Cardiovascular System
L- 3  Physiology of the Heart and Blood Circulation

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Goals

Understanding:-

Functional anatomy of the heart, - pericardium, myocardium, cardiac muscle.

Excitability and conductive pathway of the heart, heart beat

Explain the functioning of the valves of the heart and how they relate to the heart sounds.

Blood flow, blood pressure
Cardiovascular System (CVS)

The system consists of:
- Fluid (blood)
- Vessels (arteries, veins, capillaries)
- A pump (heart)
Plasma and its constituents

In Lecture 2 – a little about plasma has been discussed

Plasma = Blood minus formed elements
   (remember hematocrit)

Serum = plasma minus most of cloting factors
   (supernatant yellow fluid that remains after a clot forms; contains antibody fractions of the blood)
Some typical plasma constituents

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Typical range</th>
<th>Units of measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sodium</td>
<td>135-155</td>
<td>mEq/L</td>
</tr>
<tr>
<td>Potassium</td>
<td>3.0-5.5</td>
<td>mEq/L</td>
</tr>
<tr>
<td>Chloride</td>
<td>95-110</td>
<td>mEq/L</td>
</tr>
<tr>
<td>Bicarbonate</td>
<td>22-26</td>
<td>mEq/L</td>
</tr>
<tr>
<td>Total protein</td>
<td>6-8</td>
<td>g/dL</td>
</tr>
<tr>
<td>Albumin</td>
<td>3-4</td>
<td>g/dL</td>
</tr>
<tr>
<td>Blood urea nitrogen</td>
<td>10-25</td>
<td>mg/dL</td>
</tr>
<tr>
<td>Creatinine</td>
<td>1.0-1.5</td>
<td>mg/dL</td>
</tr>
<tr>
<td>Glucose</td>
<td>70-100</td>
<td>mg/dL</td>
</tr>
</tbody>
</table>
Plasma and its constituents

• Plasma - 92% water; 8% other substances
• Osmolality = 290mOsm/kg at normal body temperature
• Na\(^+\) and Cl\(^-\) ions contribute the most to total osmolality
• Albumin and globulin, 2 major proteins synthesized in liver
  - many small compounds and electrolytes bind to albumin, circulate in bound forms preventing their rapid loss in urine
• Albumin and other large molecules do not readily pass capillary walls; provide an effective osmotic force - prevent excessive fluid loss from capillaries to outside
Plasma and its constituents

• $\alpha$- and $\beta$-globulins
  - functions as albumins
  - body defense
  - as precursor enzymes in blood clotting

• $\gamma$-globulin (synthesized in cells of immune system)
  - immunoglobulins: IgG, IgE, IgA, IgM, IgD
  - IgG most abundant

• In some animals immunoglobulins pass placenta; give immunity to the newborns

• Some animals through colostrum to newborns
The Heart and circulation
Location of the Heart

- Hollow muscular structure located in the thorax
- Large arteries & veins – continuous with the heart at its base
- Base directed upward and forward; apex, the opposite end, directed downward and backward
- in pericardial space (sac)
Covering of the heart - Pericardium

1. Fibrous pericardium - tough, collagenous
2. Parietal pericardium (lines fibrous pericardium)
3. Visceral pericardium (epicardium) adheres to the heart surface
4. Pericardial space filled with small amount of pericardial fluid important for lubrication of the heart for near-continuous motion
Structure of Heart Wall (myocardium)

- **Epicardium** = visceral Pericardium (serosa)
- **Myocardium**: muscle tissue + C/T + blood vessels + ?
- **Endocardium**:
  - simple squamous epithelium continuous with endothelia of blood vessels
  - because of its smooth surface
    - reduce friction
    - minimize resistance for blood flow and thus lower energy requirement

What will happen when -

**Endocarditis** – inflammation of endothelial lining of the heart

**Valvular endocarditis** – endocarditis involving inflammation of endothelium of the valves
Myocardium

- Myocardium - forms the wall + compartments (chambers)
- Muscles - arranged in a manner so that when they contract the blood is ejected from the chambers
- Right side and left side chambers; each side has an atrium and a ventricle
- Each atrium has an extension k/s auricle (to conserve space)
- Atria receive blood from the veins and the ventricles receive blood from the atria
- Right and left ventricles pump blood from the heart through the pulmonary trunk and aorta, respectively
Left vs. Right Ventricle Muscles

**Left**: high pressure pump (Why?)

**Right**: low pressure pump  
⇒ right chamber is thinner walled than left

Ventricles separated by interventricular septum
Cardiac Muscle

- Striated, aerobic, interwoven, autorhythmic

- Intercalated discs - gap junctions, strong junctional complex (desmosomes)
Properties of the cardiac muscle

Excitability

• It is the ability of the cardiac muscle to respond to a stimulus.

• The index for excitability is **Chronaxie**.
  the minimum time required for excitation of a nerve or muscle when the stimulus is double the minimum (threshold) necessary to elicit a basic response.
Properties of the cardiac muscle

**Electrophysiology of the heart:**

I. Resting membrane potential (RMP) = -60 MV
   This is because cardiac muscle is more permeable to Na+ ions
   Cardiac muscle, being less excitable, has higher Chronaxie than skeletal muscles
   (RMP of skeletal muscle = -90 mv and smooth muscle = -70 mv)

II. Prolonged action potential
   Due to the plateau caused by opening of slow Ca+ channels which prolongs depolarization and thus mechanical shortening of the cardiac muscle occurs.
Properties of the cardiac muscle

Contractility
- The cardiac muscle has the ability to contract isometrically and isotonically

  **Isometric contraction**: The length remains constant but the tension increases e.g. early phase of ventricular systole

  **Isotonic contraction**: The tension remains constant while the length shortens e.g. late phase of ventricular contraction

Contractility obeys "All or None Law" and "Starling Law"

**All or None Law**: the strength by which a nerve or muscle fiber responds to a stimulus is not dependent on the strength of the stimulus. If the stimulus is any strength above threshold, the nerve or muscle fiber will give a complete response or otherwise no response at all.
A. Resting
B. **Isometric** contraction; m/s no change in length, sarcomeres shorten, stretching the series elastic elements
C. **Isotonic** contraction; the contractile elements shorten, stretching the series elastic elements, before they develop tension to lift the load.
D. Muscle begins to shorten when contractile elements shorten further.
Starling Law:

- The further the stretch of the muscle fibers, the stronger is the contraction.
- Up to a certain limit beyond which the muscle fibers can no longer contract stronger even with greater stretch of the muscle fibers.

Conductivity

-- Ability of the myocardial fibers to spread conduction along the conduction system all over the heart.
-- Conductivity myocardial fibers vary but generally have a high conductive velocity.
Metabolism of cardiac muscle

Cardiac Muscle

- Heart metabolism is different from skeletal muscle in 3 ways.
- Heart muscle can function only under aerobic conditions. Heart muscle cells are rich in mitochondria facilitating aerobic respiration.
- Heart muscle - unable to store glycogen.
- Fatty acids are the preferred fuel of the heart. Glucose is the least favored fuel.
- Ketone bodies and lactate are used under stress when the energy demand is high.
Rhythmicity

-- Ability of the heart to contract with regular intervals of relaxation
-- the distance between consecutive beats or myocardial contractions is almost equal or the duration of relaxation is almost the same

Autorythmicity

-- the ability to conduct and contract regularly without an external stimulus.
-- In spite of that, the heart is still being adjusted by ANS and hormones to adjust cardiac muscle function in certain conditions e.g. stress
**Autorythmicity**

- **Sinoatrial Node** (S.A): 60 – 80 charge/min (natural pacemaker of the heart)
- **Atrioventricular Node** (A.V): 40-60 charges/min
- **Bundle of His**: 30 – 40 charges/min
- **Purkinjé fibers**: 15 charges /min (incompatible with life)

- If S-A node fails to initiate a stimulus, any of the other areas will initiate the stimulus and will be considered an **ectopic pacemaker** for the heart.
The Cardiac conduction system
Heart valves

• Atrioventricular (A-V) valves
  - Right side = tricuspid valve
  - Left side = bicuspid (mitral) valve
  - A-V valves prevent expulsion of ventricular blood into the atria when the ventricles contract.

• Tendency of A-V valves eversion is prevented by cords (chordae tendineae) attached to the free margin of the cusps at one end and to small muscles (papillary m/s) at the other end that extend from the myocardium

• Papillary m/s contraction is synchronized with the myocardial contraction so that tension to the chordae tendineae is approximately timed
Heart Valves

Opening to left coronary artery

Aortic semilunar valve
Left atrium
Aorta

Right atrium
Coronary vessel
Right A-V valve

Aortic semilunar valve
Right A-V (tricuspid) valve
Coronary arteries

Chordae tendineae
Pulmonary semilunar valve
Coronary sinus

Papillary muscle
Coronary veins

Left ventricle
Left A-V (mitral) valve

A Location related to the chambers and aorta

B Valves viewed from above ventricles
Heart valves

- Back flow of blood just ejected from the ventricles is prevented by valves located at the exits of the arteries from the ventricles
- **Pulmonary semilunar valve** - for pulmonary trunk
- **Aortic semilunar valve** – for aorta

- All heart valves ensure unidirectional blood flow
The Mammalian Heart
Showing direction of blood flow

Superior vena cava (from head)
Right pulmonary artery
Right pulmonary vein
Pulmonary semilunar valve
Right atrium
Right atrioventricular (AV) valve
Inferior vena cava (from body)
Right ventricle
Aorta
Left pulmonary artery
Left pulmonary vein
Left atrium
Left atrioventricular (AV) valve
Aortic semilunar valve
Left ventricle
Interventricular septum

Arrows indicate direction of the blood flow.

- Red = O₂-rich blood
- Blue = O₂-poor blood

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Blood flow through the Heart

Systemic and Pulmonary
Blood flow through the Heart

Venous Blood

- Blood from tissues in forward part of the body
- Blood from tissues in rear part of the body

Cranial vena cava

R - V

L - V

R - A

L - A

Aorta

Lung

Pulmonary vein

Fig 21.6
Structure and Function of Valves

- Mitral valve
- 4 sets of valves
- Close passively under blood pressure
- Prevent backflow of blood
- Heart sounds produced by valve closure
Support for AV valves:

Valves are restrained by chordae tendineae which are in turn attached to papillary muscles (prevention of backflow!)

Picture taken from R ventricle, looking toward R atrium
Heart Valve Prolapse

Mitral Valve Prolapse

- Most common cardiac variation (5-10% of population)
- Mitral valve cusps do not close properly
- Regurgitation during left ventricular systole
Blood from body enters right atrium

Passes tricuspid valve into right ventricle

Leaves by passing pulmonary semilunar valves into pulmonary trunk and to the lungs to be oxygenated

Leaves left ventricle past aortic semilunar valves into aorta

Returns from the lung by way of pulmonary veins into the left atrium

Distributed to rest of the body

From left atrium past bicuspid valve into left ventricle

Special circulation: coronary, pulmonary & cerebral
Coronary circulation

- circulation of blood in the **blood vessels** of the **heart** muscle (the **myocardium**)
- vessels - deliver oxygen-rich blood to the myocardium
- coronary **arteries**
- cardiac veins.
- Superficial coronary arteries - epicardial coronary arteries
- when healthy - capable of autoregulation to maintain coronary blood flow at levels appropriate to the needs of the **heart muscle**.
- relatively narrow vessels; commonly affected by **atherosclerosis**; become blocked; cause - **angina** or a **heart attack**.
- Deep coronary arteries - subendocardial.
- Coronary arteries – k/s "end circulation"
  - because the only source of blood supply to the myocardium
  - very little redundant blood supply
  - **blockage** of these vessels can be so **critical**
Coronary Circulation

Coronary arteries: first branches off the ascending aorta.

[Diagram of the heart with labels for various blood vessels and structures, including the aortic arch, pulmonary trunk, left coronary artery, circumflex branch, anterior interventricular (descending) branch, great cardiac vein, small cardiac vein, marginal branch, and right coronary arch.]
coronary veins ➔ coronary sinus ➔ right atrium
(inferior to opening of inferior vena cava)
Coronary heart disease

Coronary artery disease (CAD)
Arteriosclerotic heart disease (CHD)

a narrowing of the small blood vessels
supply of blood and oxygen to the heart slow down or stop
Coronary Artery Disease (CAD)

PET scan
(Positron Emission Tomography)

due to?
consequences?

the brighter the color, the greater the blood flow through tissue
Myocardial Infarction (MI)

• ~ 1.3 mil MIs / year in US
• Most commonly due to severe CAD (coronary thrombosis)
• Ischemic tissue degenerates → infarct
• Predisposing factors?
The Cardiac conduction system
Conducting System of the Heart

Specialized muscle cells (authorhythmic cells) conduct APs to time and synchronize the action of the chambers

**SA node** – Also k/s pacemaker, located on the wall of right atrium
- Initial stimulus
- spontaneously depolarizes most rapidly
- initiate heart beat
- transmits action potential across the right and left atria
- contraction of atria emptying the contents (blood) into the ventricles
Conducting System of the Heart

**AV node**

- when the impulse reaches AV node, it travels down along the **AV bundle** (bundle of His) within the septum

**Bundle of His branches**, one of which supplies each ventricle where they branch into Purkinje fibers

**Purkinje fibers** reflect up external walls of ventricles and stimulate contraction of cardiac muscle cells as a unit.

The blood in the ventricles – pumped into pulmonary artery and aorta to circulate to pulmonary and systemic circuits.
Conducting System of the Heart

- Atria and ventricles - separated by a fibrous ring surrounding the AV valves.
- It acts as an insulator.
- Therefore the impulse that spreads throughout the atria does not spread to the ventricles and vice versa.
- This permit independent contractions of atria and ventricles.
- i.e, the ventricles are filled during their relaxation by the contraction and emptying of the atria.
- AV bundle fibers - smaller diameter than other Purkinje fibers - conductivity - 10% slower than cardiac muscle fibers.
- Ventricular m/s - thicker than atria and conduction distance is greater – therefore to achieve coordinated contraction of muscle fibers of ventricles, it is essential to have a greater velocity of conduction which is provided by Purkinje fibers.
Conducting System of the Heart

Cardiac muscle – contract more slowly than skeletal m/s

- longer refractory period (the period during repolarization when a stimulus cannot evoke another depolarization.

Autorhythmic stimulation may be modified by sympathetic and parasympathetic nerves changing the nature of heart beat in terms of frequency and force of contraction
Cardiac cycle and Heart Beat

Cardiac cycle = the sequence of events that occurs during one complete heart beat.

2 phases – systole (contraction)
   diastole (relaxation)

2 phases are continuous
   - assigned periods are arbitrary
   - The two atria are in systole and diastole together as are the two ventricles.

After ventricular systole and during ventricular diastole: the following sequence of events occurs
Cardiac cycle

1. Atria filled by blood from Venae cavae and pulmonary veins; vol. & pressure (occurs during ventricular systole)
   AV valves open when arterial pressure exceeds the ventricular pressure (occurs at the beginning of ventricular diastole)
2. Blood flows into relaxed ventricles (abt 70% filled)
3. Atria contract (filling of ventricles complete)
4. Atria relax and begin filling.
5. Ventricles begin contraction; AV valves closed b/c ventricle pressures exceeds atrial pressures
6. Continued contraction of ventricles
7. Semilunar valves open
8. Blood ejected from ventricles.
9. Ventricles begin to relax.
10. Atrial pressures begin to exceed the ventricular pressures and semilunar valves closed.
Heart sounds

Two heart sounds by auscultation: -

1\textsuperscript{st} sound = Lub = closure of aterioventricular valves when ventricles contract

2\textsuperscript{nd} sound = dub = closure of semilunar valves when ventricles start to fill following contraction

(3\textsuperscript{rd} and 4\textsuperscript{th} sound may be detected on ECG; 3\textsuperscript{rd} sound due to flowing of blood into ventricles and 4\textsuperscript{th} sound due to atrial contraction)

Murmurs: abnormal heart sounds resulted from valve disorders.
Factors that affect heart rate

**Physiological**
- excitement
- muscular exercise (activity, work, exercise)
- high environmental temperature
- digestion
- sleep
- high altitude
- smoking
- some food or drinks – e.g. caffeine (coffee, tea)
- respiration (slight changes)
- metabolic rate
Heart rate control

Metabolic rate
- HR - small animal > large animal
  - small animal has larger surface area/unit body mass
  - higher metabolic rate and O\textsubscript{2} consumption

<table>
<thead>
<tr>
<th>Animal</th>
<th>Beats/min</th>
<th>Animal</th>
<th>Beats/min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Horse</td>
<td>33-44</td>
<td>Cat</td>
<td>110-130</td>
</tr>
<tr>
<td>Horse (Thoroughbred)</td>
<td>38-48</td>
<td>Chicken</td>
<td>200-400</td>
</tr>
<tr>
<td>Dairy cow</td>
<td>60-70</td>
<td>Elephant</td>
<td>30</td>
</tr>
<tr>
<td>Sheep and goats</td>
<td>70-80</td>
<td>Mouse</td>
<td>670</td>
</tr>
<tr>
<td>Pig</td>
<td>60-80</td>
<td>Rat</td>
<td>420</td>
</tr>
<tr>
<td>Small dog</td>
<td>80</td>
<td>guinea pig</td>
<td>280</td>
</tr>
<tr>
<td>Large dog</td>
<td>120</td>
<td>Human</td>
<td>60-90</td>
</tr>
</tbody>
</table>
Heart rate control

Pathological
- cardiac diseases
- infections (fever)
- toxins
- medication
Cardiac output

the volume of blood being pumped by the heart, in particular by a left or right ventricle in the time interval of one minute.

Stroke volume: The amount of blood pumped by the left ventricle of the heart in one contraction.

- stroke volume is not all of the blood contained in the left ventricle. The heart does not pump all the blood out of the ventricle. Only about 2/3 of the blood in the ventricle is put out with each beat.

- The cardiac output is therefore:

\[ Q = \text{Stroke Volume} \times \text{Heart rate/min} \]