CHAPTER 2

Ventilation
Ventilation

- Process that exchanges gases between the external environment and the alveoli
- Oxygen is inhaled from the atmosphere to the alveoli
- Carbon dioxide is exhaled from the alveoli to the atmosphere
1. Pressure differences across the lungs
2. Elastic properties of the lungs and chest wall and how they affect ventilation
3. Dynamic characteristics of the lungs
4. Characteristics of normal and abnormal ventilatory patterns
Pressure Differences Across the Lungs

• The difference between two pressures is called a pressure gradient.

• Pressure gradients are responsible for:
  1. Moving air in and out of the lungs
  2. Maintaining the lungs in an inflated state
Common Pressure Differences Across the Lungs

- Driving pressure
- Transairway pressure
- Transmural pressure
- Transpulmonary pressure
- Transthoracic pressure
Driving Pressure

• Pressure difference between two points in a tube
• For example:
  – 20 mm Hg – 15 mm Hg = 5 mm Hg (driving pressure)
Fig. 2-1. Driving pressure.

Driving Pressure

20 mm Hg
A

Gas Flow

Driving Pressure
15 mm Hg

5 mm Hg
B
Transairway Pressure

• Transairway pressure ($P_{ta}$)
  – Barometric pressure difference between mouth pressure ($P_m$) and alveolar pressure ($P_{alv}$)

\[
P_{ta} = P_m - P_{alv}
\]
Transairway Pressure

Fig. 2-2. Transairway pressure.
**Transmural Pressure**

- Transmural pressure ($P_{tm}$)
  - Differences that occur across the airway wall
  - Calculated by subtracting the intra-airway pressure ($P_{iaw}$) from the pressure outside of the airway ($P_{oaw}$)

\[
P_{tm} = P_{iaw} - P_{oaw}
\]
Transmural Pressure

Fig. 2-3. Transmural pressure. A. airway with a positive transmural pressure. B. airway with a negative transmural pressure.
Transpulmonary Pressure

- Transpulmonary pressure ($P_{tp}$)
  - Difference between alveoli pressure ($P_{alv}$) and pleural pressure ($P_{pl}$)

$$P_{tp} = P_{alv} - P_{pl}$$
Transpulmonary Pressure

Fig. 2-4. Transpulmonary pressure.
Transthoracic Pressure

- Transthoracic pressure ($P_{tt}$)
  - Difference between alveoli pressure ($P_{alv}$) and body surface pressure ($P_{bs}$)

$$P_{tt} = P_{alv} - P_{bs}$$
Fig. 2-5. Transthoracic pressure.
Role of the Diaphragm in Ventilation

Fig. 2-6. The diaphragm.

- Phrenic nerves
- Central tendon
- Inferior vena cava
- Esophagus
- Aorta
- Lumbar vertebrae
- Diaphragm
Normal Inspiration and Expiration

**Inspiration**
- Intra-alveolar pressure below atmospheric pressure
- Intrapleural pressure progressively decreases
- Diaphragm progressively moves downward

**End-Inspiration**
- Gas Flow
- No Gas Flow
- Intra-alveolar pressure in equilibrium with atmospheric pressure
- Intrapleural pressure holds at a level below that at rest
- Downward movement of diaphragm stops

**Expiration**
- Intra-alveolar pressure above atmospheric pressure
- Intrapleural pressure progressively increases
- Diaphragm progressively moves upward

**End-Expiration**
- Gas Flow
- No Gas Flow
- Intra-alveolar pressure in equilibrium with atmospheric pressure
- Intrapleural pressure holds at resting level
- Upward movement of diaphragm stops

Fig. 2-7. Normal inspiration and expiration.
Normal Inspiration

Fig. 2-7. Normal inspiration.

<table>
<thead>
<tr>
<th>Normal Inspiration and Expiration</th>
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</thead>
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<tr>
<td><strong>Inspiration</strong></td>
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<tr>
<td>Intra-alveolar pressure below atmospheric pressure</td>
</tr>
<tr>
<td>Intrathoracic pressure progressively decreases</td>
</tr>
<tr>
<td>Diaphragm progressively moves downward</td>
</tr>
<tr>
<td>Gas Flow</td>
</tr>
</tbody>
</table>

| **End-Inspiration**               |
| Intra-alveolar pressure in equilibrium with atmospheric pressure |
| Intrathoracic pressure holds at a level below that at rest |
| Downward movement of diaphragm stops |
| No Gas Flow                       |
Normal Expiration

Fig. 2-7. Normal expiration.

Expiration

- Intra-alveolar pressure above atmospheric pressure
- Intrapleural pressure progressively increases
- Diaphragm progressively moves upward
- Gas Flow

End-Expiration

- No Gas Flow
- Intra-alveolar pressure in equilibrium with atmospheric pressure
- Intrapleural pressure holds at resting level
- Upward movement of diaphragm stops
Mechanical Ventilation Positive Pressure Breath
(30 cm H₂O Pressure Above Atmospheric Pressure)

**Inspiration**
- Intra-alveolar pressure progressively increases above atmospheric pressure
- Intrapleural pressure progressively increases above atmospheric pressure
- Diaphragm is progressively pushed downward

**Gas Flow**

**End-Inspiration**
- Intra-alveolar pressure is 30 cm H₂O above atmospheric pressure
- Intrapleural pressure is about 30 cm H₂O above atmospheric pressure
- Downward movement of diaphragm stops

**Expiration**
- Intra-alveolar pressure progressively decreases toward atmospheric pressure
- Intrapleural pressure progressively decreases to its resting level (below the atmospheric pressure)
- Diaphragm progressively moves upward to its resting level

**Gas Flow**

**End-Expiration**
- Intra-alveolar pressure in equilibrium with atmospheric pressure
- Intrapleural pressure holds at resting level (below the atmospheric pressure)
- Upward movement of diaphragm stops

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**Fig. 2-8. Mechanical ventilation positive pressure (30 cm H₂O pressure above atmospheric pressure).**
Fig. 2-9 Right-side tension pneumothorax. In severe cases, the gas accumulation and subsequent pressure causes the lung to collapse on the affected side, push the diaphragm downward, and push the heart and mediastinum to the unaffected side.
Elastic Properties of the Lung and Chest Wall

• Both the lungs and the chest wall have elastic properties
• Under normal conditions:
  – Each elastic system works against each other
• Chest wall has a natural tendency to move outward, or to expand
  – This is a result of the bones of the thorax and surrounding muscles
• The lungs have a natural tendency to move inward, or collapse
  – Because of the natural elastic properties of the lung tissue
Lung Compliance ($C_L$)

• How readily the elastic force of the lungs accepts a volume of inspired air

• $C_L$ is defined as the change in lung volume ($\Delta V$) per unit pressure change ($\Delta P$)
Lung Compliance \( (C_L) \)

\[
(C_L) = \frac{\Delta V \text{ (L)}}{\Delta P \text{ (cm H}_2\text{O)}}
\]

\[
= \frac{.75 \text{ L of gas}}{5 \text{ cm H}_2\text{O}}
\]

\[
= .15 \text{ L/cm H}_2\text{O (or 150 ml cm H}_2\text{O)}
\]
Lung Compliance ($C_L$)

- It is irrelevant whether the change in driving pressure is in the form of positive or negative pressure.
Lung Compliance ($C_L$)

- At rest, the average $C_L$ for each breath is about:

  $0.1 \text{ L/cm H}_2\text{O} \ (100 \text{ mL})$
Normal Volume-Pressure Curve

Fig. 2-10. Normal volume-pressure curve.
Fig. 2-11. How changes in lung compliance affect the volume-pressure curve.
Chest Wall Compliance

• The chest wall has a natural tendency to move outward, or to expand
  – As a result of the bones of the thorax and surrounding muscles.
Chest Wall Compliance

• The chest wall works to offset the normal elastic properties of the lungs.
• The normal lung compliance of the combined chest wall and lung compliance is 0.1 L/H$_2$O.
Hooke’s Law

• Provides another way to explain compliance
  – Describes the physical properties of an elastic substance
In pulmonary physiology, elastance is defined as the change in pressure per change in volume:

$$\text{Elastance} = \frac{\Delta P}{\Delta V}$$
• Elastance is the reciprocal (opposite) of compliance.
  – Thus, lungs with high compliance (greater ease of filling) have low elastance
  – Lungs with low compliance (lower ease of filling) have high elastance.
Hooke’s Law

• When a truly elastic body, like a spring, is acted on by one unit of force, the elastic body will stretch one unit of length.

• When acted on by two units of force it will stretch two units of length, and so forth.
Hooke’s Law

• When the force exceeds the elastic limits of the substance, the ability of length to increase in response to force rapidly decreases.

• Should the force continue to rise, the elastic substance will ultimately break.
Fig. 2-12. Hooke’s law.
Hooke’s Law—Applied to the Lungs

• When Hooke’s law is applied to the elastic properties of the lungs:
  – Volume is substituted for length
  – Pressure is substituted for force
Fig. 2-13. Hooke’s law applied to the elastic properties of the lungs.
Surface Tension and Effects on Lung Expansion

1. Surface tension
2. Laplace’s law
3. How pulmonary surfactant offsets alveolar surface tension
Surface Tension

• When a liquid-gas interface exists
  – Liquid molecules at the liquid-gas interface are strongly attracted to the liquid molecules within the liquid mass.

• This molecular, cohesive force at the liquid-gas interface is called surface tension.
Liquid Molecules

Fig. 2-14. A. Liquid molecules mutually attracted to each other in middle of the container. B. Liquid molecules near the liquid-gas interface are strongly attracted to each other.
Laplace’s Law

\[ P = \frac{2 \ ST}{r} \]
Laplace’s Law

\[ P = \frac{4 \ ST}{r} \]
Surface Tension Differences

Fig. 2-15. Bubbles A and B are the same size. The surface tension is different.
Surface Tension

Fig. 2-16. The surface tension of bubbles A and B is identical. The radius of the bubbles is different.

\[ P = \frac{4 \text{ st}}{r} \]

**Bubble A**
Distending Pressure
5 cm H₂O

**Bubble B**
Distending Pressure
10 cm H₂O
Fig. 2-17. Bubbles A and B have the same surface tension. Thus, pressure in smaller bubble (A) is higher and will empty into larger bubble (B).
Fig. 2-18. A. Model showing the formation of a new liquid bubble. B. Graph showing the distending pressure required to maintain the bubble’s size at various stages.
Rate and Time

Fig. 2-19. Rate and time are inversely proportional (as rate increases, time decreases; and as rate decreases, time increases).

Rate (mph)

Time = \frac{Distance}{Rate} \quad \text{(constant 400 mi)}

or

Distance = \text{Rate} \times \text{Time}

Time (Hrs)
Fig. 2-20. In the normal lung, surface tension is low in small alveoli and high in large alveoli.
In the normal lung, the surface tension progressively increases as the alveolar size increases.
Causes of Pulmonary Surfactant Deficiency

• General causes
  – Acidosis
  – Hypoxia
  – Hyperoxia
  – Atelectasis
  – Pulmonary vascular congestion
Causes of Pulmonary Surfactant Deficiency

• Specific causes
  – Acute respiratory distress syndrome (ARDS)
  – Infant respiratory distress syndrome (IRDS)
  – Pulmonary edema
  – Pulmonary embolism
Causes of Pulmonary Surfactant Deficiency

- Specific causes
  - Pneumonia
  - Excessive pulmonary lavage or hydration
  - Drowning
  - Extracorporeal oxygenation
Comparison of Surface Tension

Fig. 2-22. Comparison of surface tension, elastic force, and the effects of pulmonary surfactant.
Dynamic Characteristics of the Lungs

- Dynamic refers to study of forces in action
- In the lungs, dynamic refers to:
  - Movement of gas in and out of the lungs
  - Pressure changes required to move the gas
• The dynamic features of the lung are best explained by
  – Poiseuille’s law for flow and pressure
  – The airway resistance equation
Fig. 2-23. Bronchial changes during inspiration and expiration.
Poiseuille’s Law for Flow

\[ \dot{V} = \frac{\Delta P \ r^4 \ B}{8 \ l \ n} \]
Poiseuille’s Law for Flow Applied to Bronchial Airway

\[ \dot{V} = \Delta Pr^4 \]

Fig. 2-24. Flow applied to airway with its radius reduced 50 percent.

Flow Rate = 16 mL/sec

Flow Rate = 1 mL/sec

1 cm Radius

0.5 cm Radius

Bronchial Airway

Pressure Remains Constant
Fig. 2-25. Flow applied to an airway with its radius reduced 16 percent.
Poiseuille’s Law for Pressure

\[ P = \frac{\dot{V} 8 \ln}{r^4 B} \]
Poiseuille’s Law for Pressure

\[ P \sim \frac{V}{r^4} \]

Flow Rate Remains Constant

1 cm Radius

0.5 cm Radius

Bronchial Airway

1 cm H_2O Driving Pressure

16 cm H_2O Driving Pressure

Fig. 2-26. Pressure applied to airway with its radius reduced by 50 percent.
Poiseuille’s Law for Pressure

\[ P \propto \frac{V}{r^4} \]

Flow Rate Remains Constant

1 cm Radius

.84 cm Radius

Bronchial Airway

10 cm H$_2$O Driving Pressure

20 cm H$_2$O Driving Pressure

Fig. 2-27. Pressure applied to an airway with its radius reduced by 16 percent.
Poiseuille’s Law Rearranged to Simple Proportionalities

\[ \cdot \dot{V} = P \cdot r^4 \]

\[ P = \frac{\cdot \dot{V}}{r^4} \]
Airway Resistance

\[ R_{aw} = \frac{\Delta P \ (\text{cm H}_2\text{O})}{V \ (\text{L/sec})} \]
Airway Resistance Example

• If an individual produces a flow rate of 4 L/sec during inspiration by generating a transairway pressure of 4 cm H₂O, then $R_{aw}$ would equal:
Airway Resistance Example

$$Raw = \frac{\Delta P \text{ (cm H}_2\text{O)}}{\dot{V} \text{ (L/sec)}}$$

$$= \frac{4 \text{ cm H}_2\text{O}}{4 \text{ L/sec}}$$

$$= 1 \text{ cm H}_2\text{O/L/sec}$$
Chronic Bronchitis

Figure 2-28. Chronic bronchitis. Pathology includes (1) inflammation and swelling of the peripheral airway, (2) excessive mucus production and accumulation and, (3) alveolar hyperinflation.
Classifications of Flow

• Laminar flow
• Turbulent flow
• Combination of laminar flow and turbulent flow
  – Tracheobronchial flow or transitional flow
Figure 2-29. Types of gas flow.
Time Constants

\[ TC \text{ (sec)} = \frac{\Delta P \text{ (cm H}_2\text{O})}{\dot{V} \text{ (L/sec)}} \times \frac{\Delta V \text{ (L)}}{\Delta P \text{ (cm H}_2\text{O})} \]

(Raw) \hspace{1cm} (CL)

\[ = \frac{\text{cm H}_2\text{O} \times \text{L}}{\text{L/sec} \times \text{cm H}_2\text{O}} \]
Figure 2-30. Time constants for alveoli with differing lung $C_L$, supplied by airways with differing $R_{aw}$. 

- **Figure A**: Identical $R_{aw}$ and $C_L$. Thus Time Constants Are Equal.
  - Units A & B
  - $C_L = 1$
  - $R_{aw} = 1$
  - Vol. = 1

- **Figure B**: Identical $R_{aw}$, but Unit "B" is 1/2 as compliant as Unit "A".
  - Unit A
  - Unit B
  - $C_L = 1$
  - $R_{aw} = 1$
  - Vol. = 1

- **Figure C**: Identical $C_L$, but Unit "B" has twice the resistance as Unit "A".
  - Unit A
  - Unit B
  - $C_L = 1$
  - $R_{aw} = 1$
  - Vol. = 1
  - $C_L = 1$
  - $R_{aw} = 2$
  - Vol. = 1 But Takes Twice as Long as "A" to Inflate
Figure 2-31. Dynamic compliance/static compliance ratio at different breathing frequencies.
• Positive end expiratory pressure (PEEP)
  – Caused by inadequate expiratory time
Positive End Expiratory Pressure (PEEP)

• Also called:
  – Auto-PEEP
  – Air trapping
  – Intrinsic PEEP
  – Occult PEEP
  – Inadvertent PEEP
  – Covert PEEP
• The ventilatory pattern consist of:
  – Tidal volume ($V_T$)
  – Ventilatory rate
  – Time relationship of the I:E ratio
Tidal Volume

- Volume of air that normally moves into and out of the lungs in one quiet breath
Tidal Volume

- $V_T = 7$ to $9\ \text{mL/kg}$ (3 to 4 mL/lb)
- I:E ratio = 1:2
Normal Breathing

Figure 2-32. Normal, spontaneous breathing (eupnea). The I:E ratio typically is 1:2.
Alveolar Ventilation versus Dead Space Ventilation

• Anatomic
• Alveolar
• Physiologic
Dead Space Ventilation

Figure 2-33. Dead space ventilation (V_D).
Anatomic Dead Space =

• 1 mL/lb (2.2 mL/kg)
  – Thus, a 150-lb. male would have about 150 mL of anatomic dead space for each breath
Figure 2-34 Alveolar vs dead-space ventilation.
$V_A = (V_T - V_D) \times \text{breaths/min}$

• For example, if:
  – $V_T = 450 \text{ ml}$
  – $V_D = 150 \text{ ml}$
  – Breaths/min = 12
$V_A = (V_T - V_D) \times \text{breaths/min}$

- Minute alveolar ventilation would be:
  
  $= 450 \text{ mL} - 150 \text{ mL} \times 12$
  
  $= 300 \times 12$
  
  $= 3600 \text{ mL}$
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<thead>
<tr>
<th>Subject</th>
<th>Breathing Depth $V_T$ (mL)</th>
<th>Breathing Frequency (min⁻¹)</th>
<th>MV (mL.min⁻¹)</th>
<th>$V_D$ (mL.min⁻¹)</th>
<th>$V_A$ (mL.min⁻¹)</th>
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<td>A</td>
<td>150</td>
<td>40</td>
<td>6000</td>
<td>$150 \times 40 = 6000$</td>
<td>0</td>
</tr>
<tr>
<td>B</td>
<td>500</td>
<td>12</td>
<td>6000</td>
<td>$150 \times 12 = 1800$</td>
<td>4200</td>
</tr>
<tr>
<td>C</td>
<td>1000</td>
<td>6</td>
<td>6000</td>
<td>$150 \times 6 = 900$</td>
<td>5100</td>
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How Normal Intrapleural Pressure Differences Cause Regional Differences in Normal Lung Ventilation

Figure 2-35. Intrapleural pressure gradient in the upright position.
Effect of Airway Resistance and Lung Compliance on Ventilatory Patterns

Figure 2-36. The effects of increased airway resistance and decreased lung compliance on ventilatory frequency and tidal volume.
Overview of Specific Ventilatory Patterns

- Apnea
- Eupnea
- Biot’s Respiration
- Hyperpnea
- Hyperventilation
- Hypoventilation
Overview of Specific Ventilatory Patterns

- Tachypnea
- Cheyne-Stokes Respiration
- Kussmaul’s Respiration
- Orthopnea
- Dyspnea
Biot’s Respiration

Figure 2-37 Biot’s respiration.
Hyperpnea

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<tr>
<th>Ventilation</th>
<th>mL</th>
<th>Time (sec)</th>
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<td>Normal Ventilation</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Alveolar Ventilation</td>
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</tr>
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<td>6</td>
</tr>
<tr>
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<td>7</td>
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<td>Alveolus</td>
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<tr>
<td>$P_{ACO_2}$</td>
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<td>9</td>
</tr>
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<tr>
<td>$P_{AO_2}$</td>
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Figure 2-38 Hyperpnea: Increased depth of breathing
Hyperventilation

Figure 2-39  Hyperventilation. Increased rate (A) or depth (B), or combination of both.
Hypoventilation

<table>
<thead>
<tr>
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<th>mL</th>
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<td>Normal</td>
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</tr>
<tr>
<td>Alveolar</td>
<td>200</td>
</tr>
<tr>
<td>Dead Space</td>
<td>350</td>
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Figure 2-40  Hypoventilation. Decreased rate (A) or depth (B), or some combination of both.
Cheyne-Stokes Respiration

Figure 2-41  Cheyne-Stokes respiration.
Kussmaul’s Respiration

Fig. 2-42. Kussmaul's respiration. Increased rate and depth of breathing.
Clinical Application 1 Discussion

• How did this case illustrate …
  – An acute decreased lung compliance?
  – How Poiseuille’s law can be used to demonstrate the effects of bronchial constriction and airway secretions on gas flow and work of breathing?
Clinical Application 1 Discussion

• How did this case illustrate …
  – Effects of an increased $R_{aw}$ on time constants?
  – Frequency-dependent effects of a decreased ventilatory rate on the ventilation of alveoli?
Clinical Application 2 Discussion

• How did this case illustrate …
  – Effects on transthoracic pressure when the thorax is unstable?
  – How the excursions of the diaphragm affect the intrapleural pressure?
  – Acute decreased lung compliance?
  – Therapeutic effects of positive pressure ventilation in flail chest cases?