M1 - Cardiovascular / Respiratory, Fall 2007

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Pulmonary Blood Flow

Thomas Sisson, M.D.
Objectives

• The student will know the structure, function, distribution and control of pulmonary blood supply
  – Compare pulmonary and bronchial circulation
  – Compare and contrast pulmonary and systemic circulation
  – Describe and explain the effects of cardiac output and lung volume on pulmonary vascular resistance
  – Describe the effects of hypoxia on pulmonary vascular resistance
  – Describe the effects of gravity of pulmonary blood flow
  – Explain Starling’s equation
  – Describe the mechanisms of pulmonary edema
Two Circulations in the Lung

- Pulmonary Circulation.
  - Arises from Right Ventricle.
  - Receives 100% of blood flow.

- Bronchial Circulation.
  - Arises from the aorta.
  - Part of systemic circulation.
  - Receives about 2% of left ventricular output.
Bronchial Circulation

Image of bronchopulmonary anastamosis removed
Pulmonary Circulation

• In series with the systemic circulation.

• Receives 100% of cardiac output (3.5L/min/m²).

• RBC travels through lung in 4-5 seconds.

• 280 billion capillaries, supplying 300 million alveoli.
  – Surface area for gas exchange = 50 – 100 m²
Alveolar Architecture

Source: Undetermined
Alveolar Airspace

Source: Undetermined
Functional Anatomy of the Pulmonary Circulation

• Thin walled vessels at all levels.

• Pulmonary arteries have far less smooth muscle in the wall than systemic arteries.

• Consequences of this anatomy- the vessels are:
  – Distensible.
  – Compressible.
Pulmonary Vascular Resistance

Vascular Resistance = \frac{\text{input pressure} - \text{output pressure}}{\text{blood flow}}

PVR = k \cdot \frac{\text{mean PA pressure} - \text{left atrial pressure}}{\text{cardiac output (index)}}

\text{mean PA pressure} - \text{left atrial pressure} = 10 \text{ mmHg}

\text{mean aorta pressure} - \text{right atrial pressure} = 98 \text{ mmHg}

Therefore PVR is 1/10 of SVR
Vascular Resistance is Evenly Distributed in the Pulmonary Circulation
Reasons Why Pressures Are Different in Pulmonary and Systemic Circulations?

- **Gravity and Distance:**
  - Distance above or below the heart adds to, or subtracts from, **both** arterial and venous pressure
  - Distance between Apex and Base

<table>
<thead>
<tr>
<th></th>
<th>Systemic</th>
<th>Pulmonary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>100 mmHg</td>
<td>Main PA</td>
</tr>
<tr>
<td>Head</td>
<td>50 mmHg</td>
<td>15 mmHg</td>
</tr>
<tr>
<td>Feet</td>
<td>180 mmHg</td>
<td>Apex</td>
</tr>
<tr>
<td></td>
<td></td>
<td>2 mmHg</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25 mmHg</td>
</tr>
</tbody>
</table>
Control of regional perfusion in the systemic circulation:

- Large pressure head allows alterations in local vascular resistance to redirect blood flow to areas of increased demand (e.g. to muscles during exercise).

- Pulmonary circulation is all performing the same job, no need to redirect flow (exception occurs during hypoxemia).

Consequences of pressure differences:

- Left ventricle work load is much greater than right ventricle
- Differences in wall thickness indicates differences in work load.
Influences on Pulmonary Vascular Resistance

Pulmonary vessels have:
- Little vascular smooth muscle.
- Low intravascular pressure.
- High distensibility and compressibility.

Vessel diameter influenced by extravascular forces:
- Gravity
- Body position
- Lung volume
- Alveolar pressures/intrapleural pressures
- Intravascular pressures
Influences of Pulmonary Vascular Resistance

• Transmural pressure = Pressure Inside – Pressure Outside.
  – Increased transmural pressure-increases vessel diameter.
  – Decreased transmural pressure-decreased vessel diameter (increase in PVR).
  – Negative transmural pressure-vessel collapse.

• Different effects of lung volume on alveolar and extraalveolar vessels.
Effect of Transmural Pressure on Pulmonary Vessels During Inspiration

Resistance $\propto$ Length and Resistance $\propto 1/(\text{Radius})^4$

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Pulmonary Vascular Resistance During Exercise

- During exercise cardiac output increases (e.g., 5-fold), but with little change in mean pulmonary artery pressure
  - How is this possible?

\[
\text{Vascular Resistance} = \frac{\text{input pressure} - \text{output pressure}}{\text{blood flow}}
\]

- \(\Delta\text{Pressure} = \text{Flow} \times \text{Resistance}\)
- If pressure does not change, then PVR must decrease with increased blood flow
  - Passive effect (seen in isolated lung prep)
    - Recruitment: Opening of previously collapsed capillaries
    - Distensibility: Increase in diameter of open capillaries.
Recruitment and Distention in Response to Increased Pulmonary Artery Pressure

Control of Pulmonary Vascular Resistance

- **Passive Influences on PVR:**

<table>
<thead>
<tr>
<th>Influence</th>
<th>Effect on PVR</th>
<th>Mechanism</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\uparrow$ Lung Volume (above FRC)</td>
<td>Increase</td>
<td>Lengthening and Compression</td>
</tr>
<tr>
<td>$\downarrow$ Lung Volume (below FRC)</td>
<td>Increase</td>
<td>Compression of Extraalveolar Vessels</td>
</tr>
<tr>
<td>$\uparrow$ Flow, $\uparrow$ Pressure</td>
<td>Decrease</td>
<td>Recruitment and Distension</td>
</tr>
<tr>
<td>Gravity</td>
<td>Decrease in Dependent Regions</td>
<td>Recruitment and Distension</td>
</tr>
<tr>
<td>$\uparrow$ Interstitial Pressure</td>
<td>Increase</td>
<td>Compression</td>
</tr>
<tr>
<td>Positive Pressure Ventilation</td>
<td>Increase</td>
<td>Compression and Derecruitment</td>
</tr>
</tbody>
</table>
Regional Pulmonary Blood Flow Depends Upon Position Relative to the Heart

- Main PA: 15 mmHg
- Apex: 2 mmHg
- Base: 25 mmHg

Source: Undetermined
Gravity, Alveolar Pressure and Blood Flow

- Pressure in the pulmonary arterioles depends on both mean pulmonary artery pressure and the vertical position of the vessel in the chest, relative to the heart.

- Driving pressure (gradient) for perfusion is different in the 3 lung zones:
  - Flow in zone 1 may be absent because there is inadequate pressure to overcome alveolar pressure.
  - Flow in zone 3 is continuous and driven by the pressure in the pulmonary arteriole – pulmonary venous pressure.
  - Flow in zone 2 may be pulsatile and driven by the pressure in the pulmonary arteriole – alveolar pressure (collapsing the capillaries).
Gravity, Alveolar Pressure, and Blood Flow

Typically no zone 1 in normal healthy person

Large zone 1 in positive pressure ventilation + PEEP

Arterial Pressure, \( P_a \)

Venous Pressure, \( P_v \)

Alveolar Dead Space

Zone 1
\( P_A > P_a > P_v \)

Zone 2
\( P_a > P_A > P_v \)

Zone 3
\( P_a > P_v > P_A \)

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Gravity Influences Pressure
**Control of Pulmonary Vascular Resistance**

- **Active Influences on PVR:**

<table>
<thead>
<tr>
<th>Increase</th>
<th>Decrease</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sympathetic Innervation</td>
<td>Parasympathetic Innervation</td>
</tr>
<tr>
<td>α-Adrenergic agonists</td>
<td>Acetylcholine</td>
</tr>
<tr>
<td>Thromboxane/PGE2</td>
<td>β-Adrenergic Agents</td>
</tr>
<tr>
<td>Endothelin</td>
<td>PGE1</td>
</tr>
<tr>
<td>Angiotensin</td>
<td>Prostacycline</td>
</tr>
<tr>
<td>Histamine</td>
<td>Nitric oxide</td>
</tr>
<tr>
<td>Alveolar Hypoxemia</td>
<td>Bradykinin</td>
</tr>
</tbody>
</table>
**Hypoxic Pulmonary Vasoconstriction**

- Alveolar hypoxia causes active vasoconstriction at level of pre-capillary arteriole.

- Mechanism is not completely understood:
  - Response occurs locally and does not require innervation.
  - Mediators have not been identified.
  - Graded response between pO2 levels of 100 down to 20 mmHg.

- Functions to reduce the mismatching of ventilation and perfusion.

- Not a strong response due to limited muscle in pulmonary vasculature.

- General hypoxemia (high altitude or hypoventilation) can cause extensive pulmonary artery vasoconstriction.
Barrier Function of Alveolar Wall

- Capillary endothelial cells:
  - permeable to water, small molecules, ions.
  - barrier to proteins.

- Alveolar epithelial cells:
  - more effective barrier than the endothelial cells.
  - recently found to pump both salt and water from the alveolar space.
Alveolar airspace

Source: Undetermined
Fluid Movement Due to Osmotic Pressure

Water moves through the semi-permeable membrane down a concentration gradient to dilute the solute.
Osmotic Pressure Gradient Can Move Fluid Against Hydrostatic Pressure

Before

Glass tube

After

Permeable membrane
Osmotic Gradient Counteracts Hydrostatic Gradient

• Hydrostatic pressure in the pulmonary capillary bed > hydrostatic pressure in the interstitium
  – hydrostatic pressure drives fluid from the capillaries into the pulmonary interstitium

• Osmotic pressure in the plasma > osmotic pressure in the interstitium
  – osmotic pressure normally would draw fluid from the interstitial space into the capillaries
Starling’s Equation

\[ Q = K \left[ (P_c - P_i) - \sigma (\pi_c - \pi_i) \right] \]

- \( Q \): flux out of the capillary
- \( K \): filtration coefficient
- \( P_c \) and \( P_i \): capillary and interstitial hydrostatic pressures
- \( \pi_c \) and \( \pi_i \): capillary and interstitial osmotic pressures
- \( \sigma \): reflection (sieving) coefficient
Normally Starling’s Forces Provide Efficient Protection

• Normal fluid flux from the pulmonary capillary bed is approximately 20 ml/hr.
  – recall that cardiac output through the pulmonary capillaries at rest is ~5 l/min.
  – < 0.0066% leak.

• Abnormal increase in fluid flux can result from:
  – Increased hydrostatic pressure gradient (cardiogenic pulmonary edema).
  – Decreased osmotic pressure gradient (cirrhosis, nephrotic syndrome).
  – Increased protein permeability of the capillary wall (ARDS).