Cardiac Muscle and the Cardiac Conduction System
Electrical and Contractile Activity of the Heart

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LEARNING OUTCOMES

As a result of the lesson you will be able to:

- *Describe the unique metabolic characteristics of cardiac muscle;*
- *Explain the functional significance of the intercellular junctions between cardiac muscle cells;*
- *Describe the heart's pacemaker and internal electrical conduction system and the pathway of impulses through this system.*
- *Describe the nerve supply to the heart and explain its role*
- *Explain why the SA node fires spontaneously and rhythmically*
- *Describe the unusual action potentials of cardiac muscle and relate them to the contractile behavior of the heart;*

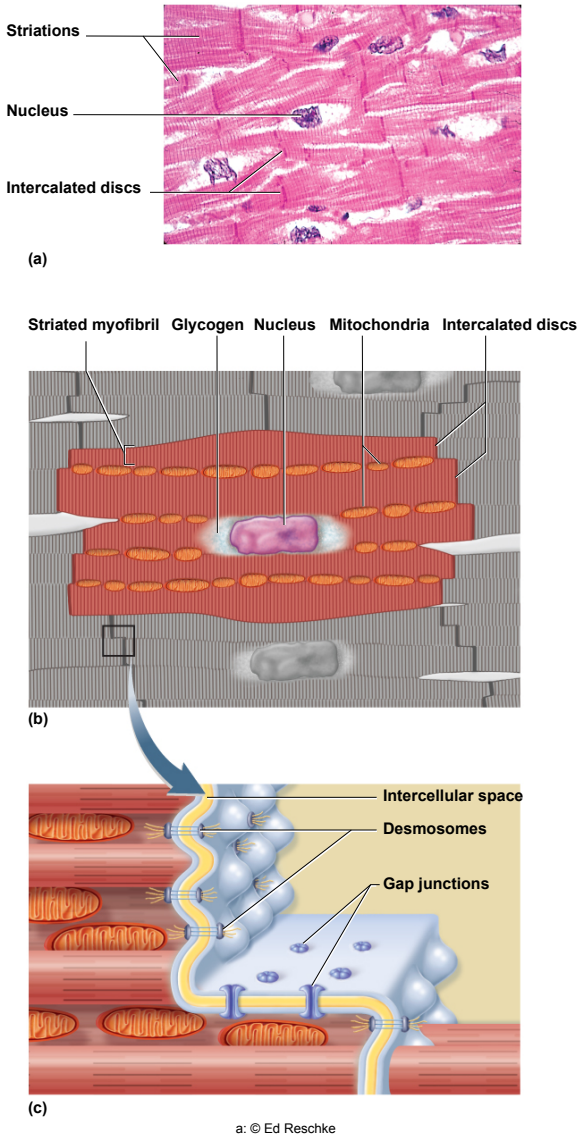
Structure of Cardiac Muscle

- **cardiocytes** - striated, short, thick, branched cells, one central nucleus surrounded by light staining mass of glycogen

- **intercalated discs -** join cardiocytes end to end
  - **interdigitating folds** – folds interlock with each other, and increase surface area of contact
  - **mechanical junctions** tightly join cardiocytes
    - **fascia adherens** – broad band in which the actin of the thin myofilaments is anchored to the plasma membrane
      - each cell is linked to the next via transmembrane proteins
    - **desmosomes** - weldlike mechanical junctions between cells
      - prevents cardiocytes from being pulled apart
  - **electrical junctions** - **gap junctions** allow ions to flow between cells – can stimulate neighbors
    - entire myocardium of either two atria or two ventricles acts like single unified cell

- repair of damage of cardiac muscle is almost entirely by **fibrosis** (scarring)

Structure of Cardiac Muscle Cell



a: © Ed Reschke

Figure 19.11 a-c

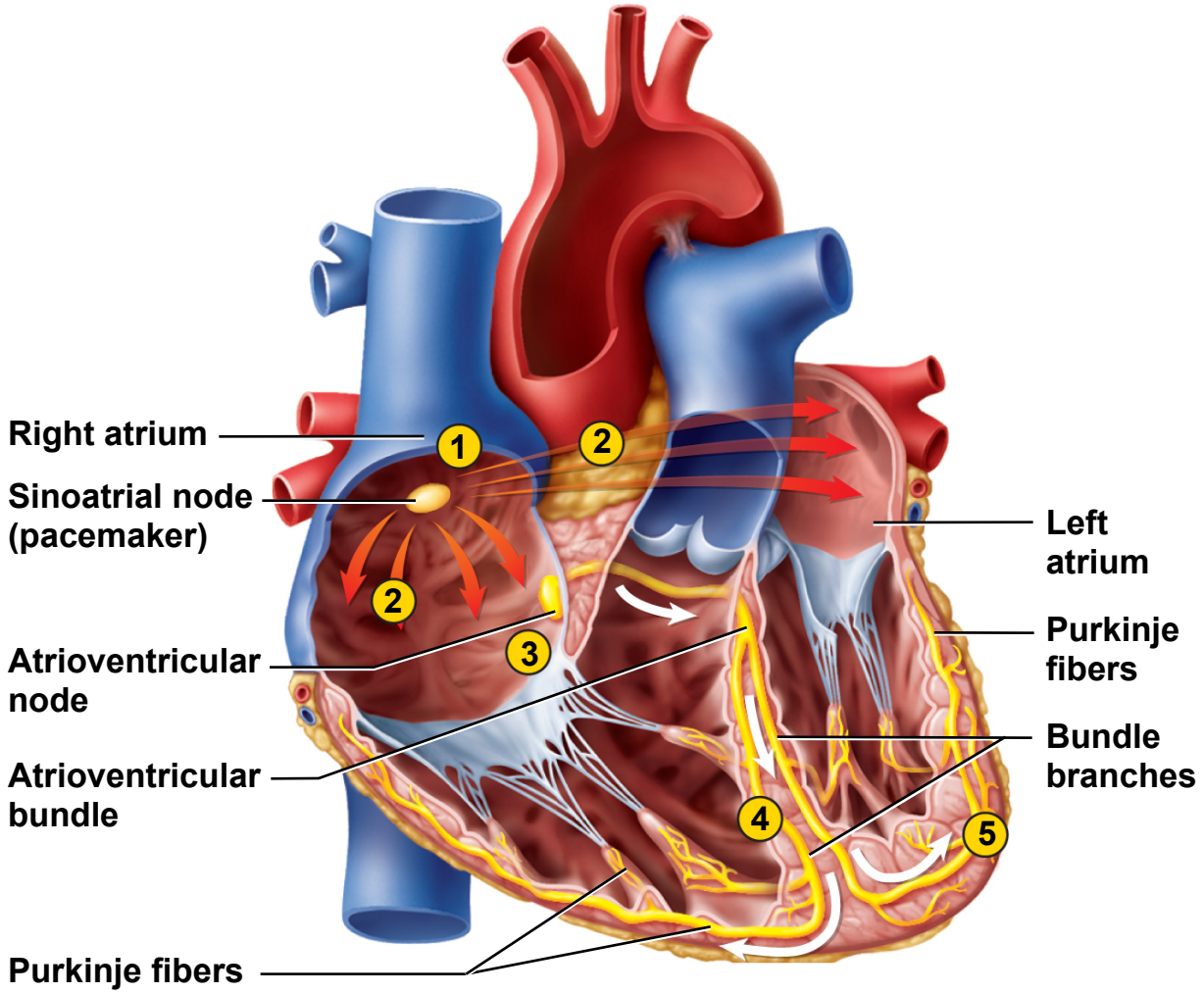
Metabolism of Cardiac Muscle

- **cardiac muscle** depends almost exclusively on **aerobic respiration** used to make ATP
  - rich in myoglobin and glycogen
  - huge mitochondria – fill 25% of cell
- **adaptable to organic fuels** used
  - fatty acids (60%), glucose (35%), ketones, lactic acid and amino acids (5%)
  - more vulnerable to oxygen deficiency than lack of a specific fuel
- **fatigue resistant** since makes little use of anaerobic fermentation or oxygen debt mechanisms
  - does not fatigue for a lifetime

Cardiac Conduction System

- coordinates the heartbeat
  - composed of an **internal pacemaker** and **nervelike conduction pathways** through myocardium
  - generates and conducts rhythmic electrical signals in the following order:
- **sinoatrial (SA) node** - modified cardiocytes
  - initiates each heartbeat and determines heart rate
  - signals spread throughout atria
  - **pacemaker** in right atrium near base of superior vena cava
- **atrioventricular (AV) node**
  - located near the right AV valve at lower end of interatrial septum
  - electrical gateway to the ventricles
  - fibrous skeleton acts as an insulator to prevent currents from getting to the ventricles from any other route
- **atrioventricular (AV) bundle (bundle of His)**
  - bundle forks into right and left bundle branches
  - these branches pass through interventricular septum toward apex
- **Purkinje fibers**
  - nervelike processes spread throughout ventricular myocardium
- signal pass from cell to cell through **gap junctions**

Cardiac Conduction System



1. SA node fires.
2. Excitation spreads through atrial myocardium.
3. AV node fires.
4. Excitation spreads down AV bundle.
5. Purkinje fibers distribute excitation through ventricular myocardium.

Figure 19.12

Nerve Supply to Heart

- **sympathetic nerves (raise heart rate)**
  - sympathetic pathway to the heart originates in the **lower cervical** to **upper thoracic segments** of the spinal cord
  - continues to adjacent **sympathetic chain ganglia**
  - some pass through **cardiac plexus** in mediastinum
  - continue as **cardiac nerves** to the heart
  - fibers terminate in SA and AV nodes, in atrial and ventricular myocardium, as well as the aorta, pulmonary trunk, and coronary arteries
    - increase heart rate and contraction strength
    - dilates coronary arteries to increase myocardial blood flow
- **parasympathetic nerves (slows heart rate)**
  - pathway begins with **nuclei of the vagus nerves** in the **medulla oblongata**
  - extend to **cardiac plexus** and continue to the heart by way of the **cardiac nerves**
  - fibers of **right vagus nerve** lead to the **SA node**
  - fibers of **left vagus nerve** lead to the **AV node**
  - little or no vagal stimulation of the myocardium
    - parasympathetic stimulation reduces the heart rate

Cardiac Rhythm

- cycle of events in heart – special names
  - **systole** – atrial or ventricular contraction
  - **diastole** – atrial or ventricular relaxation
- **sinus rhythm** - normal heartbeat triggered by the SA node
  - set by SA node at 60 – 100 bpm
  - adult at rest is 70 to 80 bpm (vagal tone)
- **ectopic focus** - another parts of heart fires before SA node
  - caused by hypoxia, electrolyte imbalance, or caffeine, nicotine, and other drugs

Abnormal Heart Rhythms

- spontaneous firing from some part of heart not the SA node
  - **ectopic foci** - region of spontaneous firing
    - **nodal rhythm** – if SA node is damaged, heart rate is set by AV node, 40 to 50 bpm
    - **intrinsic ventricular rhythm** – if both SA and AV nodes are not functioning, rate set at 20 to 40 bpm
      - this requires pacemaker to sustain life

- **arrhythmia** – any abnormal cardiac rhythm
  - failure of conduction system to transmit signals (heart block)
    - bundle branch block
    - total heart block (damage to AV node)

Cardiac Arrhythmias

- **atrial flutter** – ectopic foci in atria
  - atrial fibrillation
  - atria beat 200 - 400 times per minute
- **premature ventricular contractions** (PVCs)
  - caused by stimulants, stress or lack of sleep
- **ventricular fibrillation**
  - serious arrhythmia caused by electrical signals reaching different regions at widely different times
    - heart can't pump blood and no coronary perfusion
  - kills quickly if not stopped
    - **defibrillation** - strong electrical shock whose intent is to depolarize the entire myocardium, stop the fibrillation, and reset SA nodes to sinus rhythm

Pacemaker Physiology

- **SA node** does not have a stable resting membrane potential
  - starts at -60 mV and drifts upward from a slow inflow of Na^+
    - gradual depolarization is called **pacemaker potential**
      - slow inflow of Na^+ without a compensating outflow of K^+
  - when reaches **threshold** of -40 mV, voltage-gated **fast Ca^{2+} and Na^+ channels** open
    - faster **depolarization** occurs peaking at 0 mV
    - **K^+ channels** then open and K^+ leaves the cell
      - causing **repolarization**
      - once K^+ channels close, pacemaker potential starts over
- each depolarization of the SA node sets off one heartbeat
  - at rest, fires every 0.8 seconds or 75 bpm
- SA node is the system's pacemaker

SA Node Potentials

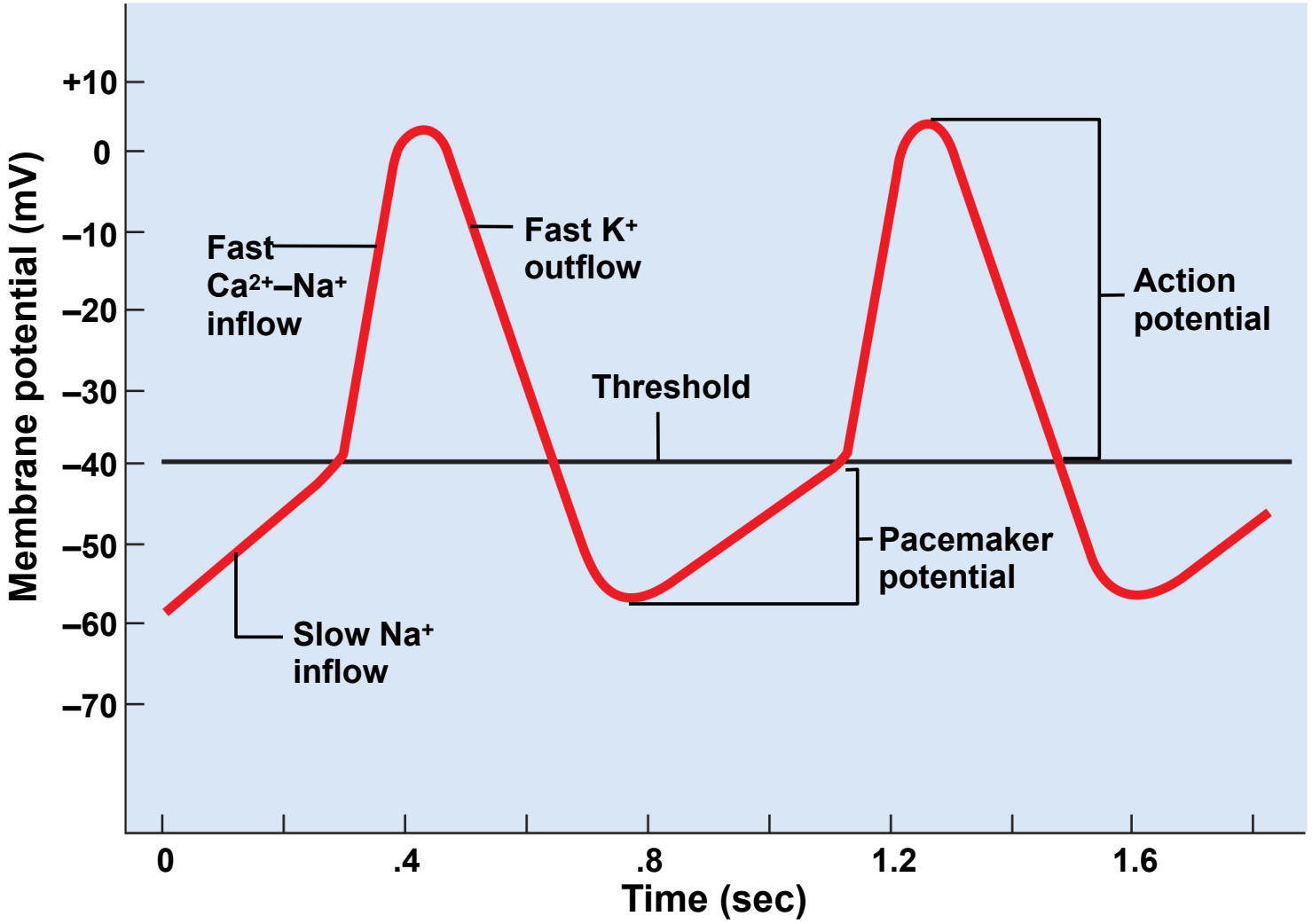


Figure 19.13

Impulse Conduction to Myocardium

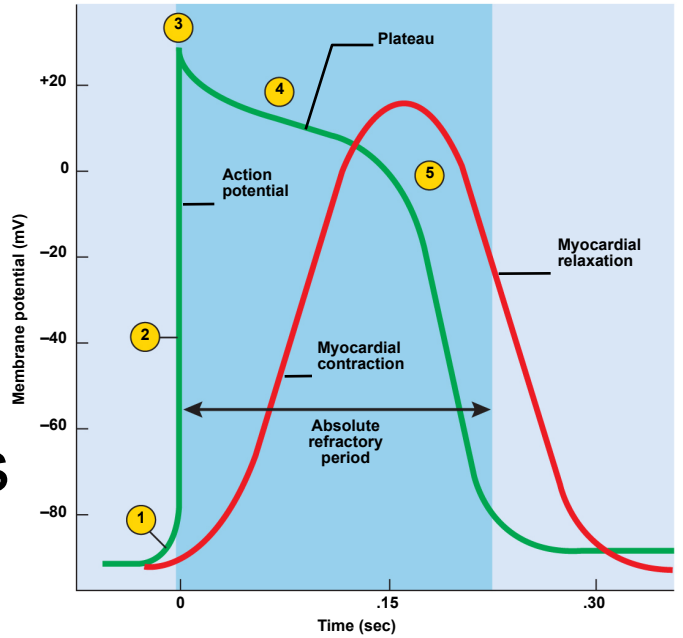
- signal from **SA node** stimulates two atria to contract almost simultaneously
  - reaches AV node in 50 msec
- signal slows down through **AV node**
  - thin cardiocytes have fewer gap junctions
  - delays signal 100 msec which allows the ventricles to fill
- signals travel very quickly through **AV bundle** and **Purkinje fibers**
  - entire ventricular myocardium depolarizes and contracts in near unison
    - papillary muscles contract an instant earlier than the rest, tightening slack in chordae tendineae
- ventricular systole progresses up from the apex of the heart
  - spiral arrangement of cardiocytes twists ventricles slightly
  - like someone wringing out a towel

Electrical Behavior of Myocardium

- cardiocytes have a stable resting potential of -90 mV
- depolarize only when stimulated
  - **depolarization phase** (very brief)
    - stimulus opens voltage regulated Na^+ gates, (Na^+ rushes in) membrane **depolarizes rapidly**
    - action potential peaks at +30 mV
    - Na^+ gates close quickly
  - **plateau phase** lasts 200 to 250 msec, sustains contraction for expulsion of blood from heart
    - Ca^{2+} channels are slow to close and SR is slow to remove Ca^{2+} from the cytosol
  - **repolarization phase** - Ca^{2+} channels close, K^+ channels open, rapid diffusion of K^+ out of cell returns it to resting potential
- has a long absolute refractory period of 250 msec compared to 1 – 2 msec in skeletal muscle
  - prevents wave summation and tetanus which would stop the pumping action of the heart

Action Potential of a Cardiocyte

1) Na^+ gates open
2) Rapid depolarization
3) Na^+ gates close
4) Slow Ca^{2+} channels open
5) Ca^{2+} channels close, K^+ channels open (repolarization)



1. Voltage-gated Na^+ channels open.
2. Na^+ inflow depolarizes the membrane and triggers the opening of still more Na^+ channels, creating a positive feedback cycle and a rapidly rising membrane voltage.
3. Na^+ channels close when the cell depolarizes, and the voltage peaks at nearly +30 mV.
4. Ca^{2+} entering through slow Ca^{2+} channels prolongs depolarization of membrane, creating a plateau. Plateau falls slightly because of some K^+ leakage, but most K^+ channels remain closed until end of plateau.
5. Ca^{2+} channels close and Ca^{2+} is transported out of cell. K^+ channels open, and rapid K^+ outflow returns membrane to its resting potential.

Figure 19.14

Electrocardiogram (ECG or EKG)

- composite of all action potentials of nodal and myocardial cells detected, amplified and recorded by electrodes on arms, legs and chest

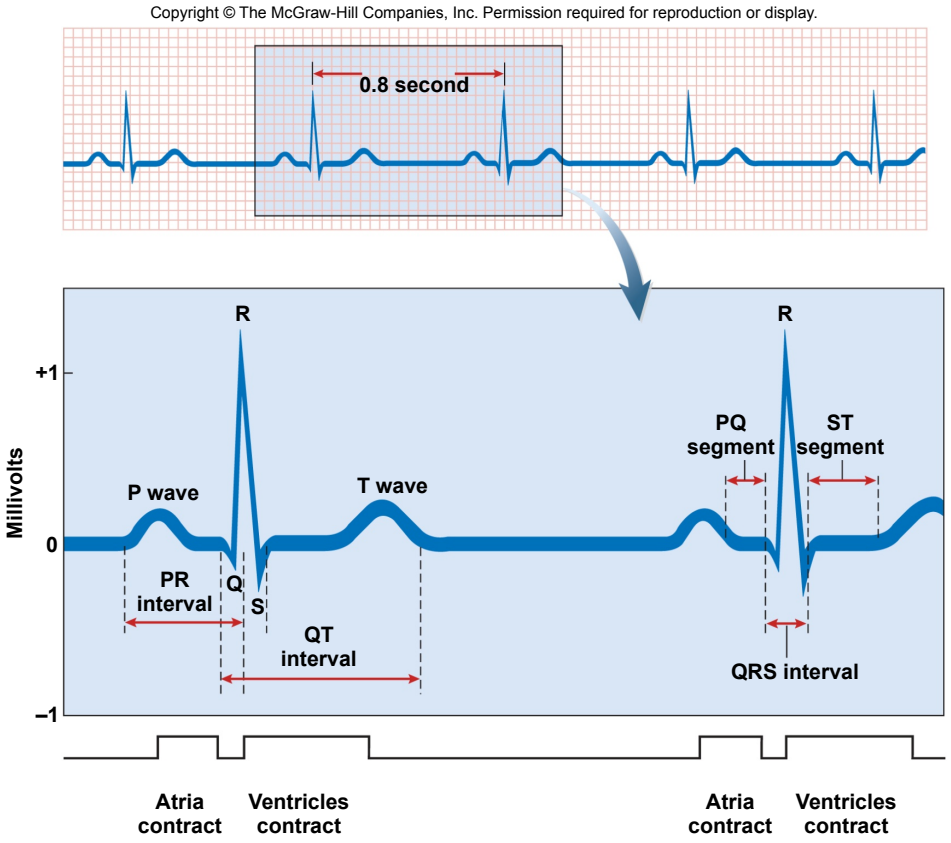


Figure 19.15

ECG Deflections

- **P wave**
  - SA node fires, **atria depolarize** and contract
  - atrial systole begins 100 msec after SA signal
- **QRS complex**
  - **ventricular depolarization**
  - complex shape of spike due to different thickness and shape of the two ventricles
- **ST segment - ventricular systole**
  - plateau in myocardial action potential
- **T wave**
  - **ventricular repolarization** and relaxation

Normal Electrocardiogram (ECG)

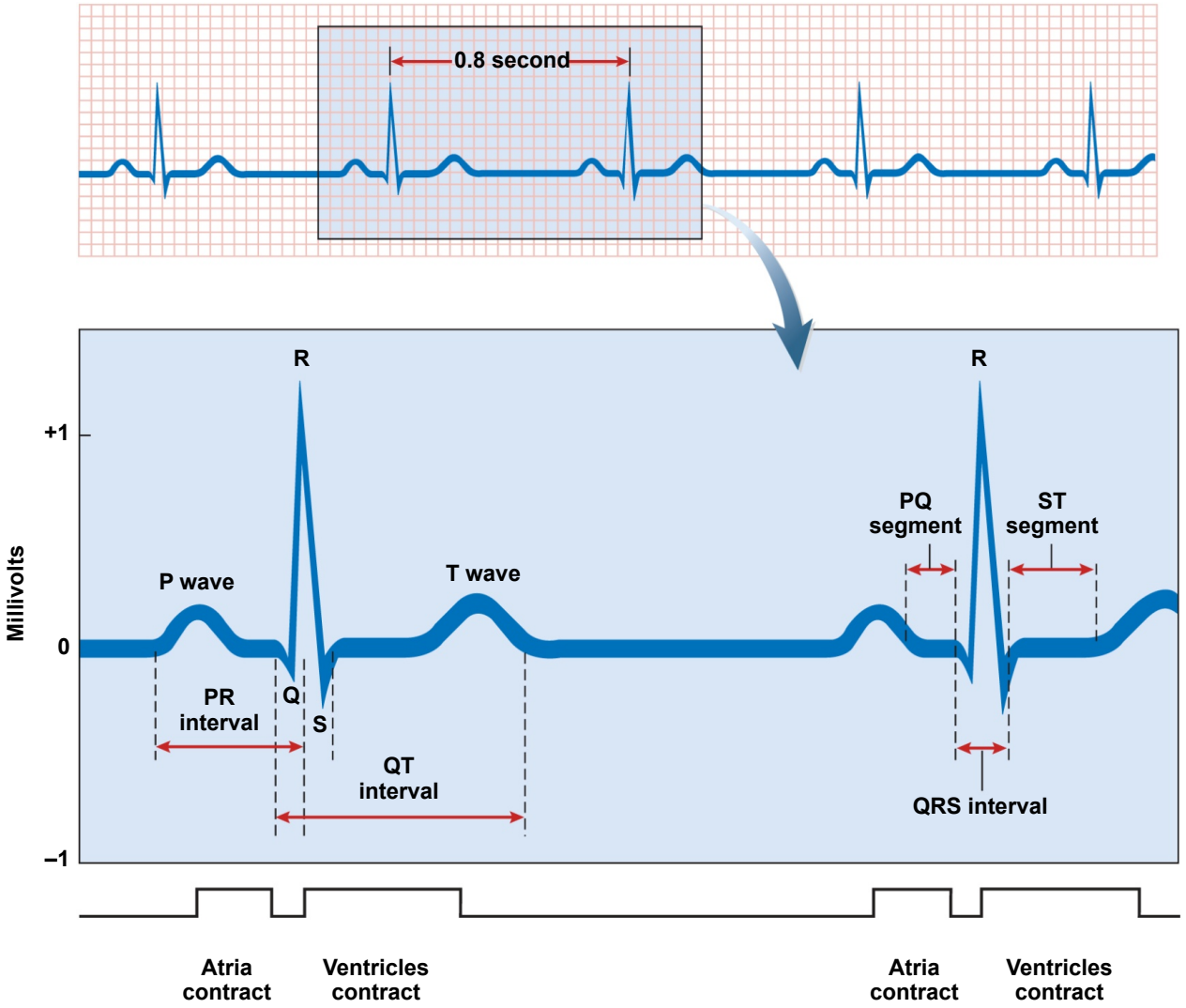


Figure 19.15

Electrical Activity of Myocardium

1) atrial depolarization begins
2) atrial depolarization complete (atria contracted
3) ventricles begin to depolarize at apex; atria repolarize (atria relaxed)
4) ventricular depolarization complete (ventricles contracted)
5) ventricles begin to repolarize at apex
6) ventricular repolarization complete (ventricles relaxed)

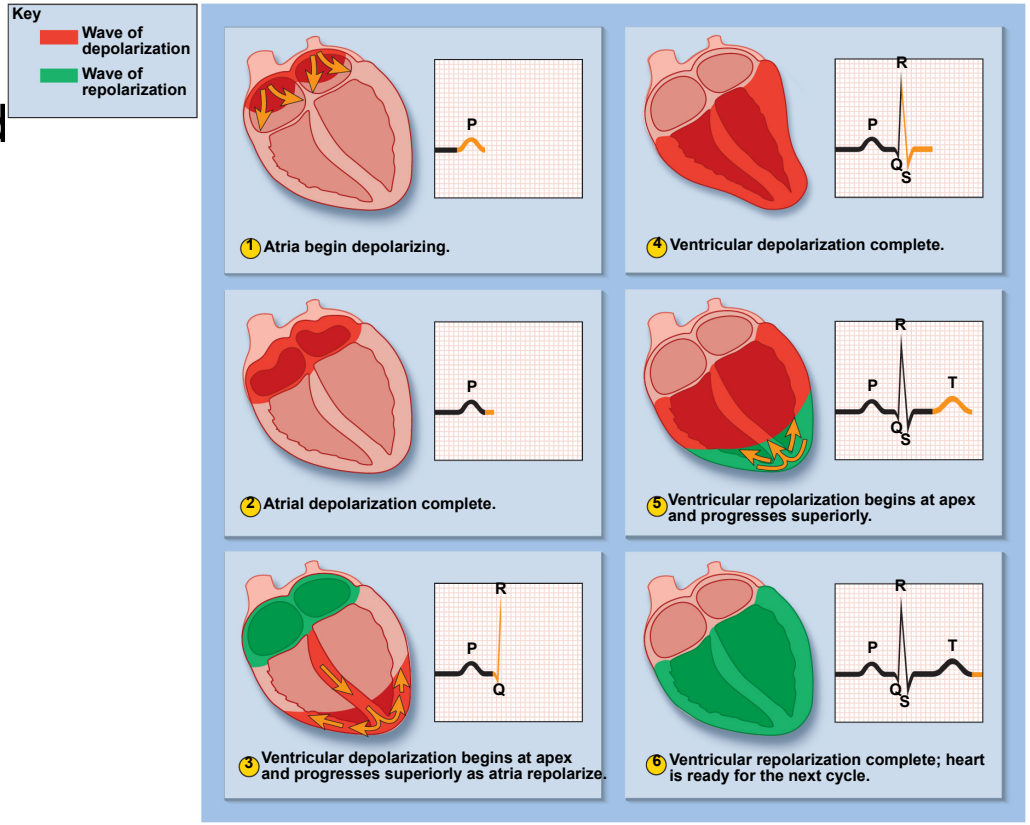


Figure 19.16

Diagnostic Value of ECG

- abnormalities in conduction pathways
- myocardial infarction
- nodal damage
- heart enlargement
- electrolyte and hormone imbalances