Chapter 19: The Heart

- Circulatory system
  - heart, blood vessels and blood

- Cardiovascular system
  - heart, arteries, veins and capillaries; 2 major divisions

- Pulmonary circuit - right side of heart
  - carries blood to lungs for gas exchange

- Systemic circuit - left side of heart
  - supplies blood to all organs of the body
Cardiovascular System Circuit

- Pulmonary capillaries
- Pulmonary veins
- Branches of aortic arch
- Left atrium
- Left ventricle
- Descending aorta
- Oxygen-rich, CO2-poor blood
- Oxygen-poor, CO2-rich blood
- Systemic capillaries

- CO₂
- O₂
- Superior vena cava
- Inferior vena cava
- Right atrium
- Right ventricle
- Pulmonary arteries
Size, Shape and Position

- Located in mediastinum, between lungs
- Base - broad superior portion of heart
- Apex - inferior end, tilts to the left, tapers to point
- 3.5 in. wide at base, 5 in. from base to apex and 2.5 in. anterior to posterior; weighs 10 oz
Heart Position

Cross Section
- Lungs
- Thoracic vertebra
- Heart
- Sternum

2nd rib
Sternum
Diaphragm
Pericardium

- Allows heart to beat without friction, room to expand and resists excessive expansion
- Parietal pericardium
  - outer, tough, fibrous layer of CT
  - inner, thin, smooth, moist serous layer
- Pericardial cavity
  - filled with pericardial fluid
- Visceral pericardium (a.k.a. epicardium of heart wall)
  - thin, smooth, moist serous layer covers heart surface
Heart Wall

- **Epicardium** (a.k.a. visceral pericardium)
  - serous membrane covers heart

- **Myocardium**
  - thick muscular layer
  - fibrous skeleton - network of collagenous and elastic fibers
    - provides structural support
    - attachment for cardiac muscle
    - nonconductor important in coordinating contractile activity

- **Endocardium**
  - smooth inner lining
• Pericardial cavity contains 5-30 ml of pericardial fluid
Heart Chambers

- 4 chambers
- Right and left atria
  - 2 superior, posterior chambers
  - receive blood returning to heart
- Right and left ventricles
  - 2 inferior chambers
  - pump blood into arteries

- Atrioventricular sulcus - separates atria, ventricles
- Anterior and posterior sulci - grooves separate ventricles (next slide)
External Anatomy - Anterior

- Ligamentum arteriosum
- Aortic arch
- Superior vena cava
- Branches of the right pulmonary artery
- Ascending aorta
- Left pulmonary artery
- Pulmonary trunk
- Left pulmonary veins
- Right atrium
- Right ventricle
- Inferior vena cava
- Auricle of left atrium
- Anterior interventricular sulcus
- Left ventricle
- Apex of heart
External Anatomy - Posterior

- Aorta
- Left pulmonary artery
- Left pulmonary veins
- Right pulmonary veins
- Superior vena cava
- Right pulmonary artery
- Right atrium
- Pericardium
- Inferior vena cava
- Posterior interventricular sulcus
- Right ventricle
- Apex of heart
- Left atrium
- Left ventricle
- Auricle
- Fat
Anterior Aspect

- Fat in interventricular sulcus
- Left ventricle
- Right ventricle
- Anterior interventricular artery
Heart Chambers - Internal

- Interatrial septum
  - wall that separates atria
- Pectinate muscles
  - internal ridges of myocardium in right atrium and both auricles
- Interventricular septum
  - wall that separates ventricles
- Trabeculae carneae
  - internal ridges in both ventricles
Internal Anatomy Anterior Aspect

- Left pulmonary artery
- Pulmonary trunk
- Pulmonary semilunar valve
- Left pulmonary veins
- Left atrium
- Aortic semilunar valve
- Left AV (bicuspid) valve
- Left ventricle
- Papillary muscle
- Interventricular septum
- Myocardium
- Epicardium
Heart Internal Anatomy

- Heart bisected in frontal plane, opened like a book
Heart Valves

• Ensure one-way blood flow

• Atrioventricular (AV) valves
  – right AV valve has 3 cusps (tricuspid valve)
  – left AV valve has 2 cusps (mitral, bicuspid valve)
  – chordae tendineae - cords connect AV valves to papillary muscles (on floor of ventricles)

• Semilunar valves - control flow into great arteries
  – pulmonary: from right ventricle into pulmonary trunk
  – aortic: from left ventricle into aorta
Heart Valves

- Pulmonary semilunar valve
- Openings to coronary arteries
- Aortic semilunar valve
- Left AV (bicuspid) valve
- Right AV (tricuspid) valve
Heart Valves

Chordae tendineae

Papillary muscle
AV Valve Mechanics

- Ventricles relax, *pressure drops*, semilunar valves close, AV valves open, blood flows from atria to ventricles
- Ventricles contract, *pressure rises*, AV valves close, (papillary m. contracts and pulls on chordae tendineae to prevent prolapse) *pressure rises* and semilunar valves open, blood flows into arteries
Operation of Atrioventricular Valves
Operation of Semilunar Valves

Semilunar valves open

Semilunar valves closed
Blood Flow Through Heart

Aorta
Superior vena cava
Right pulmonary veins
Right atrium
Right AV (tricuspid) valve
Right ventricle
Inferior vena cava
Left pulmonary artery
Pulmonary trunk
Left pulmonary veins
Left atrium
Aortic semilunar valve
Left AV (bicuspid) valve
Left ventricle
Coronary Circulation

• Blood vessels of heart wall nourish cardiac muscle
• Left coronary artery - under left auricle, 2 branches
  – anterior interventricular artery
    • supplies interventricular septum + anterior walls of ventricles
  – circumflex artery
    • passes around left side of heart in coronary sulcus, supplies left atrium and posterior wall of left ventricle
• Right coronary artery - supplies right atrium
  – passes under right auricle in coronary sulcus, divides:
  – marginal artery - supplies lateral rt. atrium + ventricle
  – posterior interventricular artery
    • supplies posterior walls of ventricles
Myocardial Infarction

• Sudden death of heart tissue caused by interruption of blood flow from vessel narrowing or occlusion

• Anastomoses defend against interruption by providing alternate blood pathways
  – circumflex artery and right coronary artery combine to form posterior interventricular artery
  – anterior and posterior interventricular arteries join at apex of heart
Venous Drainage

• 20% drains directly into right ventricle
• 80% returns to right atrium
  – great cardiac vein (anterior interventricular sulcus)
  – middle cardiac vein (posterior sulcus)
  – coronary sinus (posterior coronary sulcus) collects blood from these and smaller veins and empties into right atrium
Coronary Vessels - Anterior

- Superior vena cava
- Aortic arch
- Pulmonary trunk (divided)
- Left coronary artery
- Circumflex artery
- Great cardiac vein
- Anterior interventricular artery
- Right coronary artery
- Marginal artery
- Inferior vena cava
Coronary Vessels - Posterior

- Aortic arch
- Superior vena cava
- Great cardiac vein
- Circumflex artery
- Coronary sinus
- Right coronary artery
- Middle cardiac vein
- Posterior interventricular artery
- Posterior cardiac vein
Coronary Flow and the Cardiac Cycle

- Reduced during ventricular contraction
  - arteries compressed
- Increased during ventricular relaxation
  - openings to coronary arteries, just above aortic semilunar valve, fill as blood surges back to valve
Structure of Cardiac Muscle

- **Short**, thick, **branched** cells, 50 to 100 μm long and 10 to 20 μm wide with **one central nucleus**

- **Sarcoplasmic reticulum**
  - T tubules **much larger than in skeletal muscle**, admit more Ca$^{2+}$ from ECF during excitation

- **Intercalated discs**, join myocytes end to end
  - interdigitating folds - $\uparrow$ **surface area**
  - **mechanical junctions** tightly join myocytes
    - fascia adherens: actin anchored to plasma membrane
    - desmosomes
  - **electrical junctions** - gap junctions form channels allowing ions to flow directly into next cell
Structure of Cardiac Muscle Cell

- Intercalated discs
- Mitochondrion
- Nucleus
- Sarcolemma
- Gap junction
- Desmosomes
Metabolism of Cardiac Muscle – Why is the heart fatigue resistant?

- Aerobic respiration
- Rich in myoglobin and glycogen
- Large mitochondria
- Organic fuels: fatty acids, glucose, ketone
Cardiac Conduction System

- **Myogenic** - heartbeat originates within heart
- **Autorhythmic** - depolarize spontaneously regularly
- **Conduction system** – be able to list the path of the impulse:
  1. **SA node**: pacemaker, initiates heartbeat, sets heart rate
  2. *fibrous skeleton insulates atria from ventricles*
  3. **AV node**: electrical gateway to ventricles
  4. **AV bundle**: pathway for signals from AV node
  5. **Right and left bundle branches**: divisions of AV bundle that enter interventricular septum and descend to apex
  6. **Purkinje fibers**: upward from apex spread throughout ventricular myocardium
Cardiac Conduction System

- Right atrium
- Atrioventricular node
- Sinoatrial node (pacemaker)
- Atrioventricular bundle
- Left atrium
- Purkinje fibers
- Bundle branches
Cardiac Rhythm

• Systole = contraction; diastole = relaxation

• Sinus rhythm
  – set by SA node, adult at rest is 70 to 80 bpm

• Arrhythmia - abnormal cardiac rhythm
  – heart block: failure of conduction system
    • bundle branch block
    • total heart block (damage to AV node)
Depolarization of SA Node

- **SA node** - no stable resting membrane potential
- **Pacemaker potential**
  - gradual depolarization \textit{from} -60 mV, slow influx of Na$^+$
- **Action potential**
  - at threshold -40 mV, fast Ca$^{+2}$ channels open, (Ca$^{+2}$ in)
  - depolarizing phase \textit{to} 0 mV, K$^+$ channels open, (K$^+$ out)
  - repolarizing phase \textit{back to} -60 mV, K$^+$ channels close
- Each depolarization creates one heartbeat
  - SA node at rest fires at 0.8 sec, about 75 bpm
SA Node Potentials

- **Fast Ca²⁺ inflow**
- **Fast K⁺ outflow**
- **Threshold**
- **Pacemaker potential**
- **Action potential**

**Membrane potential (mV)**

**Time (sec)**
Impulse Conduction to Myocardium

- SA node signal travels at 1 \( m/sec \) through atria
- AV nodes thin myocytes slow signal to 0.05 \( m/sec \)
  - delays signal 100 msec, allows ventricles to fill
- AV bundle and purkinje fibers
  - speeds signal along at 4 \( m/sec \) to ventricles
- Papillary muscles - get signal first, contraction stabilizes AV valves
- Ventricular systole begins at apex, progresses up
  - spiral arrangement of myocytes twists ventricles slightly
Contraction of Myocardium

- **Myocytes have stable resting potential of -90 mV**
- **Depolarization** (very brief)
  - stimulus opens Na⁺ gates, (Na⁺ in) depolarizes to threshold, rapidly opens more Na⁺ gates in a positive feedback cycle
  - action potential peaks at +30 mV, gates close quickly
- **Plateau** - 200 to 250 msec, sustains contraction
  - slow Ca²⁺ channels open, Ca²⁺ binds to fast Ca²⁺ channels on SR, releases Ca²⁺ into cytosol: contraction
- **Repolarization** - Ca²⁺ channels close, K⁺ channels open, rapid K⁺ out returns to resting potential
Myocardial Contraction & Action Potential

1) Na\(^+\) gates open
2) Positive feedback cycle
3) Na\(^+\) gates close
4) Plateau
5) Ca\(^{+2}\) channels close
   K\(^+\) channels open
Electrocardiogram (ECG)

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

• P wave
  – SA node fires, atrial depolarization
  – atrial systole

• QRS complex
  – atrial repolarization and diastole (signal obscured)
  – AV node fires, ventricular depolarization
  – ventricular systole

• T wave
  – ventricular repolarization
Normal Electrocardiogram (ECG)
1) atria begin to depolarize
2) atria depolarize
3) ventricles begin to depolarize at apex; atria repolarize
4) ventricles depolarize
5) ventricles begin to repolarize at apex
6) ventricles repolarize
Diagnostic Value of ECG

- Invaluable for diagnosing abnormalities in conduction pathways, MI, heart enlargement and electrolyte and hormone imbalances
ECGs, Normal & Abnormal

Sinus rhythm (normal)

No P waves

Nodal rhythm – no SA node activity
ECGs, Abnormal

Arrhythmia: conduction failure at AV node

Heart block

No pumping action occurs

Fibrillation
Cardiac Cycle

- One complete contraction and relaxation of heart
- Atrial systole
- Atrial diastole
- Ventricle systole
- Ventricle diastole
- Quiescent period
Principles of Pressure and Flow

- Measurement: compared to force generated by column of mercury (mmHg) - sphygmomanometer

- Change in volume creates a pressure gradient

- Opposing pressures
  - Blood pressure in aorta, holds aortic valve closed
  - Ventricular pressure must rise above aortic pressure forcing open the valve
Heart Sounds

- **Auscultation** - listening to sounds made by body
- **First heart sound (S1)**, louder and longer “lubb”, occurs with closure of AV valves
- **Second heart sound (S2)**, softer and sharper “dupp” occurs with closure of semilunar valves
- **S3** - rarely heard in people > 30
Phases of Cardiac Cycle

• **Quiescent period**
  – all chambers relaxed
  – AV valves open
  – blood flowing into ventricles

• **Atrial systole**
  – SA node fires, atria depolarize
  – P wave appears on ECG
  – atria contract, force additional blood into ventricles
  – ventricles now contain end-diastolic volume (EDV) of about 130 ml of blood
Isovolumetric Contraction of Ventricles

• **Electrical**
  – Atria repolarize and relax
  – Ventricles depolarize
  – QRS complex appears in ECG

• **Muscle**
  – Ventricles contract

• **Pressure**
  – Rising pressure closes AV valves

• **Heart sound**
  – S1 occurs – “Lupp”

• **Volume/Flow of blood**
  – No ejection of blood yet (no change in volume)
Ventricular Ejection

• **Pressure**
  – Rising pressure opens semilunar valves

• **Flow of blood**
  – Rapid ejection of blood
  – Reduced ejection of blood (less pressure)
  – Stroke volume: amount ejected, about 70 ml
    • $\text{SV/EDV}=\text{ejection fraction}$, at rest $\sim 54\%$, during vigorous exercise as high as $90\%$, diseased heart $< 50\%$

• **End-systolic volume**: amount left in heart
Isovolumetric Relaxation of Ventricles

• **Electrical**
  – T wave appears in ECG
  – Ventricles repolarize and relax (begin to expand)

• **Valves:**
  – Semilunar valves close (dicrotic notch of aortic press. curve)
  – AV valves remain closed

• **Flow of blood**
  – Ventricles expand but do not fill

• **Heart sound**
  – S2 occurs (‘‘Dupp’’)

Ventricular Filling

• Valves
  – AV valves open

• Blood Flow
  – Ventricles fill with blood - 3 phases
    1. rapid ventricular filling - high pressure
    2. diastasis - sustained lower pressure
    3. filling completed by atrial systole

• Heart sound
  – S3 may occur
Major Events of Cardiac Cycle

- Quiescent period
- Atrial systole
- Isovolumetric contraction
- Ventricular ejection
- Isovolumetric relaxation
- Ventricular filling
Rate of Cardiac Cycle

- Atrial systole, 0.1 sec
- Ventricular systole, 0.3 sec
- Quiescent period, 0.4 sec
- Total 0.8 sec, heart rate 75 bpm
Overview of Volume Changes

End-systolic volume (ESV) 60 ml

Passively added to ventricle during atrial diastole 30 ml

Added by atrial systole 40 ml

Total: end-diastolic volume (EDV) 130 ml

Stoke volume (SV) ejected by ventricular systole -70 ml

End-systolic volume (ESV) 60 ml

Both ventricles must eject same amount of blood
Unbalanced Ventricular Output

1. Right ventricular output exceeds left ventricular output.
2. Pressure backs up.
3. Fluid accumulates in pulmonary tissue.
Unbalanced Ventricular Output

1. Left ventricular output exceeds right ventricular output.
2. Pressure backs up.
3. Fluid accumulates in systemic tissue.
Cardiac Output (CO)

- **Cardiac Output** = Amount ejected by each ventricle in 1 minute

- **CO** = **HR** x **SV**

- **Resting values**, **CO** = 75 beats/min x 70 ml/beat = 5,250 ml/min, usually about 4 to 6L/min

- **Vigorous exercise** ↑ **CO** to 21 L/min for fit person and up to 35 L/min for world class athlete

- **Cardiac reserve**: difference between maximum and resting **CO**
Heart Rate

• **Measured from pulse – Normal values:**
  – Infants have HR of 120 beats per minute or more
  – Young adult females avg. 72 - 80 bpm
  – Young adult males avg. 64 to 72 bpm
  – HR rises again in the elderly

• **Tachycardia:** persistent, resting adult HR > 100
  – stress, anxiety, drugs, heart disease or ↑ body temp.

• **Bradycardia:** persistent, resting adult HR < 60
  – common in sleep and endurance trained athletes (↑ SV)
Sympathetic Nervous System

• Cardioacceleratory center
  – stimulates sympathetic cardiac accelerator nerves to SA node, AV node and myocardium
  – these nerves secrete norepinephrine, which binds to $\beta$-adrenergic receptors in the heart (+ chronotropic effect)
  – CO peaks at HR of 160 to 180 bpm
  – Sympathetic n.s. can drive HR up to 230 bpm, (limited by refractory period of SA node), but SV and CO are less than at rest
Parasympathetic Nervous System

• Cardioinhibitory center
  – stimulates vagus nerves
    • right vagus nerve - SA node
    • left vagus nerve - AV node
  – secrete ACH (acetylcholine), binds to muscarinic receptors
    • opens K+ channels in nodal cells, hyperpolarized, fire less frequently, HR slows down
  – vagal tone: background firing rate holds HR to sinus rhythm of 70 to 80 bpm
    • severed vagus nerves - SA node fires at intrinsic rate-100bpm
    • maximum vagal stimulation ↓ HR as low as 20 bpm
Inputs to Cardiac Center

• Higher brain centers affect HR
  – sensory and emotional stimuli - rollercoaster, IRS audit
  – cerebral cortex, limbic system, hypothalamus

• Proprioceptors
  – inform cardiac center about changes in activity, HR ↑ before metabolic demands arise

• Baroreceptors
  – pressure sensors in aorta and internal carotid arteries send continual stream of signals to cardiac center
    • if pressure drops, signal rate drops, cardiac center ↑ HR
    • if pressure rises, signal rate rises, cardiac center ↓ HR
Inputs to Cardiac Center 2

• Chemoreceptors
  – sensitive to blood pH, CO$_2$ and oxygen
  – aortic arch, carotid arteries and medulla oblongata
  – primarily respiratory control, may influence HR
  – $\uparrow$ CO$_2$ (hypercapnia) causes $\uparrow$ H$^+$ levels, may create acidosis (pH < 7.35)
  – Hypercapnia and acidosis stimulates cardiac center to $\uparrow$ HR
Stroke Volume

• Governed by three factors:
  – preload, contractility and afterload
• ↑ preload or contractility ↑ SV
• ↑ afterload ↓ SV
Preload

• **Preload** = Amount of tension in ventricular myocardium before it contracts

• ↑ preload causes ↑ contraction strength
  – exercise ↑ venous return, stretches myocardium (↑preload), myocytes generate more tension during contraction, ↑ CO matches ↑ venous return

• Frank-Starling law of heart - SV ∝ EDV
  – ventricles eject as much blood as they receive, more they are stretched (↑preload) the harder they contract
Contractility

• **Contractility** = Contraction force for a given preload

• Tension caused by factors that adjust myocyte’s responsiveness to stimulation
  – factors that ↑ contractility are **positive inotropic agents**
    • hypercalcemia, catecholamines, glucagon, digitalis
  – factors that ↓ contractility are **negative inotropic agents**
    • hyperkalemia ($K^+$), hypocalcemia, hypoxia, hypercapnia
Afterload

- Afterload = Pressure in arteries above semilunar valves opposes opening of valves
- ↑ afterload ↓ SV
  - any impedance in arterial circulation ↑ afterload
- Continuous ↑ in afterload (lung disease, atherosclerosis, etc.) causes hypertrophy of myocardium, may lead it to weaken and fail
Exercise and Cardiac Output

• Effect of proprioceptors
  – HR ↑ at beginning of exercise due to signals from joints, muscles

• Effect of venous return
  – muscular activity ↑ venous return causes ↑ SV

• ↑ HR and ↑ SV cause ↑ CO

• Effect of ventricular hypertrophy
  – caused by sustained program of exercise
  – ↑ SV allows heart to beat more slowly at rest, 40-60 bpm
  – ↑ cardiac reserve, can tolerate more exertion