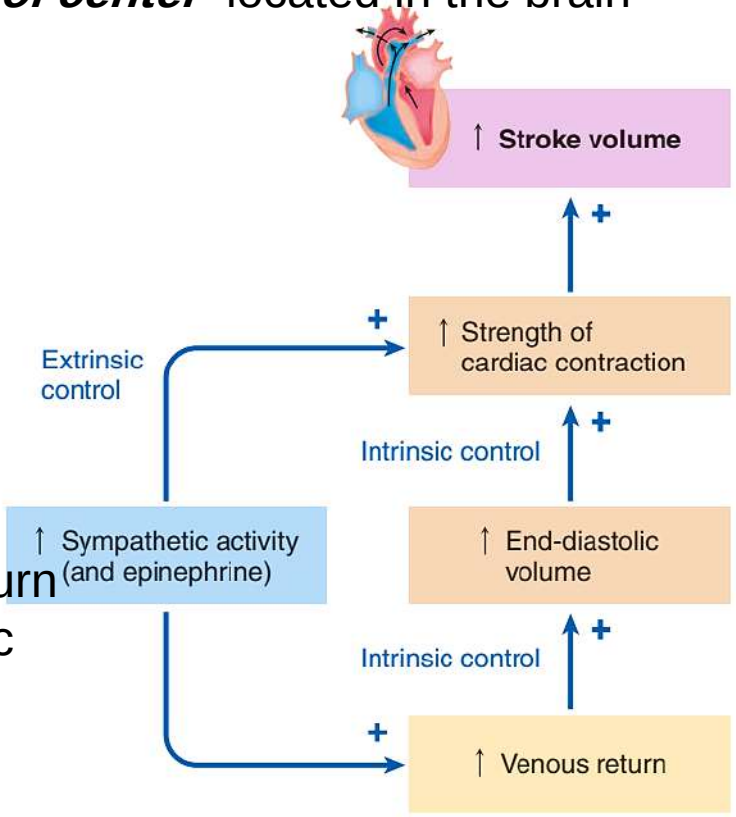
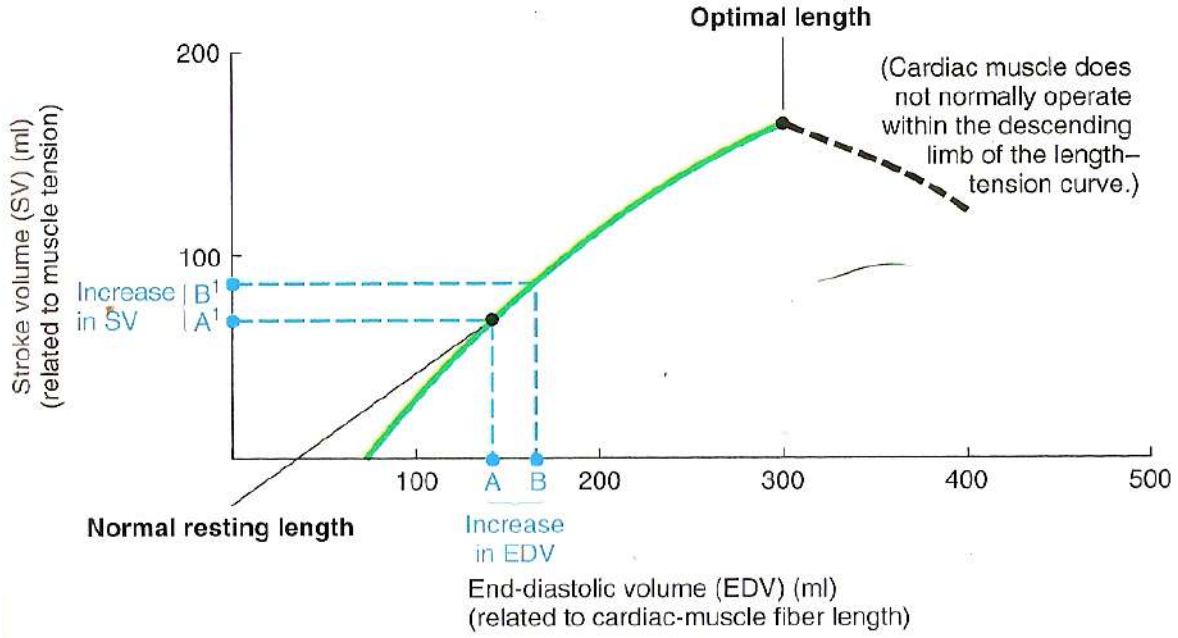



Figure 9-20 Intrinsic and extrinsic control of stroke volume.

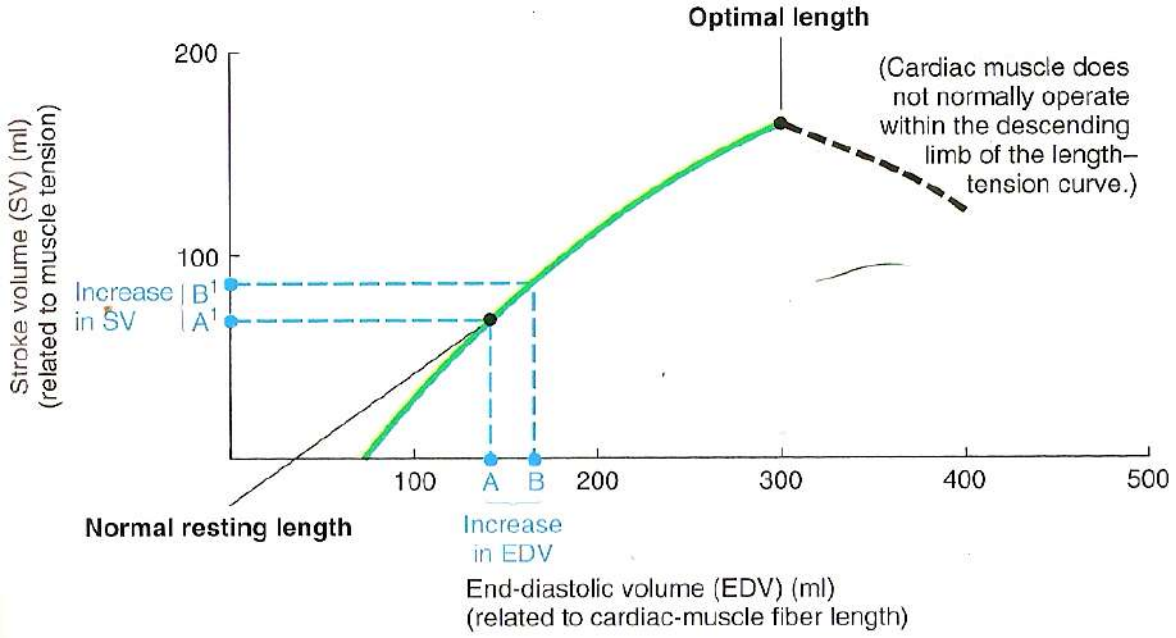
# Increased end-diastolic volume results in increased stroke volume

- As more blood is returned to the heart, the heart pumps out more blood. This intrinsic control depends on ***the length-tension relationship*** of cardiac muscle. The resting cardiac muscle fiber length is less than optimal length.
- An increase in cardiac muscle fiber length, *by moving closer to the optimal length, increases the contractile tension of the heart on the following systole*.



# Frank – Starling law of the heart

- What causes cardiac muscle fibers to vary in length before contraction?
- The main determinant of cardiac muscle fiber length is the degree of diastolic filling, the greater the extent of diastolic filling, the larger the end-diastolic volume, and the more the heart is stretched, the longer the initial cardiac-fiber length before contraction.
- **Frank-Starling law of the heart** says that **the heart normally pumps all the blood returned to it**; increased venous return results in increased stroke volume.
- The extent of filling is referred to as the **preload**.



# Advantages of the cardiac length-tension relationship

- Stoke volume and venous return relationship has two important advantages:

**First,** this intrinsic mechanism *is equalization of output between the right and left sides of the heart*. If such equalization did not happen, excessive damming of blood would occur in the venous system preceding the ventricle with the lower output.

**Second**, *when a larger cardiac output is needed*, venous return is increased through SNS activity and other mechanisms.

The resultant increase in end-diastolic volume automatically increases stroke volume correspondingly. Because exercise also increases heart rate, theses two factors act together to increase the cardiac out put so that more blood can be delivered to the exercising muscles.

**X Mechanism of the cardiac length-tension relationship**

Although the length-tension relationship in cardiac muscle fibers depends to a degree on the extent of overlap of thick and thin filaments, the key factor relating cardiac muscle fiber length to tension development is a length dependence of myofilament $Ca^{2+}$ sensitivity.

As a cardiac muscle fiber is stretched as a result of greater ventricular filling, its myofilaments are pulled closer together, more cross-bridge interactions between myosin and actin can take place, myofilament $Ca^{2+}$ sensitivity increases.

# The contractility of the heart is increased by sympathetic stimulation

- Sympathetic stimulation and epinephrine enhance the heart's **contractility**, which is the strength of contraction at any given end-diastolic volume, due to the increased $Ca^{2+}$ influx triggered by norepinephrine and epinephrine, allows the myocardial fibers to generate more force through greater cross-bridge cycling (fig 9-27).
- In effect, sympathetic stimulation shifts the Frank-Starling curve to the left, the curve can be shifted to varying degrees, up to a maximal increase in contractile strength of about 100% greater than normal, by enhancing venous return (fig. 9-28).
- Sympathetic stimulation constricts the veins, which squeezes more blood forward from the veins to the heart, increasing the end-diastolic volume and subsequently increasing the stroke volume even further.

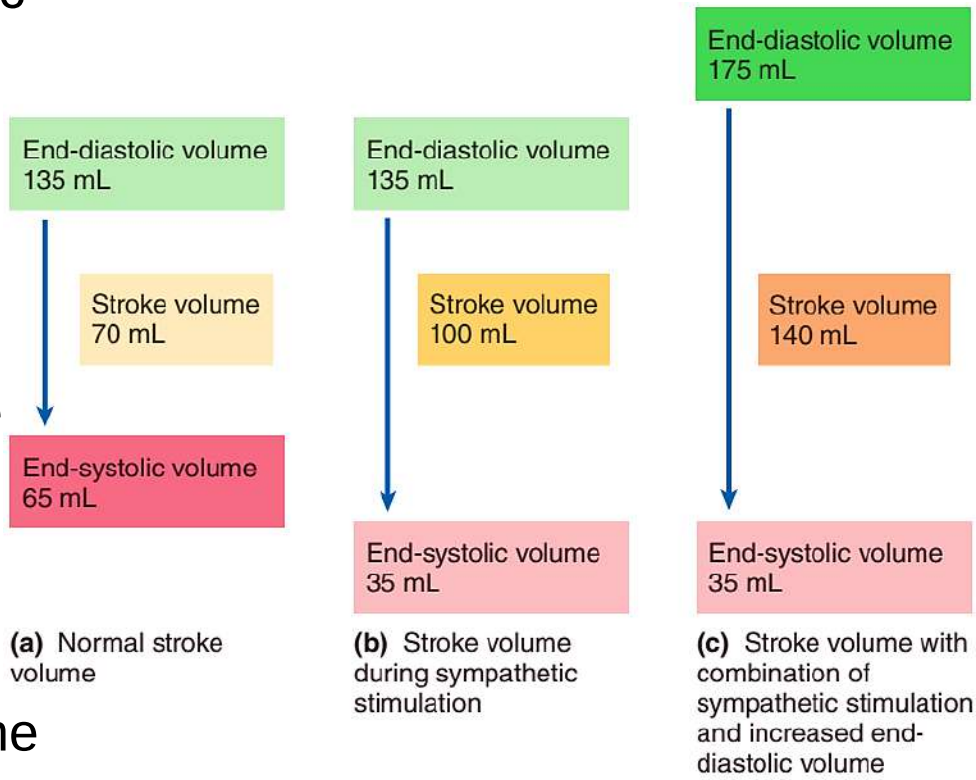



Figure 9-22 Effect of sympathetic stimulation on stroke volume.

# Summary of factors affecting stroke volume and cardiac output

- All factors that determine the cardiac output by influencing the heart rate or stroke volume are summarized in (Fig. 9-29).
- Note that sympathetic stimulation increases the cardiac output by increasing both heart rate and stroke volume.

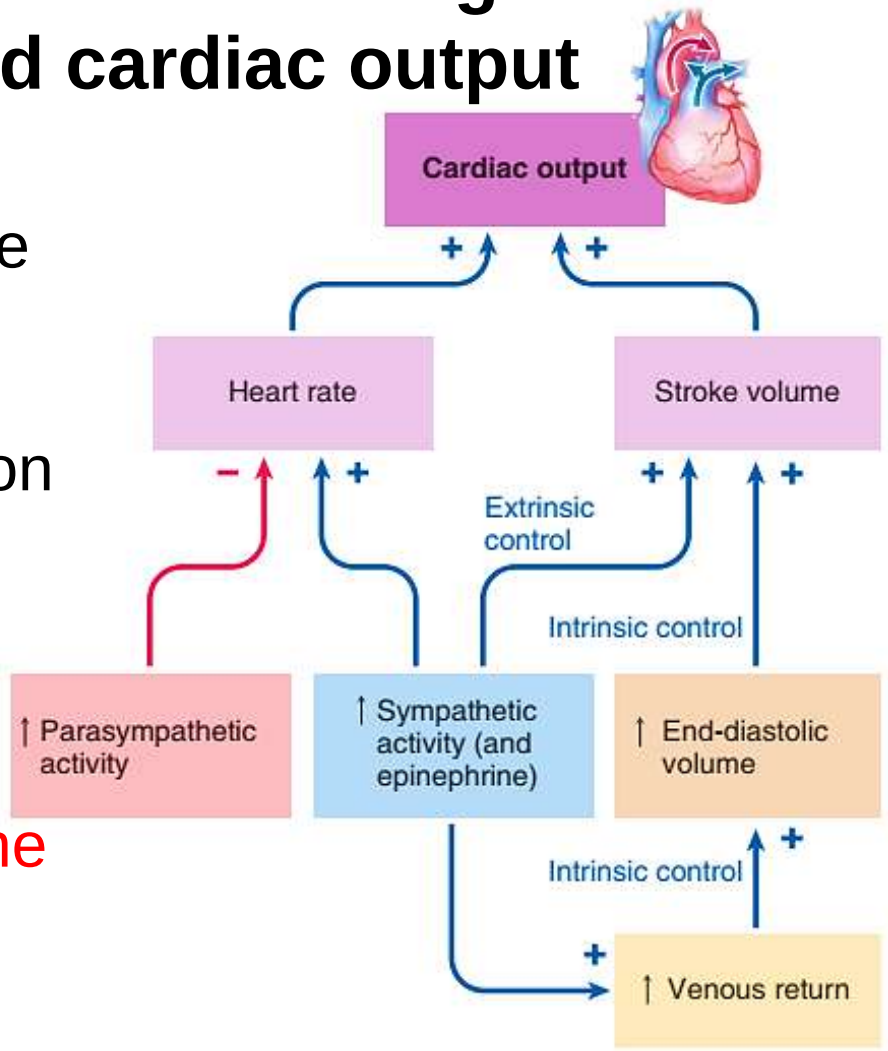



**Figure 9-24 Control of cardiac output.** Because cardiac output equals heart rate times stroke volume, this figure is a composite of Figure 9-19b (control of heart rate) and Figure 9-20 (control of stroke volume).

- How the **afterload** influences the ability of the heart to pump out blood?
- How a failing heart is unable to pump out sufficient blood??
- How the heart muscle is nourished???

# Nourishing the heart muscle

- In fact, up to 40% of the cell volume of cardiac muscle cells is occupied by mitochondria, indicative of how much the heart depends on $O_2$ delivery and aerobic metabolism to generate the energy necessary for contraction, also myoglobin, which stores limited amounts of $O_2$ within the heart for immediate use.

**The heart receives most of its own blood supply through <u>the coronary circulation</u> during diastole**

Cardiac muscle is supplied with $O_2$ and nutrients by blood delivered to it by the coronary circulation, not by blood within the heart chambers.

***First***, the watertight endocardial lining does not permit blood to pass from the chamber into myocardium.

***Second***, the heart walls are too thick to permit diffusion to the individual cardiac cells.

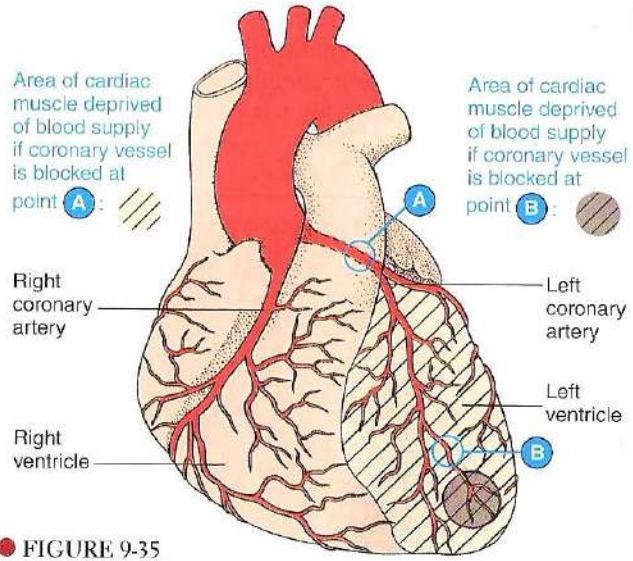
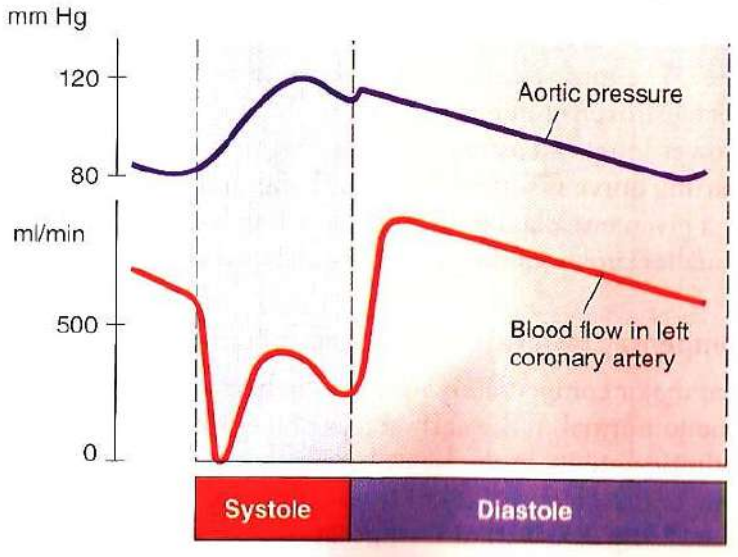



FIGURE 9-35

FIGURE 9-31

**Coronary blood flow**

Most coronary blood flow occurs during diastole because the coronary vessels are compressed almost completely closed during systole.



# Nourishing the heart muscle

- Most coronary blood flow occurs during diastole, because

**(1)** the coronary vessels are compressed by the contracting heart muscle during systole and

**(2)** the entrance to the coronary vessels is partially blocked by the open aortic valve.

- About 70% of coronary arterial flow driven by the aortic blood pressure, and only about 30% of it occurs during systole.
- The limited time for coronary blood flow becomes especially important during rapid heart rates, when diastolic time is substantially

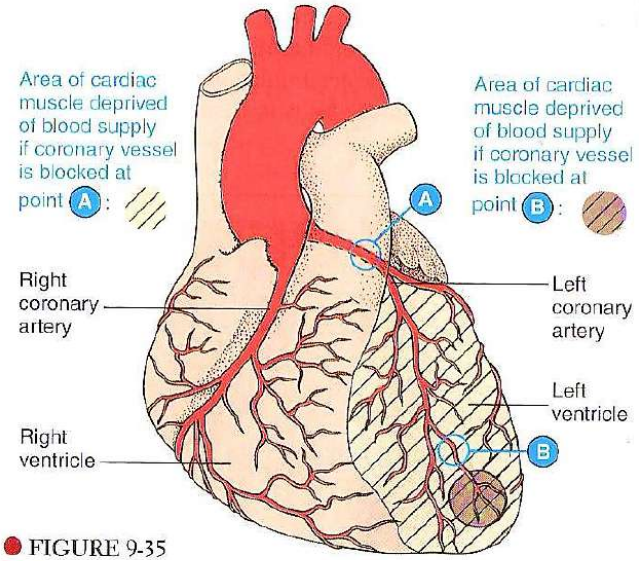
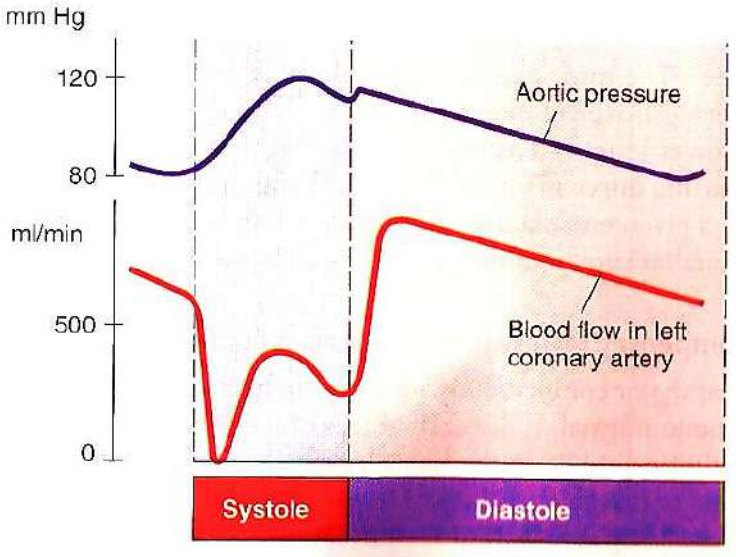



FIGURE 9-35

FIGURE 9-31

**Coronary blood flow**

Most coronary blood flow occurs during diastole because the coronary vessels are compressed almost completely closed during systole.



# Matching of coronary blood flow to heart muscle's $O_2$ needs

- The heart, even under resting conditions, removes up to 65% of the $O_2$ available in the coronary vessels, far more than is withdrawn by other tissues (25%). Therefore, the primary means by which more $O_2$ can be made available to the heart muscle is by adjusting coronary blood flow.

- Increased formation and release of adenosine from the cardiac cells occur (1) when there is a cardiac $O_2$ deficit or (2) when cardiac activity is increased, induces dilation of the coronary blood vessels, thereby allowing more $O_2$-rich blood to flow to the more active cardiac cells to meet their increased $O_2$ demand (fig. 9-32).
- The heart muscle depends on oxidative processes to generate energy, through anaerobic metabolism.
- **Nutrient supply to the heart:** As fuel sources, the heart primarily uses free fatty acids and, to a lesser extent, glucose and lactate, depending on their availability, the primary danger of insufficient coronary blood flow is not fuel shortage but $O_2$ deficiency.

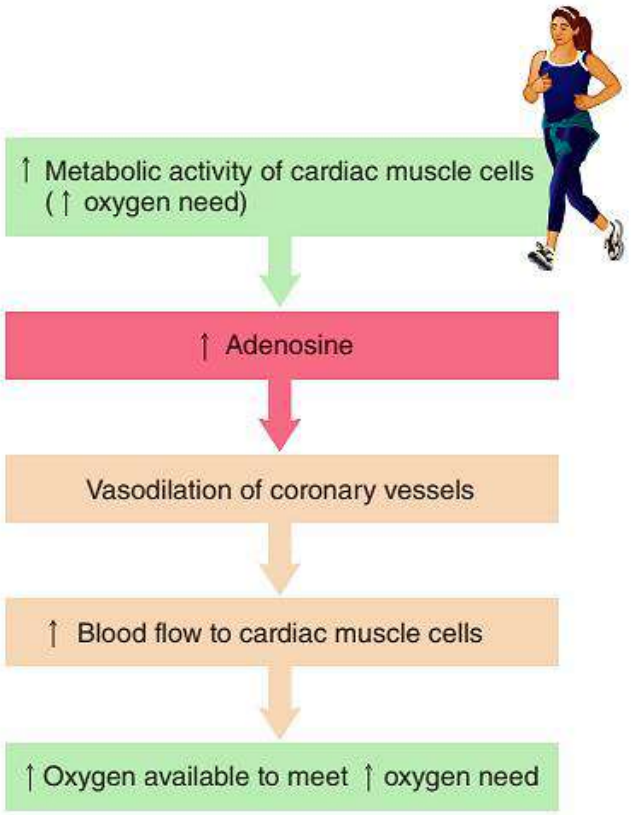
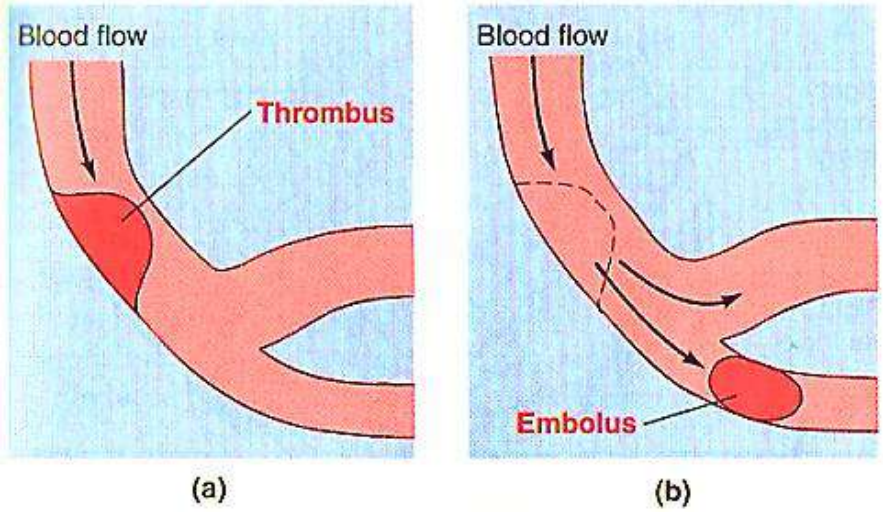



Figure 9-26 Matching of coronary blood flow to the $O_2$ need of cardi muscle cells.

# Thromboembolism and other complications of atherosclerosis

- ***Thrombolism,*** the enlarging atherosclerotic plaque can break through the weakened endothelial lining that covers it. Foam cells (lipid-rich core) release chemicals that weaken the fibrous cap of a plaque by breaking down the connective tissue fibers.
- When platelets come into contact with collagen, they stick to the site and contribute to the formation of a blood clot, **a thrombus**. Foam cells produce a potent clot promoter, may enlarge gradually until it completely blocks the vessel or the continued flow of blood past the thrombus may break it loose from its attachment. **Embolus**, may completely plug a smaller vessel as it flows downstream (fig. 9-34).
- Thus through **thromboembolism** atherosclerosis can result in a gradual or sudden occlusion of a coronary vessel.




● FIGURE 9-34

**Consequences of thromboembolism** (a) A thrombus may enlarge gradually until it completely occludes the vessel at that site. (b) A thrombus may break loose from its attachment, forming an embolus that may completely occlude a smaller vessel downstream. (c) Scanning electron micrograph of a vessel completely occluded by a thromboembolic lesion.

- **Collateral circulation** exists when small terminal branches from adjacent blood vessels nourish the same area, may be lifesaving if already developed. Often develop over a period of time when an atherosclerotic constriction progresses slowly, or they may be induced by sustained demands on the heart through a regular aerobic exercise program.
- In the absence of collateral circulation, the extent of the damaged area during a heart attack depends on the size of the blocked vessel. ( fig 9-35).
- Left coronary-artery blockage is most devastating because this vessel is responsible for supplying 85% of the cardiac tissue.

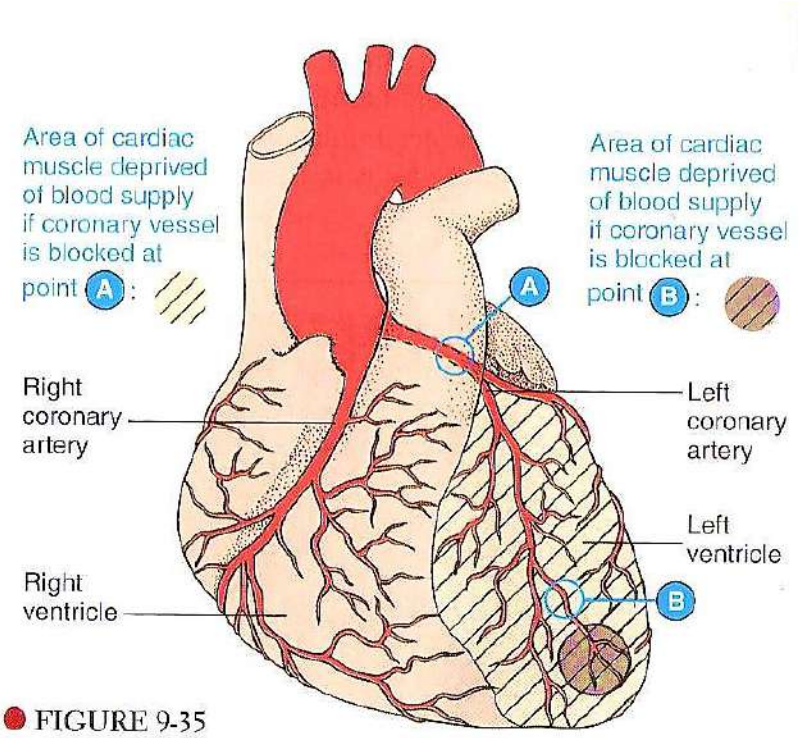



FIGURE 9-35
Extent of myocardial damage as a function of the size of the occluded vessel

- A heart attack has four possible outcomes: immediate death, delayed death from complications, full functional recovery, or recovery with impaired function (table 9-4).

▲ TABLE 9-4
**Possible Outcomes of Acute Myocardial Infarction (Heart Attack)**

| Immediate Death | Delayed Death from Complications | Full Functional Recovery | Recovery with Impaired Function |
|---|---|---|---|
| Acute cardiac failure occurring because the heart is too weakened to pump effectively to support the body tissues<br><br>Fatal ventricular fibrillation brought about by damage to the specialized conducting tissue or induced by $O_2$ deprivation | Fatal rupture of the dead, degenerating area of the heart wall<br><br>Slowly progressing congestive heart failure occurring because the weakened heart is unable to pump out all the blood returned to it | Replacement of the damaged area with a strong scar, accompanied by enlargement of the remaining normal contractile tissue to compensate for the lost cardiac musculature | Persistence of permanent functional defects, such as bradycardia or conduction blocks, caused by destruction of irreplaceable autorhythmic or conductive tissues |

# الحمد لله رب العالمين