Overview of circulation
Hemodynamics

- Fluid mechanics as they apply to the circulatory system
- Flow results from a pressure gradient
  - Hydrostatic pressure - that resulting from the weight of fluid in the system
  - Hydraulic pressure - that resulting from the pump in the system
- Flow occurs from areas of high pressure to low pressure
Hydrostatic pressure

Figure 12-7 Effect of hydrostatic pressure on the venous pressures throughout the body.
Pressures in the circulatory system

Figure 11–2 Blood pressures in the different portions of the circulatory system.
Volumes in the circulatory system

**Figure 11-1** Distribution of blood volume in the different portions of the circulatory system.
Basic Circulatory function

• Blood flow to each tissue is controlled according to tissue needs
• Cardiac output (CO) is controlled by the sum of local tissue flows
• Arterial pressure is controlled independently of local blood flow control and cardiac output control
Pressures in the circulatory system

• Ohm’s law
• \( Q = \frac{\Delta P}{R} \)
  . \( \Delta P = Q \times R \)
  . \( R = \frac{\Delta P}{Q} \)

• Blood pressure
  – Force exerted by the blood against the area of the vessel wall (mmHg)

• Resistance
  – Total peripheral resistance
    • Difference between the systemic arteries and veins
Pressure, flow, and resistance

- Ohm’s law
- $Q = \frac{\Delta P}{R}$
- $\Delta P = Q \times R$
- $R = \frac{\Delta P}{Q}$

*Figure 11-3* Relationships among pressure, resistance, and blood flow.
Poisuille’s Law

\[ R = \frac{8}{\pi r^4} \]

\( L \) = length, \( n \) = viscosity, \( r \) = radius

Resistance in arterioles is great, but lower in the aorta and arteries.
Poisuille’s Law

- $n = \text{viscosity}$
- Blood = 3x water
- Hematocrit = 40%
- Polycythemia, anemia
Poisuille’s Law

- Increase length - increase resistance - decrease flow
- Increase viscosity - increase resistance - decrease flow
- Increase radius - decrease resistance - decrease flow
- Most changes in flow are caused by altering arteriolar diameter by:
  - Local chemical changes
  - Sympathetic innervation
Vascular compliance

- Amount of storage (quantity of blood in ml) that can be stored per unit of blood pressure increase

Vascular Compliance = increase in pressure/increase in volume

- Volume pressure curves
- Sympathetic/parasympathetic control

Figure 11–8 Volume-pressure curves of the systemic arterial and venous systems, showing also the effects of sympathetic stimulation and sympathetic inhibition.
Vascular compliance

- Important
- Extra blood circulation stored here
- Can increase CO greatly
Arteries veins and capillaries
Fig. 1-1. Internal diameter, wall thickness, and relative amounts of the principal components of the vessel walls of the various blood vessels that compose the circulatory system. Cross sections of the vessels are not drawn to scale because of the huge range from aorta and vena cavae to capillary. (Redrawn from Burton, A. C.: Physiol. Rev. 34:619, 1954.)
### Arteries, veins, and capillaries

<table>
<thead>
<tr>
<th></th>
<th>Small Arteries</th>
<th>Arterioles</th>
<th>Capillaries</th>
<th>Venous Capillaries**</th>
<th>Venules</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter (lumen), μ</td>
<td>19</td>
<td>7</td>
<td>3.7</td>
<td>7.3</td>
<td>21</td>
</tr>
<tr>
<td>Tissues in wall</td>
<td>Endothelium, sm. muscle, collagen, elastin</td>
<td>Endothelium, sm muscle, collagen, elastin</td>
<td>Endothelium only</td>
<td>Endothelium, infrequent sm. muscle, collagen</td>
<td></td>
</tr>
<tr>
<td>Length, mm</td>
<td>3.5</td>
<td>0.9</td>
<td>0.2</td>
<td>0.2</td>
<td>1.0</td>
</tr>
<tr>
<td>Total X-sectional area, cm²</td>
<td>110</td>
<td>150</td>
<td>180</td>
<td>2150</td>
<td>3700</td>
</tr>
<tr>
<td>Percent of total blood volume</td>
<td>2.7</td>
<td>1.0</td>
<td>0.3</td>
<td>3.6</td>
<td>25.6</td>
</tr>
<tr>
<td>Mean pressure, mm Hg</td>
<td>76</td>
<td>56</td>
<td>25</td>
<td>4.5</td>
<td>4.1</td>
</tr>
<tr>
<td>Approx. velocity in active vessels, mm/sec</td>
<td>&gt;5</td>
<td>4</td>
<td>&gt;1</td>
<td>?</td>
<td>&gt;1</td>
</tr>
</tbody>
</table>

Diameter (equatorial) of human or canine red blood cell = 7.5 μ.
Arteries veins and capillaries
Veins

- Capacitance vessels
- Veins hold 60% - small change in capacitance changes the flow returning to the heart greatly
- Venous return to the heart is controlled by
  - Dilating the arterioles
  - Changing diameter of the veins
  - Contracting skeletal muscles around the veins
- Great compliance!
Veins

- Veins contain valves and a venous pump.
Veins

• Veins in spleen, liver, abdomen, and beneath the skin act as blood reservoirs
Arteries

- Carry blood away from heart to the microcirculation
- Have sympathetic innervation
- Elastic - propel blood forward while ventricles relax - function as “pressure reservoirs”
Arterial pressure pulsations

Figure 12–3 Changes in the pulse pressure contour as the pulse wave travels toward the smaller vessels.

Figure 12–1 A normal pressure pulse contour recorded from the ascending aorta. (From Opdyke: Fed. Proc., 11:734, 1952.)
Microcirculation

• Arteries that branch extensively to become arterioles which branch further
• Arterioles - muscular
• Metarterioles
• Precapillary sphincters - control flow through capillaries
• Vasomotion - intermittent contraction of metarterioles and arterioles that controls flow in capillaries
Microcirculation

Figure 12–9 Structure of the mesenteric capillary bed. (From Zweifach: Factors Regulating Blood Pressure. New York, Josiah Macy, Jr., Foundation, 1950.)
Capillaries

• Primary sites of nutrient and waste exchange between blood and interstitial fluids
• Thin walled, small diameter > 10um, porous, intracellular clefts.
Capillaries

Figure 13-1 Structure of the capillary wall. Note especially the intercellular cleft at the junction between adjacent endothelial cells; it is believed that most water-soluble substances diffuse through the capillary membrane along this cleft.
Figure 13-2: Diffusion of fluid molecules and dissolved substances between the capillary and interstitial fluid spaces.
## TABLE 13–1 RELATIVE PERMEABILITY OF MUSCLE CAPILLARY PORES TO DIFFERENT-SIZED MOLECULES

<table>
<thead>
<tr>
<th>Substance</th>
<th>Molecular Weight</th>
<th>Permeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>18</td>
<td>1.00</td>
</tr>
<tr>
<td>NaCl</td>
<td>58.5</td>
<td>0.96</td>
</tr>
<tr>
<td>Urea</td>
<td>60</td>
<td>0.8</td>
</tr>
<tr>
<td>Glucose</td>
<td>180</td>
<td>0.6</td>
</tr>
<tr>
<td>Sucrose</td>
<td>342</td>
<td>0.4</td>
</tr>
<tr>
<td>Inulin</td>
<td>5000</td>
<td>0.2</td>
</tr>
<tr>
<td>Myoglobin</td>
<td>17,600</td>
<td>0.03</td>
</tr>
<tr>
<td>Hemoglobin</td>
<td>68,000</td>
<td>0.01</td>
</tr>
<tr>
<td>Albumin</td>
<td>69,000</td>
<td>0.001</td>
</tr>
</tbody>
</table>
Figure 13-4 Forces operative at the capillary membrane tending to move fluid either outward or inward through the membrane.
Capillaries and Fluid movement

- Capillary pressure forces fluid out through the membrane
- Interstitial fluid pressure forces fluid inward
- Plasma colloid osmotic pressure draws water in (osmosis)
- Interstitial fluid colloid osmotic pressure draws fluid out (osmosis)
Figure 13–3 Structure of the interstitium. Proteoglycan filaments fill the spaces between the collagen fiber bundles. Free fluid vesicles and small amounts of free fluid in the form of rivulets are seen.
Local control over blood flow
Local control over blood flow

• Three major types of control:
  – Control in each tissue in proportion to the need of the tissue
  – Nervous control over blood flow
  – Humoral control (dissolved substances)
Figure 13-5 Isogravimetric method for measuring capillary pressure (explained in the text).
Local control

• Tissues require nutrients
  – Oxygen, glucose, fatty acids

• Tissues require removal of wastes
  – Carbon dioxide and fatty acids

• Mechanisms
  – Acute, long term
Local control

• Acute - minutes- seconds
• Vasodilator theory
  – Triggering substance is formed when oxygen is low - acting on sphinctors in the system (adenosine, carbon dioxide, lactic acid etc..)
• Oxygen demand theory
  – The absence of oxygen prevents muscle contraction and caused vessel dilation
• Autoregulation- return of blood flow back to normal
Local control

• Long term control, hours-days-weeks
• Changes in the vascularity of tissues
  – Size and number of vessels can go up or down
  – Angiogenesis - inresponse to angiogenic factors
  – Growth, ischemia, high metabolic rate
Humoral control

• Control by substances secreted into body fluids
  – Hormones, ions

• Vasoconstrictors
  – Epi/norepi - sympathetic stimulation - stress
  – Angiotensin (arterioles), vasopressin (kidney), endothelin (damaged bv’s)

• Vasodilators
  – Bradykinin-dilates and increases permeability
  – Histamine- response to damaged tissue
  – prostaglandin
Questions

• Define hemodynamics
• Define Poiseuille’s Law
• Describe the determinants of pressure
Nervous control

- Autonomic nervous system

The wiring:

- Sympathetic nervous system
  - Vasomotor fibers innervate the vasculature of the internal viscera of heart and spinal innervation of viscera of peripheral areas
  - Blood vessels - arteries and arterioles - increase resistance and decrease flow in system
  - Decrease volume in veins and increase venous return to the heart

- Parasympathetic control- Heart
  - Minor role in control over circulation
  - Controls heart rate by vagus nerve
Sympathetic vasoconstrictor system

• (1) Control over blood vessel diameter by nerves
• Mostly vasoconstrictor, few vasodilator
• Vasoconstrictor nerves connect to all segments of the circulatory system
• Kidney, spleen, skin receive much innervation
• Skeletal muscle, brain receive less innervation
Sympathetic vasoconstrictor system

- (2) Vasomotor center
- Located in the Pons/Medulla
- Transmits
  - Parasympathetic impulses to the heart via vagus nerves
  - Sympathetic impulses through the spinal cord to the sympathetic nerves
- Vasoconstrictor area (C-1)
- Vasodilator area (A-1)
- Sensory area (A-2)
Sympathetic vasoconstrictor system

Figure 15-2 Areas of the brain that play important roles in the nervous regulation of the circulation. The dashed lines represent inhibitory pathways.
(3) The system keeps vessels partially constricted
Achieved by continuous firing of nerves
1/2-2 impulses per second
Called vasomotor tone

Anes. 50 to 100: NE gives a pressure spike!
Vasomotor Center

- Controls heart along with blood vessels
  - Lateral parts increase heart rate and contractility
  - Medial parts transmit impulses to heart through the vagus nerves

- Higher nervous centers control the vasomotor center

*Figure 15–2* Areas of the brain that play important roles in the nervous regulation of the circulation. The dashed lines represent inhibitory pathways.
Vasomotor Center

- Higher nervous centers control the vasomotor center
  - Reticular center, pons, mesencephalon, diencephalon
  - Hypothalamus
  - Cerebral cortex, motor cortex
Vasomotor Center

- **Vasoconstriction**
  - Norepinephrine is known as the vasoconstrictor substance
  - Acts on alpha receptors of vascular smooth muscle

- **Adrenal medulla**
  - Norepinephrine and epinephrine are released after the medulla receives sympathetic stimulation
  - Epinephrine acts on beta receptors, dilates vessels
Nervous control of circulation

• Rapid control over arterial pressure
  – Vasoconstriction and cardioacceleration, and vagal inhibition
  – Mechanism

• Exercise
  – Mostly local control through vasodilator substances
  – Vasomotor center raises arterial pressure
Arterial baroreceptor system

• Anatomy
• Baroreceptors are in the walls of the systemic arteries - carotid and systemic arch
  Signals are transmitted to the medulla by the Herrings, Glossopharyngeal nerves to the tractus solaris
Arterial baroreceptor system

• Response to pressures
• Carotid
  – 0-60 mm Hg not stimulated
  – > 60 respond, >180 respond maximally
• Aortic
  – Respond above 30 mm Hg
Arterial baroreceptor system reflex

Rise in pressure → Stretch → Herrings Nerves discharges

glossopharyngeal nerves discharges

Vasoconstrictor center inhibited → Vagus stimulation

Vasodilation of arterioles/veins
Decreased heart rate and contraction strength

Pressure is decreased
Arterial baroreceptor system

- Reflex
- Carotid occlusion
- Pressure decreased
- Reflex activated
- Pressure increases
- Return to normal
- Changes in body posture cause this response
- “buffer” function

**Figure 15-5** Typical carotid sinus reflex effect on arterial pressure, caused by clamping both common carotids (after the two vagus nerves have been cut).
Arterial baroreceptor system

- Reflex
- Upper = normal
- Lower = dennervated system
- Variable pressure results
- Baroreceptors not involved in longterm control over blood pressure

Figure 15-6 Two-hour records of arterial pressure in a normal dog (above) and in the same dog (below) several weeks after the baroreceptors had been denervated. (From Cowley, Liard, and Guyton: Circ. Res., 32:564, 1973. By permission of the American Heart Association, Inc.)
Cardiac output

- Quantity of blood pumped by left ventricle per minute
- 5.6 L/min
- Controlled by venous return - Starling mechanism
- Factors controlling peripheral circulation affect venous return
- What are they?
Cardiac output regulation

- Regulated by the sum of all local blood flows
- Blood flow increases in proportion to tissue metabolism
- All blood flows summate to form venous return which is pumped automatically by the heart
Cardiac output curve

- Heart has pumping limit
- Shown on curve
- Center line = normal limit 13 L/min
- Normal flow is 5 L/min
- Hypoeffective
- Hypereffective
Nervous control of arterial pressure

- Arterial pressure with and without nervous control
- DNP - increased metabolism and flow from dilation of arterioles
- Solid = with nervous control
- Dotted = w/o

Figure 17-3: An experiment in a dog to demonstrate the importance of nervous control of arterial pressure as a prerequisite for cardiac output control. Note that with pressure control, the metabolic stimulant dinitrophenol increases cardiac output; without pressure control, the arterial pressure falls and the cardiac output rises very little. (Drawn from experiments by Dr. M. Banet.)
Figure 17-4 Cardiac output in different pathological conditions. The numbers in parentheses indicate number of patients studied in each condition. (From Guyton, Jones, and Coleman: Circulatory Physiology: Cardiac Output and Its Regulation. Philadelphia, W. B. Saunders Co., 1973.)

Figure 17-5 The Fick principle for determining cardiac output.
Additional questions

• Describe nervous control over blood pressure and cardiac output

• Describe the baroreceptor system and the baroreceptor reflex. Diagram a situation where the pressure is adjusted after dropping and rising.
Figure 17-6 Dye concentration curves used to calculate cardiac output levels by the dilution method. The rectangular areas are the calculated average concentrations of the dye in the arterial blood for the durations of the respective injection periods.

Figure 17-7 Effect of hemorrhage on cardiac output and arterial pressure.
Figure 17-3 Different types of feedback that can lead to progression of shock.
Figure 13-8: Special structure of the lymphatic capillaries that permits passage of substances of high molecular weight back into the circulation.
Figure 13-9 Relationship between interstitial fluid pressure and lymph flow. Note that lymph flow reaches a maximum as the interstitial pressure rises slightly above atmospheric pressure (0 mm Hg). (Courtesy of Drs. Harry Gibson and Aubrey Taylor.)
Figure 13-10 Structure of lymphatic capillaries and a collecting lymphatic, showing also the lymphatic valves.
Figure 14-2 Diagram of a tissue unit area for explanation of local feedback control of blood flow.

<table>
<thead>
<tr>
<th>Tissue</th>
<th>Per cent</th>
<th>ML/min</th>
<th>ML/min/100 gm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>14</td>
<td>700</td>
<td>50</td>
</tr>
<tr>
<td>Heart</td>
<td>4</td>
<td>200</td>
<td>70</td>
</tr>
<tr>
<td>Bronchi</td>
<td>2</td>
<td>100</td>
<td>25</td>
</tr>
<tr>
<td>Kidneys</td>
<td>22</td>
<td>1100</td>
<td>360</td>
</tr>
<tr>
<td>Liver</td>
<td>27</td>
<td>1350</td>
<td>95</td>
</tr>
<tr>
<td>Portal Arterial</td>
<td>(21)</td>
<td>(1050)</td>
<td>(300)</td>
</tr>
<tr>
<td>Muscle (inactive state)</td>
<td>(6)</td>
<td>(300)</td>
<td>4</td>
</tr>
<tr>
<td>Bone</td>
<td>5</td>
<td>250</td>
<td>3</td>
</tr>
<tr>
<td>Skin (cool weather)</td>
<td>6</td>
<td>300</td>
<td>3</td>
</tr>
<tr>
<td>Thyroid gland</td>
<td>1</td>
<td>50</td>
<td>160</td>
</tr>
<tr>
<td>Adrenal glands</td>
<td>0.5</td>
<td>25</td>
<td>300</td>
</tr>
<tr>
<td>Other tissues</td>
<td>3.5</td>
<td>175</td>
<td>1.3</td>
</tr>
<tr>
<td>TOTAL</td>
<td>100.0</td>
<td>5000</td>
<td></td>
</tr>
</tbody>
</table>

Based mainly on data compiled by Dr. L. A. Sapirstein.

Figure 14-3 Effect of increasing arterial pressure on blood flow through a muscle. The solid curve shows the effect if the arterial pressure is raised over a period of a few minutes. The dashed curve shows the effect if the arterial pressure is raised extremely slowly over a period of many weeks.

Figure 14-1 Effect of arterial oxygen saturation on blood flow through an isolated dog leg.