What is the Cardiovascular System?

Blood
circulated in
Arteries, veins, and capillaries
by the
Pumping action of the heart

Functions of the Heart

• Generating blood pressure sufficient to efficiently cause blood to flow from heart to veins
• Keeping oxygenated and low-oxygen blood separate
• Adjusting blood flow as conditions change (maintain homeostasis)
  – Changes in contraction rate and force match blood delivery to changing metabolic needs

Heart Anatomy

The Pulmonary and Systemic Circuits

• Heart is a transport system consisting of two side-by-side pumps
  – Right side receives low-oxygen blood from tissues
    • Moves blood to lungs to get rid of CO₂, pick up O₂, and return via pulmonary circuit
  – Left side receives oxygenated blood from lungs
    • Moves blood to body tissues via systemic circuit
Locational of the heart in the mediastinum.

**Mediastinum** = medial cavity of thorax

- **Base** (posterior surface) leans toward right shoulder
- **Apex** points toward left hip
- More of mass on left – lack of bilateral symmetry
- Fist-sized, 250-350 g
- Mediastinum = medial cavity of thorax

**Chambers and Associated Great Vessels**

- Internal features
  - Four chambers
    - Two superior atri
    - Two inferior ventricles
  - **Interventricular septum**: separates ventricles
  - **Annular valves**: remnant of foramen ovale of fetal heart
- ‘Walls’ consist of cardiac muscle, fibrous connective tissue, others in lesser amounts
**Chambers and Associated Great Vessels (cont.)**

- **Atria: the receiving chambers**
  - Small, thin-walled
  - Receive blood from veins
  - Convey blood to ventricles below
  - Auricle vs atrium
  - **Right atrium**: receives deoxygenated (aka low-oxygen) blood from body
    - Superior & inferior vena cava, coronary sinus
  - **Left atrium**: receives oxygenated blood from lungs
    - Four pulmonary veins

- **Ventricles: the discharging chambers**
  - Make up most of the volume of heart, primary pump
  - Thickness of ventricular myocardium reflects workload
  - Right ventricle
    - Pumps blood into **pulmonary trunk**
  - Left ventricle
    - Pumps blood into **aorta** (largest artery in body)
  - **Trabeculae carneae**
  - **Papillary muscles**
    - Anchor **chordae tendineae** that are attached to heart valves

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**The layers of the pericardium and of the heart wall.**

1. **Superficial fibrous pericardium**: functions to protect, anchor heart to surrounding structures, and prevent overfilling
2. **Deep two-layered serous pericardium**
   - **Parietal layer**: lines internal surface of fibrous pericardium
   - **Visceral layer (epicardium)**: on external surface of heart
   - Two layers separated by fluid-filled **pericardial cavity** (decreases friction)
Layers of the Heart Wall

• Three layers of heart wall

1. **Epicardium**: visceral layer of serous pericardium

2. **Myocardium**: circular or spiral bundles of contractile cardiac muscle cells
   - **Cardiac skeleton**: crisscrossing, interlacing layer of connective tissue
     - Anchors cardiac muscle fibers
     - Supports great vessels and valves
     - Limits spread of action potentials to specific paths

3. **Endocardium**: innermost layer; is continuous with endothelial lining of blood vessels
   - Lines heart chambers and covers cardiac skeleton of valves

The circular and spiral arrangement of cardiac muscle bundles in the myocardium of the heart.

Heart valves
The function of the atrioventricular (AV) valves.

1. Blood returning to the heart fills atria, pressing against the AV valves. The increased pressure forces AV valves open.
2. As ventricles fill, AV valve flaps hang limply into ventricles.
3. Atria contract, forcing additional blood into ventricles.

(a) AV valves open; atrial pressure greater than ventricular pressure

The function of the semilunar (SL) valves.

As ventricles contract and intraventricular pressure rises, blood is pushed up against semilunar valves, forcing them open.

(a) Semilunar valves open

As ventricles relax and intraventricular pressure falls, blood flows back from arteries, filling the cusps of semilunar valves and forcing them to close.

(b) Semilunar valves closed

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Pathway of Blood Through Heart and Connected Vessels

- Equal volumes of blood are pumped to pulmonary and systemic circuits
- Pulmonary circuit is short, low-pressure circulation – ‘reoxygenation’ of systemic blood
- Systemic circuit is long, high-friction circulation – ‘distribution’ of oxygen-saturated pulmonary blood
- Anatomy of ventricles reflects differences
  - Left ventricle walls are 3” thicker than right
    - Pumps with greater pressure

Coronary Circulation

- Coronary arteries and veins
  - Functional blood supply to heart muscle itself
    - Living muscle tissue with limited anaerobic capabilities
  - Delivered when heart is relaxed, too much pressure in cardiac arteries for blood to flow while myocardium contracted
  - Shortest circulation in body
  - Left ventricle receives most of coronary blood supply
  - Named for location – base or corona
- Narrowing, closing, plugging leads to ischemia and/or infarction
Coronary Circulation (cont.)

- **Coronary arteries**
  - Both **left** and **right coronary arteries** arise from base of aorta and supply arterial blood to heart
  - Both encircle heart in coronary sulcus
  - Branching of coronary arteries varies among individuals
  - Arteries contain many anastomoses (junctions)
    - Provide additional routes for blood delivery
    - Cannot compensate for coronary artery occlusion
  - Heart receives 1/20th of body’s blood supply
**Microscopic anatomy of cardiac muscle fibers**

- Nucleus
- I band
- A band
- Mitochondrion
- T tubule
- Sarcoplasmic reticulum
- Z disc
- Intercalated disc
- Simplicity with skeletal muscle
  - Muscle contraction is preceded by depolarizing action potential
  - Depolarization wave travels down T tubules, causing sarcoplasmic reticulum (SR) to release Ca^{2+}
  - Excitation-contraction coupling occurs – Ca binds to troponin causing filaments to slide

**Microscopic anatomy of cardiac muscle.**

**Table 18.1  Key Differences between Skeletal and Cardiac Muscle**

<table>
<thead>
<tr>
<th></th>
<th>SKELETAL MUSCLE</th>
<th>CARDIAC MUSCLE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structure</strong></td>
<td>Striated, long, cylindrical, multinucleate</td>
<td>Striated, short, branched, one or two nuclei per cell</td>
</tr>
<tr>
<td><strong>Gap junctions between cells</strong></td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Contracts as a unit</strong></td>
<td>No, motor units must be stimulated individually</td>
<td>Yes, gap junctions create a functional syncytium</td>
</tr>
<tr>
<td><strong>T tubules</strong></td>
<td>Abundant</td>
<td>Fewer, wider</td>
</tr>
<tr>
<td><strong>Sarcoplasmic reticulum</strong></td>
<td>Elaborate; has terminal cisterns</td>
<td>Less elaborate; no terminal cisterns</td>
</tr>
<tr>
<td><strong>Source of Ca^{2+} for contraction</strong></td>
<td>Sarcoplasmic reticulum only</td>
<td>Sarcoplasmic reticulum and extracellular fluid</td>
</tr>
<tr>
<td><strong>Ca^{2+} binds to troponin</strong></td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td><strong>Pacemaker cells present</strong></td>
<td>No</td>
<td>Yes, Pacemaker myocytes</td>
</tr>
<tr>
<td><strong>Tetanus possible</strong></td>
<td>Yes</td>
<td>No, Long absolute refraction</td>
</tr>
<tr>
<td><strong>Supply of ATP</strong></td>
<td>Aerobic and anaerobic (fewer mitochondria)</td>
<td>Aerobic only (more mitochondria)</td>
</tr>
</tbody>
</table>
How Does the Physiology of Skeletal and Cardiac Muscle Differ? (cont.)

– **Heart contracts as a unit**
  - All cardiomyocytes contract as unit (functional syncytium), or none contract
  - Contraction of all cardiac myocytes ensures effective pumping action
  - Skeletal muscle fibers contract independently

– **Influx of Ca\(^{2+}\) from extracellular fluid triggers Ca\(^{2+}\) release from SR**
  - Depolarization opens slow Ca\(^{2+}\) channels in sarcolemma, allowing Ca\(^{2+}\) to enter cell
  - Extracellular Ca\(^{2+}\) then causes SR to release its intracellular Ca\(^{2+}\)
  - Skeletal muscles do not use extracellular Ca\(^{2+}\)

How Does the Physiology of Skeletal and Cardiac Muscle Differ? (cont.)

– **The heart relies almost exclusively on aerobic respiration**
  - Cardiac muscle has more mitochondria than skeletal muscle so has greater dependence on oxygen
    - Cannot function without oxygen
  - Skeletal muscle can go through fermentation when oxygen not present
  - Both types of tissues can use other fuel sources
    - Cardiac is more adaptable to other fuels, including lactic acid, but must have oxygen

Setting the Basic Rhythm: The Intrinsic Conduction System

- Coordinated heartbeat is a function of:
  1. Presence of gap junctions
  2. **Intrinsic cardiac conduction system**
    - Network of noncontractile (autorhythmic) cells
    - Cardiac pacemaker cells have unstable resting membrane potentials called pacemaker potentials or prepotentials
    - Initiate and distribute impulses to coordinate depolarization and contraction of heart

What is extrinsic control?
Action potential initiation by pacemaker cells (cont.)

1. Pacemaker potential: K⁺ channels are closed, but slow Na⁺ channels are open, causing interior to become more positive
2. Depolarization: Ca²⁺ channels open (around −40 mV), allowing huge influx of Ca²⁺, leading to rising phase of action potential
3. Repolarization: K⁺ channels open, allowing efflux of K⁺, and cell becomes more negative

Pacemaker and action potentials of typical cardiac pacemaker cells.

Setting the Basic Rhythm: The Intrinsic Conduction System (cont.)

1. Sinoatrial (SA) node
   - Primary pacemaker of heart in right atrial wall
     • Spontaneously depolarizes faster than rest of myocardium
   - Generates impulses about 75×/minute (sinus rhythm)
     • Inherent rate of 100×/minute tempered by extrinsic factors
   - Impulse spreads across atria cell to cell, and to AV node
Setting the Basic Rhythm: The Intrinsic Conduction System (cont.)

2. **Atrioventricular (AV) node**
   - In inferior interatrial septum
   - Delays impulses approximately 0.1 second
     - Because fibers are smaller in diameter, have fewer gap junctions
     - Allows atrial contraction prior to ventricular contraction
   - Inherent rate of 50 bpm in absence of SA node input “ectopic focus”

3. **Atrioventricular (AV) bundle** (bundle of His)
   - In superior interventricular septum
   - Only electrical connection between atria and ventricles
     - Atria and ventricles not connected via gap junctions

4. **Right and left bundle branches**
   - Two pathways in interventricular septum
   - Carry impulses toward apex of heart

5. **Subendocardial conducting network**
   - Also referred to as Purkinje fibers
   - Complete pathway through interventricular septum into apex and ventricular walls, then cell to cell
   - AV bundle and subendocardial conducting network depolarize 30 bpm in absence of AV node input “ectopic focus”
   - Ventricular contraction immediately follows from apex toward atria
   - Process from initiation at SA node to complete contraction takes ~0.22 seconds
Action Potentials of Contractile Cardiac Muscle Cells

- **Contractile muscle fibers** make up bulk of heart and are responsible for pumping action
  - Different from skeletal muscle contraction; cardiac muscle action potentials have plateau

- Steps involved in AP:
  1. Depolarization opens **fast voltage-gated Na⁺ channels**; Na⁺ enters cell
     - Positive feedback influx of Na⁺ causes rising phase of AP (from −90 mV to +30 mV)

Heartbeat modified by ANS via cardiac centers in medulla oblongata

- Caroioacceleratory center: sends signals through sympathetic trunk to increase both rate and force
  - Stimulates SA and AV nodes, heart muscle, and coronary arteries

- Cardioinhibitory center: parasympathetic signals via vagus nerve to decrease rate
  - Inhibits SA and AV nodes via vagus nerves
2. Depolarization by Na\(^+\) also opens slow Ca\(^{2+}\) channels
   - At +30 mV, Na\(^+\) channels close, but slow Ca\(^{2+}\) channels remain open, prolonging depolarization
   - Seen as a plateau
3. After about 200 ms, slow Ca\(^{2+}\) channels are closed, and voltage-gated K\(^+\) channels are open
   - Rapid efflux of K\(^+\) repolarizes cell to RMP
   - Ca\(^{2+}\) is pumped both back into SR and out of cell into extracellular space

**Action Potentials of Contractile Cardiac Muscle Cells (cont.)**

- Difference between contractile muscle fiber and skeletal muscle fiber contractions
  - AP in skeletal muscle lasts 1–2 ms; in cardiac muscle it lasts 200 ms
  - Contraction in skeletal muscle lasts 15–100 ms; in cardiac contraction lasts over 200 ms
- Benefit of longer AP and contraction:
  - Sustained contraction ensures efficient ejection of blood
  - Longer refractory period prevents tetanic contractions

The action potential of contractile cardiac muscle cells.
Mechanical Events of Heart

- **Systole**: period of heart contraction
- **Diastole**: period of heart relaxation
- **Cardiac cycle**: blood flow through heart during one complete heartbeat
  - Atrial systole and diastole are followed by ventricular systole and diastole
  - Cycle represents series of pressure and blood volume changes
  - Mechanical events follow electrical events seen on ECG
- **Three phases of the cardiac cycle** (following left side, starting with total relaxation)
- Blood flows from area of high pressure to area of low pressure unless impeded (by things like valves)

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1. **Ventricular filling**: mid-to-late diastole
   - Passive filling = atrial and ventricular diastole, all chambers filling
   - Active filling = atrial systole but ventricles relaxed = ‘forced’ filling of ventricles
   - End diastolic volume (EDV): volume of blood in each ventricle at end of ventricular diastole

2. **Ventricular systole**
   2a: Isovolumetric contraction phase: all valves are closed
   2b: Ejection phase: ventricular pressure exceeds pressure in large arteries, forcing SL valves open
   - Pressure in aorta around 120 mm Hg
   - End systolic volume (ESV): volume of blood remaining in each ventricle after systole

3. **Isovolumetric relaxation**: early ventricular diastole, atria already in diastole and accepting venous blood

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Heart Sounds

- Two sounds (lub-dup) associated with closing of heart valves
  - First sound is closing of AV valves at beginning of ventricular systole
  - Second sound is closing of SL valves at beginning of ventricular diastole
  - Pause between lub-dups indicates heart relaxation
Electrocardiography

- **Electrocardiograph** can detect electrical currents generated by heart
- **Electrocardiogram (ECG or EKG)** is a graphic recording of electrical activity
  - Composite of all action potentials at given time; **not a tracing of a single AP**
  - Electrodes are placed at various points on body to measure voltage differences
- A diagnostic tool
Cardiac Output (CO)

- Volume of blood pumped by each ventricle in 1 minute
- Highly variable
  - CO changes (increases/decreases) if either or both SV or HR is changed

- CO = heart rate (HR) \times stroke volume (SV)
  - HR = number of beats per minute
  - SV = volume of blood pumped out by one ventricle with each beat
- At rest:
  \[
  \text{CO (ml/min)} = \text{HR (75 beats/min)} \times \text{SV (70 ml/beat)} \\
  = 5.25 \text{ L/min}
  \]

Regulation of Pumping

- Maximal CO is 4–5 times resting CO in nonathletic people (20–25 L/min)
- Maximal CO may reach 35 L/min in trained athletes
- **Cardiac reserve**: difference between resting and maximal CO
Regulation of Stroke Volume

- Mathematically: SV = EDV – ESV
  - EDV is affected by length of ventricular diastole and venous pressure (~120 ml/beat)
  - ESV is affected by arterial BP and force of ventricular contraction (~50 ml/beat)
  - Normal SV = 120 ml – 50 ml = 70 ml/beat

- Three main factors that affect SV:
  - Preload
  - Contractility
  - Afterload

Regulation of Stroke Volume (cont.)

- Preload: degree of stretch of heart muscle
  - Preload: degree to which cardiac muscle cells are stretched just before they contract
    - Changes in preload cause changes in SV
      - Affects EDV
      - Relationship between preload and SV called Frank-Starling law of the heart
    - Cardiac muscle exhibits a length-tension relationship
      - At rest, cardiac muscle cells are shorter than optimal length
      - When stretched by increases in EDV a big increase in contractile force

Regulation of Stroke Volume (cont.)

- Preload (cont.)
  - Most important factor in preload stretching of cardiac muscle is venous return—amount of blood returning to heart
    - Slow heartbeat and exercise increase venous return
    - Increased venous return distends (stretches) ventricles and increases contraction force

- Venous Return → EDV → SV → CO
- Frank-Starling Law
Regulation of Stroke Volume (cont.)

- **Contractility**
  - Contractile strength at given muscle length
    - Independent of muscle stretch and EDV
  - Increased contractility lowers ESV; caused by:
    - Sympathetic epinephrine release stimulates increased Ca\(^{2+}\) influx, leading to more cross bridge formations
    - *Positive inotropic agents* increase contractility
      - Thyroxine, glucagon, epinephrine, digitalis, high extracellular Ca\(^{2+}\)
    - Decreased by *negative inotropic agents*
      - Acidosis (excess H\(^{+}\)), increased extracellular K\(^{+}\), calcium channel blockers

- **Afterload**: back pressure exerted by arterial blood
  - Afterload is pressure that ventricles must overcome to eject blood
    - Back pressure from arterial blood pushing on SL valves is major pressure
      - Aortic pressure is around 80 mm Hg
      - Pulmonary trunk pressure is around 10 mm Hg
    - Hypertension increases afterload, resulting in increased ESV and reduced SV
Factors involved in determining cardiac output.

- Exercise (by sympathetic activity, skeletal muscle, and respiratory pumps; see Chapter 19)
- Venous return
- Heart rate (due to ventricular filling time)
- Bloodborne epinephrine, thyroxine, excess Ca²⁺
- CNS output in response to exercise, fright, anxiety, or blood pressure
- Venous return
- Heart rate (due to ventricular filling time)
- Bloodborne epinephrine, thyroxine, excess Ca²⁺
- CNS output in response to exercise, fright, anxiety, or blood pressure
- Initial stimulus
- Physiological response
- Final

Cardiac output (CO) = SV x HR