Principles of Biomedical Systems & Devices

Lecture 16
The Respiratory System

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The function of the Respiratory System is gas exchange

3 basic processes:

- Ventilation
- External respiration
- Internal respiration
Anatomy

- Generally consists of upper and lower respiratory structures
- Upper respiratory includes nasal passages, pharynx and associated structures
- Lower respiratory includes larynx, trachea, bronchi, bronchioles, alveoli
Respiratory System Anatomy

- Nose
- Nasal cavity
- Oral cavity
- Pharynx
- Larynx
- Trachea
- Right primary bronchus
- Lungs
Can also classify the anatomy functionally
- Conduits for air flow: nasal passages all the way down to terminal bronchioles
- Gas exchange areas: respiratory bronchioles and alveoli
GROSS ANATOMY OF LUNGS

- Larynx
- Trachea
- Visceral pleura
- Parietal pleura
- Pleural cavity
- Right secondary bronchus
- Right primary bronchus
- Right tertiary bronchus
- Right bronchiole
- Right terminal bronchiole
- Carina
- Left primary bronchus
- Left secondary bronchus
- Left tertiary bronchus
- Left bronchiole
- Left terminal bronchiole
- Diaphragm

Branching of Bronchial Tree:
- Trachea
- Primary bronchi
- Secondary bronchi
- Tertiary bronchi
- Bronchioles
- Terminal bronchioles
Two lungs located in thoracic cavity
Right lung has three lobes, left lung has 2 lobes
Major blood vessels, nerves, lymph vessels and bronchi enter on medial surface of each lung at the hilus
Each lung is covered by a serous membrane called the pleura, the visceral pleura covers the surface of the lung and the parietal pleura lines the inside of the chest wall
Pleural fluid lubricates the two pleural surfaces
Lungs in the Chest Cavity

First rib

Apex of lung

Left lung

Base of lung

Pleural cavity

Pleura
(a) Diagram of a portion of a lobule of the lung
Ventilation is the mechanical process of moving air (breathing).

- Air flow follows pressure gradients.
- The pressures to consider are outside the body and inside the thoracic cavity.
- Since the pressure outside the body doesn’t change, the pressure inside must...
Two processes: inspiration and expiration (inhalation and exhalation)

- Inspiration is an active process
- Normal expiration is a passive process
- Can have forced expiration
Muscles of Respiration

MUSCLES OF INHALATION
- Sternocleidomastoid
- Scalenes
- External intercostals
- Diaphragm

MUSCLES OF EXHALATION
- Internal intercostals
- External oblique
- Internal oblique
- Transversus abdominis
- Rectus abdominis

Sternum: Exhalation
Inhalation
Diaphragm: Exhalation
Inhalation
During inspiration the pressure in the thoracic cavity becomes negative relative to the pressure outside the body. This is accomplished by the contraction of the respiratory muscles, primarily the diaphragm and the intercostal muscles. Contraction of these muscles increases the volume of the thoracic cavity and decreases the pressure.
Pressure Changes in Pulmonary Ventilation

1. At rest (diaphragm relaxed)
   - Atmospheric pressure = 760 mmHg
   - Alveolar pressure = 760 mmHg
   - Intrapleural pressure = 756 mmHg

2. During inhalation (diaphragm contracting)
   - Atmospheric pressure = 760 mmHg
   - Alveolar pressure = 758 mmHg
   - Intrapleural pressure = 754 mmHg
Normal expiration is caused by the elastic recoil of the lung
- Lung is full of elastic connective tissue
- When it is inflated the elastic tissue stretches
- Once the force that is causing the inflation is removed the elastic tissue goes back to its resting shape
- Doesn’t completely collapse because of the pleura and the dynamic connection between the lung and the chest wall
During normal quiet inhalation, the diaphragm and external intercostals contract. During labored inhalation, sternocleidomastoid, scalenes, and pectoralis minor also contract.

Alveolar pressure increases to 762 mmHg

Atmospheric pressure is about 760 mmHg at sea level

Thoracic cavity increases in size and volume of lungs expands

Alveolar pressure decreases to 758 mmHg

(a) Inhalation

During normal quiet exhalation, diaphragm and external intercostals relax. During forceful exhalation, abdominal and internal intercostal muscles contract.

Thoracic cavity decreases in size and lungs recoil

(b) Exhalation
Pneumothorax
Hemothorax

Hemothorax

Hemorrhage occurs
Blood enters thorax

Pneumothorax

Something penetrates chest wall
Air enters thorax
Respiratory Volumes

- Measured with a spirometer
- Tidal volume – amount of air moved in and out of lungs during normal breathing
- Inspiratory reserve volume – amount of air inspired over normal tidal inspiration at maximal effort
- Expiratory reserve volume – amount of air expired over normal tidal expiration at maximal effort
❖ Vital capacity – total amount of air moved in and out of lungs at maximal effort
❖ Residual volume – air left in lung after maximal expiration
❖ Total lung capacity – vital capacity plus residual volume
Lung Volumes

- **Inspiratory Reserve Volume**: 3,100 mL
- **Tidal Volume**: 500 mL
- **Expiratory Reserve Volume**: 1,200 mL
- **Residual Volume**: 1,200 mL
- **Inspiratory Capacity**: 3,600 mL
- **Vital Capacity**: 4,800 mL
- **Total Lung Capacity**: 6,000 mL

Lung Volumes

- Exhalation
- Inhalation

End of record

Start of record

Functional Residual Capacity: 2,400 mL
Two basic types of diseases interfere with ventilation

- Restrictive diseases – these are related to an inability to inflate the lungs
- Obstructive diseases – these are related to difficulty in getting air out of the lungs
Factors That Influence Air Flow

- Surface tension – the tendency of the alveoli to collapse – countered by surfactant
- Compliance – the relative ease of inflation - dependent on elastic tissue
- Airway resistance – air movement against the walls of the tubes - related to diameter of airways
Eupnea – normal breathing
Dyspnea – abnormal breathing
Apnea – cessation of breathing
Gas exchange depends on pressure gradients – in this case the pressure differences across the alveolar capillary membrane for oxygen and carbon dioxide.

All gas exchange in any capillary bed depends on diffusion.
Alveoli are the small air sacs that make up the greater portion of the lung.

Consist of simple squamous epithelium (one layer of flat cells and a basement membrane) and a few specialized cells (Type II epithelial cells and alveolar macrophages).

Completely surrounded by extensive capillaries which are made up of endothelial cells (one layer of flat cells and a basement membrane).
GAS EXCHANGE

(a) Section through an alveolus showing its cellular components

(b) Details of respiratory membrane
Dalton’s Law of Partial Pressure- each gas in a mixture of gases exerts a pressure independent of the other gases in the mixture

\[ P_T = P_{O_2} + P_{CO_2} + P_{N_2} + P_{H_2O} \]

Henry’s Law- the quantity of a gas that can dissolve in a liquid is proportional to the partial pressure and the solubility coefficient

\[ \text{Pressure} = \frac{P_{\text{GAS}}}{\text{Solubility Coefficient}} \]
CO₂ is more soluble than O₂ so the concentration gradient for CO₂ will be considerably smaller than the gradient for O₂.

O₂ is less soluble so the concentration gradient for O₂ will be considerably greater than for CO₂.
External Respiration

- Gas exchange between the air in the lung and the blood in alveolar capillaries
- $O_2$ is high in the air and low in the blood so $O_2$ diffuses from air into blood
- $CO_2$ is low in the air and high in the blood so $CO_2$ diffuses from blood to the air
Partial Pressure Changes

Atmospheric air:
- $P_{O_2} = 159$ mmHg
- $P_{CO_2} = 0.3$ mmHg

CO$_2$ exhaled
- O$_2$ inhaled

Alveolar air:
- $P_{O_2} = 105$ mmHg
- $P_{CO_2} = 40$ mmHg

Pulmonary capillaries

(a) External respiration: pulmonary gas exchange

To lungs

To left atrium
Internal Respiration

- Gas exchange between blood in systemic capillaries and working tissue
- $O_2$ is high in the blood and low in the tissue so $O_2$ diffuses from blood into tissue
- $CO_2$ is low in the blood and high in the tissue so $CO_2$ diffuses from tissue to blood
(b) Internal respiration: systemic gas exchange

Systemic capillaries

Systemic tissue cells:

$P_{O_2} = 40 \text{ mmHg}$

$P_{CO_2} = 45 \text{ mmHg}$
Gas Transport

O₂ is transported in two ways
- Dissolved in the plasma ~1.5%
- Carried on hemoglobin~98.5%

CO₂ is transported in 3 ways
- Dissolved in the plasma ~9%
- Carried on carbamino compounds ~13%
- As HCO₃⁻ ~78%
Hemoglobin has an increasing affinity for O$_2$
O$_2$ saturation depends on the PO$_2$
The partial pressure of the tissue the blood (hemoglobin) is equilibrating in determines the level of O$_2$ saturation
$O_2 – CO_2$ Dissociation Curve

- Deoxygenated blood (contracting skeletal muscle)
- Deoxygenated blood in systemic veins (average at rest)
- Oxygenated blood in systemic arteries

Percent saturation of hemoglobin

$P_{O_2}$ (mm Hg)
Bohr Effect

- Multiple factors affect the saturation of hemoglobin: pH, PCO₂, temperature, 2,3DPG
- Lower pH, higher PCO₂, higher temperature, and more 2,3DPG shift the curve to the right, causing hemoglobin to release more O₂.
- Higher pH, lower PCO₂, lower temperature, and less 2,3DPG cause hemoglobin to hold on to more O₂.
**PH AND PCO₂ EFFECTS**

(a) Effect of pH on affinity of hemoglobin for oxygen

(b) Effect of PCO₂ on affinity of hemoglobin for oxygen
Temperature Effects

- Low temperature (20°C, 68°F)
- Normal blood temperature (37°C, 98.6°F)
- High temperature (43°C, 110°F)

Graph showing relationship between oxygen partial pressure (P₀₂) in mmHg and temperature.
Carbon Dioxide Transport

- CO₂ is transported in 3 ways
- Dissolved in the plasma
- Carried on carbamino compounds - proteins in plasma and hemoglobin (on the way back to the lung, hemoglobin doesn’t carry CO₂ in the same way it carries O₂)
- As HCO₃⁻ most CO₂ is carried in this form
Gas Exchange – External Respiration

(a) Exchange of $O_2$ and $CO_2$ in pulmonary capillaries (external respiration)
Gas Exchange – Internal Respiration

(b) Exchange of $O_2$ and $CO_2$ in systemic capillaries (internal respiration)
Respiratory centers are located in the brain stem
- Medullary rhythmicity center—inspiratory area and expiratory area
- Pneumotaxic area—“off switch,” limits inspiration
- Apneustic area—influences pneumotaxic center, in effect it prevents the off switch from working, only see its effect when some type of damage has occurred
Respiratory Center in the Brain

Respiratory Center:
- Pneumotaxic area
- Apneustic area
- Medullary rhythmicity area:
  - Inspiratory area
  - Expiratory area

Midbrain
Pons
Medulla oblongata
Spinal cord
NORMAL AND FORCEFUL BREATHING

(a) During normal quiet breathing

(b) During forceful breathing
Factor That Influence Respiration

- Peripheral and central receptors for blood gas concentrations
- Peripheral receptors in the carotid and aortic bodies, central receptors in hypothalamus and brain stem
- Factors that influence respiratory rate
  - $\text{PCO}_2$, $\text{PO}_2$, pH
  - Higher brain centers
  - Temperature
Respiratory Nerves & Vessels
Regulation of breathing