M1 - Cardiovascular / Respiratory, Fall 2007

Abrams, G.; Sisson, T.; Jacobson, P.

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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 anastomosis removed
Pulmonary Circulation
Pulmonary Circulation

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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 Circulation Pressures

Systemic Capillaries
P = 10
P = 30
Right Atrium
P = 25/0
P = 10
Right Ventricle
P = 5
P = 10
Systemic Artery
P = 120/80
Mean = 100
Pulmonary Artery
P = 25/8
Mean = 15
Left Atrium
P = 5
P = 12
Left Ventricle
P = 8
P = 12
Pulmonary Capillaries

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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

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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>Systemic</th>
<th>Pulmonary</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aorta</td>
<td>100 mmHg</td>
</tr>
<tr>
<td>Head</td>
<td>50 mmHg</td>
</tr>
<tr>
<td>Feet</td>
<td>180 mmHg</td>
</tr>
<tr>
<td>Main PA</td>
<td>15 mmHg</td>
</tr>
<tr>
<td>Apex</td>
<td>2 mmHg</td>
</tr>
<tr>
<td>Base</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
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

During Inspiration

Extraalveolar Space

Alveolar Space

Blood Vessel Elongates and Narrows

Resistance

Negative Pressure

Blood Vessel Distension

↓ Resistance

Alveoli distend

Alveoli

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Resistance $\propto$ Length and Resistance $\propto 1/(\text{Radius})^4$
Effect of Lung Volume on PVR

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?

\[
\text{ΔPressure} = \text{Flow} \times \text{Resistance}
\]

- 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.

Vascular Resistance = \( \frac{\text{input pressure} - \text{output pressure}}{\text{blood flow}} \)
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>↑Lung Volume (above FRC)</td>
<td>Increase</td>
<td>Lengthening and Compression</td>
</tr>
<tr>
<td>↓Lung Volume (below FRC)</td>
<td>Increase</td>
<td>Compression of Extraalveolar Vessels</td>
</tr>
<tr>
<td>↑Flow, ↑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>↑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

<table>
<thead>
<tr>
<th>Source: Undetermined</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blood flow/unit volume</td>
</tr>
<tr>
<td>Distance up lung (cm)</td>
</tr>
</tbody>
</table>

Main PA | 15 mmHg |
Apex    | 2 mmHg  |
Base    | 25 mmHg |
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

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## 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><strong>Alveolar Hypoxemia</strong></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.
Water moves through the semi-permeable membrane down a concentration gradient to dilute the solute.
Osmotic Pressure Gradient Can Move Fluid Against Hydrostatic Pressure
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

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

- **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).