Cardiac Mechanics

Bioengineering/Physiology 6000

The Heart

- Structure
  - Macro and micro
- Function
- Cells
  - Pacemaker
  - Conduction system
  - Contractile myocytes
- Electrophysiology
  - Action potentials
  - Cell to cell coupling
- Mechanics
  - EC coupling
  - Cardiac cycle
### Average Hemodynamic Values

<table>
<thead>
<tr>
<th>Variable</th>
<th>Cow</th>
<th>Man</th>
<th>Dog</th>
<th>Rabbit</th>
<th>Rat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weight (kg)</td>
<td>414</td>
<td>70</td>
<td>20</td>
<td>4</td>
<td>0.6</td>
</tr>
<tr>
<td>Cardiac Output (ml/sec)</td>
<td>680</td>
<td>110</td>
<td>42</td>
<td>5.2</td>
<td>1.2</td>
</tr>
<tr>
<td>Heart rate (min⁻¹)</td>
<td>71</td>
<td>76</td>
<td>99</td>
<td>288</td>
<td>349</td>
</tr>
<tr>
<td>Stroke Volume (ml)</td>
<td>570</td>
<td>87</td>
<td>25</td>
<td>1.1</td>
<td>0.21</td>
</tr>
<tr>
<td>Velocity in ascending aorta</td>
<td>16</td>
<td>18</td>
<td>32</td>
<td>22</td>
<td></td>
</tr>
</tbody>
</table>

### Hummingbird Physiology

(What we need to explain)

- Heart is 20% of body volume (largest of any animal), 2-3% of body mass
- Heart rate varies from 30 (deep rest), 500 (while perching), to 1200 (during high speed chases)
- Highest known mass-specific metabolic rates among vertebrate homeotherms (100 times greater than elephant)
- Eats .5-8 times body weight per day
- Respiratory rate of 250 at rest
- Dives produce 7-10 G at speeds of up to 100 kph.
Electrophysiology Review

- Pacemaker cells
  - Neurogenic vs. myogenic
- SA Node
- AV Node
- Purkinje Fibers
- Conduction system
- Ventricular myocytes
- The Electrocardiogram (ECG)

Excitation-Contraction Coupling (ECC)
EC Coupling

- Action potential causes influx of Ca$^{2+}$
- In mammals and birds, this causes release of more Ca$^{2+}$
- Ca$^{2+}$ interacts with actin/myosin to cause contraction
- Pumps gather up Ca$^{2+}$ or remove it from cell
Calcium Measurement

- Calcium-sensitive dye
- Optical recording system
- Stimulate cell and synchronize with optics
EC Coupling and Ca$^{2+}$

1) Control

2) SR disabled (caffeine)

3) No Ca$^{2+}$ entry (Ba$^{2+}$)

CICR Summary

- Calcium causes contraction
- Calcium is stored in the sarcoplasmic reticulum (SR)
- A small increase of Ca in the vicinity of the SR causes a much larger release of Ca from the SR.
- Contraction can be graded
Contractile Proteins

Pretension, Frank-Starling, and Control of Contraction
**Pretension of Muscle (Explain?)**

Isometric Contraction with Pretension

- Pretension
- Active tension
- Resting tension

**Isotonic Contraction and Preload**

- Isotonic tension
- Pretension

Cardiac Mechanics

Bioengineering 6000 – Systems Physiology I

Cardiovascular Review

Bioengineering 6960B-TAC
Intrinsic Regulation of Cellular Contraction

- Spacing in contractile elements
  - Determines contractility
  - Adjusted passively

Frank Starling Mechanism

- Increased pretension can increase contraction
- Cell: striation spacing
- Muscle: pretension
- Heart: Increased filling produces increased output
- Does not require neural input
Extrinsic Regulation of Contractility

- Free [Ca]i is key component
- Positive inotropic agents:
  - epinephrine: stimulate β receptors and increase Ca influx and uptake (load SR)
- Negative inotropic agents:
  - ACh: acts mostly on atria to shorten AP and reduce [Ca]i
  - Acidosis

The Cardiac Cycle and Afterload
Cardiac Cycle

(1) Mid-diastole  (2) Atrial contraction
(3) Isometric ventricular contraction  (4) Ventricular ejection  (5) Isometric ventricular relaxation

(a) Changes in pressure and volume during heartbeat

<table>
<thead>
<tr>
<th>Electro-cardiogram</th>
<th>QRS</th>
<th>T</th>
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<tbody>
<tr>
<td>P</td>
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<table>
<thead>
<tr>
<th>Pressure (mm Hg)</th>
</tr>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>50</td>
</tr>
<tr>
<td>110</td>
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<table>
<thead>
<tr>
<th>Ventricle volume (ml)</th>
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<tbody>
<tr>
<td>0</td>
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<tr>
<td>65</td>
</tr>
<tr>
<td>130</td>
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Cardiac Mechanics

Bioengineering 6000 -- Systems Physiology I
Work of the Heart

- Work = Pressure * Volume (force * distance)
- Cardiac cycle as PV diagram
- Efficiency
  - Convert work to O₂ consumption
  - Compare to total O₂ consumption
  - 10--15% efficient

Effect of E/NE on Contraction

- constant pretension
- reduced end-systolic volume
- increased stroke volume
Isotonic Contraction and Afterload

- Afterload reduces shortening
- Isotonic tension
- Pretension

Contraction at the Whole Heart
Whole Heart Simulation

Animal Hearts
Animal Hearts

- Air-breathing vs. water breathing vs. fetal
- Open Systems
- Separate left and right hearts
  - Higher pressure good for rapid transport but require lymphatic system
  - Lower pressure (e.g., pulmonary) does not require lymphatics and stays drier
  - Both sides must have equal flow
- Shared ventricles
  - Shunts from pulmonary to systemic (P->S)
  - Allows adjustment of flow through lungs/gills
  - Flows to both parts of circulation are not equal but pressures are

Open Systems

- Blood empties into body space
- Bathes tissues directly, blood in small chambers
- Low pressure system (4-10 mm Hg)
- Typically limited regulation and low oxygen transport (with exceptions)
- Insects bypass lungs and transport oxygen directly so open circulation does not carry oxygen
Rigid Pericardium

- Compliant
  - Minimal constraint
  - Lubrication
- Non-compliant
  - Contraction of one chamber assists filling the other

Water Breathing Fishes

- 4-chambered, sequential heart with valves
- Gills perform gas exchange and also ion balance (like kidneys in mammals)
- Gill circulation under higher pressure than systemic circulation
Air Breathing Fishes

- Gills and vascularized air sac both provide $O_2$; gills used for $CO_2$ and ion balance
- Blood directed to different parts of system by the heart, also between gills and air-breathing organs

Amphibians (e.g., Frog)

- Shared ventricle but blood separated
  - Spiral fold
  - Initial flow through pulmonary because of reduced pressure
  - Resistance to flow varies with breathing (inhale reduces resistance)
**Frog II**

- Partial mixing of systemic blood flow
  - Cerebral flow oxygenated, systemic mixed

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**Reptiles (non crocodilian)**

- Partial separation of single ventricle by 2 septa
- In ventricular systole, flow determined by relative resistances of pulmonary and system, e.g., breathing, diving
- Pressure differences in arteries also directs flow: lower pressure value opens first
Fetal Heart

- Lungs collapsed so minimal pulmonary flow
- Oxygenated blood comes from placenta and some passes through foramen ovale to left atrium
- Rest of returning blood goes from RV and most through Ductus arteriosus to aorta
- At birth, lungs inflate, flow to them increases, placenta flow gone so systemic resistance increases
- Left side pressure increases, D.A. and F.O close

Numbers are percentage of ventricular output