Chapter 15:  
The Cardiovascular System

The cardiovascular system
• Provides the drive for blood flow

• Four-chambered organ

• Weighs 11 oz for the average male, 9 oz for the average female

• Pumps ~70 mL for each beat
  - At rest, ~1900 gals/day or 52 million gals over a 75-year lifetime

• The heart muscle is called myocardium and its muscle fibers interconnect in latticework fashion to allow the heart to function as a unit
• The right side of the heart:
  - Receive blood returning from throughout the body
  - Allow for pulmonary circulation

• The left side of the heart:
  - Receive oxygenated blood from the lungs
  - Allow for systemic circulation

• The two sides are separated by the interventricular septum
Atrioventricular valves:
- Tricuspid: Provides one-way blood flow from the right atrium to the right ventricle
- Bicuspid/Mitral: Provides one-way blood flow from the left atrium to the left ventricle

Semilunar valves:
- Located in the arterial wall just outside the heart, prevent blood from flowing back into the heart between contractions
The heart and its vessels

- **Right lung**: The right atrium receives deoxygenated blood from the body's tissues. Blood passes through the tricuspid (AV valve) to the right ventricle. The right ventricle pumps blood into the pulmonary artery.

- **Left lung**: Oxygenated blood from the pulmonary vein returns to the left atrium. Blood passes through the bicuspid (mitral) valve to the left ventricle. The left ventricle ejects blood through the aortic (semilunar) valve into the aorta for transport in the systemic circuit.

- **Head, neck, and upper body**: The aorta and pulmonary artery are connected to various branches for blood distribution.

- **Trunk and lower extremity**: The inferior vena cava and other vessels supply blood to these areas.
Atrial chambers serve as primer pumps to receive and store blood during ventricular contraction.

~70% of the blood returning to the atria flows directly into the ventricles before the atria contract.

The simultaneous contraction of both atria forces the remaining blood into the ventricles.

Almost immediately after atrial contraction, the ventricles contract and propel blood into the arterial system.
Review

- Hollow chambers on the right side of the heart perform which of the following functions?
  a. Pump blood throughout the body
  b. Pump blood into the lungs
  c. Pump blood into the aorta
  d. Pump blood into the myocardium
• High-pressure tubing that propels oxygen-rich blood to the tissues

• Consist of layers of connective tissue and smooth muscle

• No gaseous exchange occurs between arterial blood and surrounding tissues because of the thickness of arteries

• Blood pumped from the left ventricle enters the aorta and is distributed throughout the body through a network of arteries and arterioles
  
  – The walls of arterioles contain smooth muscle that either constrict or relax to regulate blood flow to the periphery
• Peripheral vessels do not permit blood to “run off” into the arterial system as rapidly as it ejects from the heart

• The aorta “stores” a portion of blood, which creates pressure within the entire arterial system

• Arterial blood pressure reflects the combined effects of arterial blood flow per minute and resistance to that flow in the peripheral vasculature
  - Blood pressure = Cardiac output x Total peripheral resistance (TPR)
Blood pressure represents the force exerted by blood against the arterial walls during a cardiac cycle.

- **Systolic Blood Pressure (SBP):** Provides an estimate of the work of the heart and force that blood exerts against the arterial walls during ventricular systole.

- **Diastolic Blood Pressure (DBP):** The relaxation phase of the cardiac cycle.

  - Indicates peripheral resistance or the ease that blood flows from the arterioles into the capillaries.
• Normotensive: SBP <120 mm Hg AND DBP <80 mm Hg

• Prehypertension: SBP 120-139 mm Hg OR DBP 80-89 mm Hg

• Hypertension:
  - Stage 1: SBP ≥140 mm Hg OR DBP ≥90 mm Hg
  - Stage 2: SBP ≥160 mm Hg OR DBP ≥100 mm Hg

• Lifestyle changes to reduce BP: Regular physical, modest weight loss, stress management, smoking cessation, reduced sodium and alcohol consumption, and adequate potassium, calcium, and magnesium
Hypertension in the United States

![Graph showing hypertension rates by age, sex, and race from 1988-1994 and 2001-2004.]

- **1988-1994**
  - About 1 in 4 (50 million)

- **2001-2004**
  - About 1 in 3 (73 million)

**Age (y) by Percentage of Population**
- 20-34: Men 11.2%, Women 6.4%
- 35-44: Men 23.2%, Women 18.3%
- 45-54: Men 37.5%, Women 37.4%
- 55-64: Men 49.1%, Women 55.4%
- 65-74: Men 63.6%, Women 73.9%
- 75+: Men 83.8%

**Hypertension rate by race**
- White: 27.9%
- Black: 33.5%
1. Subject is seated in a quiet room

2. Locate the brachial artery at the inner side of the upper arm, approximately 1 inch above the bend in the elbow

3. Take the free end of the cuff, wrap over exposed Velcro, and flap it back over so the cuff wraps around the upper arm at heart level

4. Align the arrows on the cuff with the brachial artery

5. Secure the Velcro parts of the cuff

6. Place the stethoscope bell below the antecubital space over the brachial artery
7. Before inflating the cuff, ensure that the air-release switch remains closed (turn the knob clockwise)

8. Inflate the cuff to 180-200 mm Hg

9. Gradually release cuff pressure (3–5 mm per s) by slowly opening the air-release knob (counterclockwise turn) and note the pressure when you hear the first sound (this represents SBP)

10. Continue to reduce cuff pressure, noting when the sound muffles (4th phase DBP) and when it disappears (5th phase DBP, which is when clinicians usually record DBP)
Review

- Blood pressure is a product of:
  a. Stroke volume and heart rate
  b. Heart rate and total peripheral resistance
  c. Cardiac output and total peripheral resistance
  d. Stroke volume and total peripheral resistance
Mean Arterial Pressure

- Represents the average force exerted by the blood against the arterial walls during a cardiac cycle
- Averages 93 mm Hg at rest
- MAP = DBP + [0.333 (SBP - DBP)]
Cardiac Output and Total Peripheral Resistance

- Cardiac output = MAP ÷ Total peripheral resistance
  - MAP and cardiac output estimate the change in total resistance to blood flow in the transition from rest to exercise

- Total peripheral resistance = MAP ÷ Cardiac output
Capillaries

- The arterioles branch and form smaller and less muscular vessels called metarterioles.
- These vessels end in microscopically small blood vessels called capillaries, which contain 6% of total blood volume.
- The capillary wall usually consists of a single layer of rolled up endothelial cells.
- Some capillaries are so narrow that only one blood cell at a time can squeeze through.
The structure of the blood vessels

Veins
- One-way valves prevent backflow of blood

Arteries
- Arterial walls contain elastic fibers and muscle fibers

Smooth muscle layer

Vessel diameter and blood flow velocity

<table>
<thead>
<tr>
<th>Structure</th>
<th>Diameter (cm)</th>
<th>Blood velocity (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ascending aorta</td>
<td>2.0–3.3</td>
<td>62</td>
</tr>
<tr>
<td>Descending aorta</td>
<td>1.7–2.0</td>
<td>28</td>
</tr>
<tr>
<td>Main arteries</td>
<td>0.2–0.6</td>
<td>20–50</td>
</tr>
<tr>
<td>Capillaries</td>
<td>0.0005–0.001</td>
<td>0.05–0.1</td>
</tr>
<tr>
<td>Main veins</td>
<td>0.5–1.1</td>
<td>15–20</td>
</tr>
<tr>
<td>Vena cava</td>
<td>2.0</td>
<td>10–16</td>
</tr>
</tbody>
</table>

Smooth muscle layer

Arteriole
- Smooth muscle fibers in arterioles control blood flow to capillary beds

Capillary bed
- Blood pressure forces fluid from capillary
- Osmotic pressure within capillaries draws fluid back

Endothelial cells

A tube's resistance is inversely proportional to the fourth power of its radius

Flow resistance = \( \frac{L}{A^4} \)

Flow resistance = 16A

Flow resistance = \( \frac{L}{2^4A^4} \)
The precapillary sphincter, a ring of smooth muscle that encircles the vessel at its origin, controls capillary diameter.

Sphincter constriction and relaxation provides a means of blood flow regulation within a specific tissue to meet metabolic requirements.

Two factors trigger the relaxation of precapillary sphincters to open more capillaries:

- Driving force of increased local blood pressure plus intrinsic neural control
- Local metabolites produced in exercise
The capillaries feed deoxygenated blood into the small veins or venules.

The veins in the lower portion of the body eventually empty into the inferior vena cava, the body’s largest vein:
- This vessel returns blood to the right atrium from the abdomen, pelvis, and lower extremities.

Venous blood from vessels in the head, neck, shoulder regions, thorax, and part of the abdominal wall flows into the superior vena cava to join the inferior vena cava at heart level.

The mixed-venous then enters the right atrium.
• Valves within the veins allow blood to flow in only one direction toward the heart

• The smallest muscular contractions or minor pressure changes within the thoracic cavity with breathing readily compress the veins

• The alternate compression and relaxation of veins and the one-way action of their valves provide a “milking” action that propels blood back to the heart

• Without valves, blood would stagnate in veins of the extremities and people would faint every time they stood up because of reduced venous return and cerebral blood flow
The valves in veins

A: Blood pooling
   Valve closed

B: One-way blood flow keeps blood moving toward heart
   Valve open

C: Muscular contractions squeeze veins

D: Smooth muscle bands
• A condition in which the valves within a vein fail to maintain their one-way blood flow and blood gathers in them so they become excessively distended and painful

• Usually occurs in the surface veins of the lower extremities

• In severe cases, phlebitis occurs where the venous wall becomes inflamed and progressively deteriorates

• Those with varicose veins should avoid static, straining-type exercises that accompany resistance training

• Exercise does not prevent varicose veins but regular exercise can minimize complications because repeated muscle actions continually propel blood toward the heart
Review

- Venous blood from the tributary vessels in the head, neck, shoulder regions, thorax, and part of the abdominal wall flows into the:
  
a. Superior vena cava
  
b. Inferior vena cava
  
c. Venules
  
d. Aorta
阻力运动

- 过度运动机械性地压缩供应肌群的周围动脉血管。
  - 动脉血管压缩显著增加周围血管阻力并降低肌肉灌注量。
  - 为恢复肌肉血流量，副交感神经系统活动、心脏输出量和MAP显著增加。

- 急性心血管负担与重力阻力运动可能对心脏病和血管疾病患者有害。

- 中度至高强度的阻力运动可作为康复的手段，促进肌肉的生长与增厚，延长肌肉的持续时间和力量。
Exercise Blood Pressure

- Rest
- Aerobic exercise
- 2-arm curl heavy load
- 2-leg press heavy load

Blood pressure (mm Hg)
During rhythmic muscular activity, vasodilation in the active muscles reduces TPR to enhance blood flow through large portions of the peripheral vasculature.

Alternate muscle contraction and relaxation propel blood through the vascular circuit and return it to the heart.

Increased blood flow during steady-rate exercise rapidly increases SBP during the first few minutes of exercise.

As exercise continues, SBP gradually declines because the arterioles in the active muscles continue to dilate, further reducing peripheral resistance to blood flow.

DBP remains unchanged throughout exercise.
After an initial rapid rise from the resting level, SBP increases linearly with exercise intensity.

DPB remains stable or decreases slightly at the higher exercise levels.

During maximum exercise by healthy, fit adults, SBP may increase to 200 mm Hg or higher, despite reduced TPR.

This level of blood pressure most likely reflects the heart’s large cardiac output during maximal exercise by individuals with high aerobic capacity.
SBP and DBP during graded exercise

Blood pressure (mm Hg)

Treadmill elevation (% grade)

Rest 2 4 6 8 10 12 14

Systolic blood pressure

Diastolic blood pressure
Exercise with the arms produces considerably higher SBP and DBP than leg exercise performed at a given percentage of $V\cdot O_{2\text{max}}$ in each form of exercise.

Occurs because the smaller arm muscle mass and vasculature offer greater resistance to blood flow than the larger leg mass and blood supply.

Individuals with cardiovascular dysfunction should exercise relatively large muscle groups in contrast to exercise that engages a limited muscle mass.
• Upon completion of a single bout of submaximal exercise, blood pressure temporarily falls below pre-exercise levels for normotensive and hypertensive individuals from an unexplained peripheral vasodilation.

• The hypotensive response to exercise can last up to 12 hours.

• It occurs in response to either low- and moderate-intensity aerobic exercise or resistance exercise.
• The heart has its own circulatory network, the coronary circulation, that arises from the top portion of the heart
  – The right and left coronary arteries
  – The greatest volume of blood flows in the left coronary artery to the left atrium and left ventricle and small sections of the right ventricle

• Blood leaves the tissues of the left ventricle through the coronary sinus and the right ventricle from the anterior cardiac veins

• Normal blood flow to the myocardium at rest equals 200-250 mL per minute
Coronary circulation

Anterior view
- Superior vena cava
- SA node
- Pulmonary artery
- Left main coronary artery
- Great cardiac vein
- Left marginal artery
- Anterior descending (interventricular) branch of left coronary artery

Posterior view
- Pulmonary veins
- Coronary sinus
- Inferior vena cava
- Circumflex branch of left coronary artery
- Left coronary artery
- Descending posterior (interventricular) branch of right coronary artery

Obstructed artery
- Sight of obstruction (thrombus)
- Area of myocardial infarction and cell death
• At rest, the myocardium extracts 70-80% of the oxygen from the blood in the coronary vessels.

• A proportionate increase in coronary blood flow in exercise provides the sole mechanism to increase myocardial oxygen supply.

• Blood flow increases because of:
  - Elevated myocardial metabolism dilates coronary vessels.
  - Increased aortic pressure during exercise forces a proportionately greater volume of blood into the coronary circulation.
Effects of Impaired Blood Supply

- The myocardium depends on an adequate oxygen supply since it has limited anaerobic energy-generating capacity.
- Extensive vascular perfusion supplies at least one capillary to each of the heart’s muscle fibers.
- Tissue hypoxia provides a potent stimulus to myocardial blood flow:
  - Can produce chest pains, or angina pectoris.
- Exercise provides an effective way to evaluate adequacy of myocardial blood flow:
  - A blood clot in a coronary vessel can impair normal heart function, leading to a myocardial infarction.
Rate-Pressure Product

- An estimate of myocardial workload and resulting oxygen consumption
- Uses the product of peak SBP measured at the brachial artery and heart rate (HR)
- This index of relative cardiac work relates closely to directly measured myocardial oxygen consumption and coronary blood flow in healthy subjects over a wide range of exercise intensities
- \[ RPP = SBP \times HR \]
  - Ranges from 6000 at rest to \( \geq 40,000 \) during exercise, depending on intensity and mode
• The myocardium relies almost exclusively on energy released in aerobic reactions

• Its muscle fibers contain the greatest mitochondrial concentration of all tissues

• Glucose, fatty acids, and lactate from glycolysis in skeletal muscle provide energy for myocardial functioning
  – At rest, most of the energy comes from free fatty acid breakdown
  – Following a meal, it “prefers” glucose
  – During intense exercise, it derives its major energy by oxidizing circulating lactate
Generalized pattern of myocardial substrate use

- Rest: Glucose and glycogen (purple), Fatty acids (green), Lactate (blue)
- Moderate exercise: Glucose and glycogen (purple), Fatty acids (green), Lactate (blue)
- Intense exercise: Glucose and glycogen (purple), Fatty acids (green), Lactate (blue)
Review

- Myocardial muscle fibers contain the least mitochondrial concentration of all tissues.
  a. True
  b. False