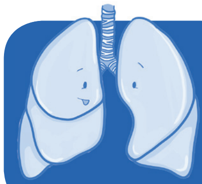

NOTES
BREATHING MECHANICS

LUNG VOLUMES & CAPACITIES

osms.it/lung-volumes-capacities

- *Spirometry:* spirometer used to measure air volume moving in, out of lungs
- *Static lung volumes:* volumes not involved in airflow rate
- *Capacities:* combination of > one lung volume

Volume variations

- Related to age, sex, body size, posture
- Tidal volume (V_T)
  - 500mL
  - Air volume inspired, expired during quiet breathing
- Inspiratory reserve volume
  - Maximum volume inhaled air above V_T = 3L
- Expiratory reserve volume
  - Maximum expired air volume below V_T = 1.2L
- Residual volume (RV)
  - Air remaining in lungs after forced expiration = 1.2L (not measured by spirometry)
- Functional residual capacity (FRC)
  - Expiratory reserve volume (ERV) + RV = 2.4L
- VT + inspiratory reserve volume = 3.5L
- Vital capacity (V_C)
  - V_T + inspiratory reserve volume (IRV) + ERV = 4.7L
- Total lung capacity (TLC)
  - Combination of all lung capacities = 5.9L

MEASURING FRC

Helium dilution method

- Helium placed in spirometer → inhaled
- Helium concentration in lungs equalizes with amount of helium placed in spirometer (helium insoluble in blood) after few breaths
- Total helium mass measured in spirometer = FRC

Body plethysmograph method

- Application of Boyle's law (P X V = k)
- Person sits inside plethysmograph (airtight box) → breathes in/out through mouthpiece → measures air pressure in mouth
- Mouthpiece closed after expiring V_T; as person attempts to breathe FRC calculated using measurements of alveolar pressure, lung volume, pressure changes within plethysmograph

ANATOMIC & PHYSIOLOGIC DEAD SPACE

osms.it/anatomic-physiologic-dead-space

- *Dead space:* air volume enters airways, lungs; no gas exchange occurs

ANATOMIC DEAD SPACE

- Air inaccessible to body for gas exchange (due to anatomical structure)
- Air contained in conducting zone (nose → terminal bronchioles)
- Conduit for air movement in/out of lungs; warms, humidifies air; removes debris, pathogens
- Volume = 150mL (⅓ of tidal volume)

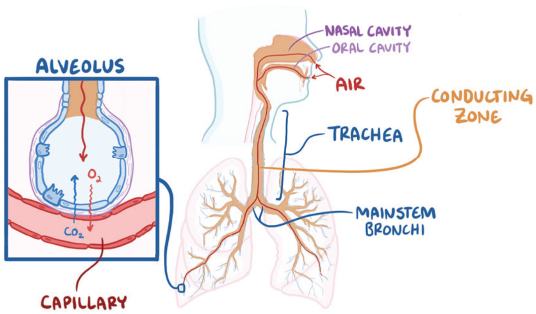

Figure 68.1 The volume of air contained in the conducting zone is called anatomic dead space because no gas exchange occurs here; therefore, no oxygen can be extracted from this air.

PHYSIOLOGIC DEAD SPACE

- Air physiologically inaccessible to body for gas exchange
- *Composition:* anatomic dead space + dead space in respiratory zone (respiratory bronchioles, alveolar duct, alveolar sac, alveoli) that does not partake in gas exchange
  - *Ventilation/perfusion defect:* alveoli ventilated, not well perfused (alveolar dead space)
- Volume = approx. 0 (in healthy adult)
  - Anatomic dead space = physiologic dead space

$$V_T = V_D + V_A$$

  - V_T = tidal volume
  - V_D = physiological dead space volume
  - V_A = air volume present in functioning alveoli

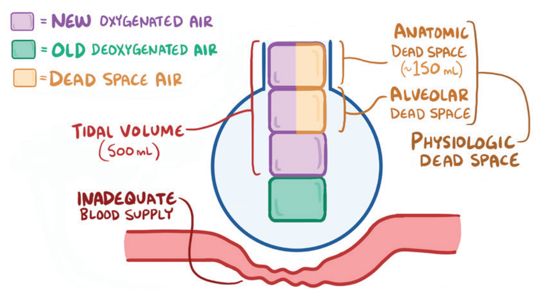

Figure 68.2 The green block represents residual air from the previous inhalation that participated in gas exchange. The purple blocks represent new oxygenated tidal volume inhaled during the current breath. Some of this new air also ends up being dead space air ("alveolar dead space") due to an inadequate blood supply to the alveolus.

Physiological dead space volume (Bohr equation)

- Assumptions
  - Environmental air CO_2 = 0 (actual amount ≅ 0.04%)
  - Dead space CO_2 contribution = 0
  - All CO_2 in exhaled air comes from functioning alveoli
- V_D = V_T x arterial CO_2 partial pressure ($PaCO_2$) - expired CO_2 partial pressure ($PeCO_2$) ÷ $PaCO_2$

$$V_D = V_T \times \frac{Pa_{CO_2} - Pe_{CO_2}}{Pa_{CO_2}}$$

VENTILATION

osms.it/ventilation

- Air movement between environment, lungs
- *Ventilation rates:* measure air volume moving in/out of lungs over period of time

MINUTE VENTILATION (V_E)

- V_E = amount of air moved in/out of lungs in one minute; does not factor in physiological dead space

$$V_E = (VT) \times (\text{Respiratory Rate/RR})$$
$$V_E = 500\text{mL} \times 15/\text{minute} = 7.5\text{L/minute}$$

ALVEOLAR VENTILATION (V_A)

- V_A = V_E corrected for physiological dead space

$$V_A = (VT - VD) \times RR$$
$$V_A = (500\text{ mL} - 150\text{mL}) \times 15 = 5.2\text{L/minute}$$

- V_A without measuring dead space
  - V_A = volume of CO_2 (V_{CO2}) ÷ fraction CO_2 (F_{CO2})

$$VA = (V_{CO2}) / (F_{CO2})$$

- *Partial pressure:* proportional to fractional concentration of that gas in mixture; based on constant K
  - Assumes gases are saturated with water vapor (normal body temperature, sea-level atmospheric pressure)
  - CO_2 partial pressure in alveolar air: $P_{CO2} = F_{CO2} \times K$
  - Alveolar ventilation equation: $V_A = [(V_{CO2}) / (P_{CO2})] \times K$
  - Replacing P_{CO2} with $_{CO2}$ pressure in arterial blood (Pa_{CO2}) in alveolar equation
  - Inverse relationship between alveolar ventilation, CO_2 partial pressure in alveolar air, pulmonary arteries (e.g. ↑ air ventilating the alveoli → ↓ CO_2 in blood, vice versa)

$$V_A = \frac{V_{CO_2} \times K}{P_{ACO_2}}$$

ALVEOLAR GAS EQUATION

osms.it/alveolar-gas-equation

- Pressure in alveoli = atmospheric pressure (P_{atm}); air in alveoli contains water vapor
- Alveolar pressure (P_{atm}) = water vapor pressure (P_{vapor}) + gas mixture pressure → total alveolar pressure exerted from all gases minus water vapor = $P_{atm} - P_{vapor}$
- O_2 partial pressure dissolved in blood (P_{aO2}) = CO_2 partial pressure in alveoli (P_{ACO2}) ÷ by R (respiratory quotient)

$$P_{aO2} = (P_{ACO2}) / R$$

- Partial pressure of O_2 inside alveolus (P_{AO2}) = partial pressure of inspired oxygen (P_{iO2}) minus partial pressure of oxygen going into blood (P_{aO2})

Partial pressure: gas particle mixture

- Gas' partial pressure proportional to fractional gas concentration in mixture
- Fractional CO_2 concentration (F_{CO2}) = 0.3
  - Accounts for 30% of gas molecules (F_{CO2} x total pressure of gas mixture P_{gases})
- Fractional concentration of O_2 (F_{O2}) = 0.7
  - Accounts for remaining 70% (F_{O2} x total pressure of gas mixture P_{gases})
- Pressure exerted by O_2 > pressure exerted by CO_2 (proportional to fractional concentrations)
  - If P_{gases} = 20mmHg; partial pressure of O_2 = 14mmHg (0.7 x 20); partial pressure of CO_2 = 6mmHg (0.3 x 20)
  - Partial pressure of inspired air (P_{iO2}), fractional oxygen concentration in inspired air (F_{iO2}), accounting for water vapor

$$P_{iO2} = F_{iO2} \times (P_{atm} - P_{vapor})$$

Alveolar gas equation

- Relationship between O_2 partial pressure inside alveolus to CO_2 partial pressure in alveolus

$$P_{AO2} = [F_{iO2} \times (P_{atm} - P_{vapor})] - [(P_{ACO2}) / R]$$
$$P_{AO2} = 150 - (1.25 \times P_{ACO2})$$

  - F_{iO2} = 0.21 (normal air = 21% O_2)
  - Atmospheric pressure = 760mmHg
  - Water vapor pressure i = 47mmHg
  - R = 0.8

COMPLIANCE OF LUNGS & CHEST WALL

osms.it/compliance-lungs-chest-wall

- Compliance measures how changes in pressure → lung volume change
- *Lung, chest wall compliance:* inversely correlated with elastic, "snap back" properties (elastance)
  - Compliance = ΔV/ΔP
  - Elastance = ΔP/ΔV
- ↑ compliance → lungs easier to fill with air
  - *Forces promoting open alveoli:* compliance, transmural pressure gradient, surfactant
- ↓ compliance → lungs harder to fill with air
  - *Forces promoting collapse of alveoli:* elastic recoil/elastance, alveolar surface tension

COMBINED PRESSURE-VOLUME CURVES FOR THE LUNG & CHEST WALL

osms.it/pressure-vol_curves_lung_chest_wall

- Pressure-volume relationship is curvilinear
- Volume at FRC (zero airway pressure)
  - *Lung inward recoil:* balanced with chest wall's tendency to expand outward (e.g. at equilibrium with no tendency to collapse/expand)
- Volume > FRC
  - Positive transmural pressure
  - ↑ lung recoiling force
  - ↓ chest wall outward force
- Volume < FRC (forced expiration)
  - Negative transmural pressure
  - ↓ lung recoiling force
  - ↑ chest wall outward force
- Pressure-volume curves plotted on graph
  - *X-axis:* pressure
  - *Y axis:* volume
  - Slope of curve = compliance
- Curve flattens out when lung, chest wall compliance combined
- *Hysteresis:* compliance for inspiration, expiration are different → slopes will be different

ALVEOLAR SURFACE TENSION & SURFACTANT

osms.it/alveolar-surface-tension-surfactant

- Alveoli lined with fluid film; water tends to form spheres (e.g. drops)
  - Due to intrinsic surface tension (caused by attraction of water molecules to each other)
- Surface tension creates pressure → pulls alveoli closed → collapses into sphere → ↓ gas exchange
- *Law of Laplace:* pressure that promotes lungs' collapse is (1) directly proportional to surface tension, (2) inversely proportional to alveoli radius

$$P = 2T/r$$

  - P = pressure on alveolus
  - T = surface tension
  - r = alveolar radius
- Smaller alveolus (r = 1) → ↑ pressure
  - P = 2 x 50/1 = 100
- Larger alveolus (r = 2) → ↓ pressure
  - P = 2 x 50/2 = 50
- Alveoli are small (allows ↑ surface area relative to volume), so have ↑ collapsing pressure

SURFACTANT

- ↓ collapsing pressure in alveoli → ↑ gas exchange, ↑ lung compliance, ↓ work of breathing
  - Lipoprotein mixture primarily containing dipalmitoyl phosphatidylcholine (DPPC)
  - Synthesized by type II pneumocytes, coats inside of alveoli

- Contains both hydrophilic, hydrophobic group (amphipathic nature)—intermolecular forces produced by repelling hydrophobic groups, attracting hydrophilic groups → ↓ surface tension, collapsing pressure

AIRFLOW, PRESSURE, & RESISTANCE

osms.it/airflow-pressure-resistance

AIR FLOW & PRESSURE

- Airflow in lungs determined by Ohm's law
  - Air flow directly proportional to pressure difference between alveoli, mouth/nose; inversely proportional to airway resistance

$$Q = \Delta P/R$$

  - Q = air flow
  - ΔP = change in pressure
  - R = resistance
- Pressure gradient
  - Driving force for air flow
  - Diaphragm contracts during inspiration → creates pressure gradient (↑ lung volume, ↓ alveolar pressure) → air flows into lungs

RESISTANCE

Poiseuille's law

- Resistance in lungs determined by Poiseuille's law
  - Air flow directly proportional to resistance along airway

$$R = \frac{8nl}{\pi r^4}$$

  - R = resistance
  - n = gas viscosity
  - l = length of airway
  - $\pi r4$ = flow is related exponentially to airway's radius
- Highlights critical importance of airway diameter on airflow
  - E.g. if airway radius ↓ by a factor of 2 → ↑ resistance by 24 (16-fold)

Resistance changes

- Parasympathetic muscarinic receptor stimulation → bronchial smooth muscle constriction → ↓ airway diameter → ↓ airflow; sympathetic stimulation of β2 receptors → bronchial smooth muscle relaxation → ↑ airway diameter → ↑ airflow
- ↓ lung volume → ↑ resistance; ↑ lung volume → ↓ resistance
- ↑ viscosity (e.g. deep sea diving) → ↑ resistance; ↓ viscosity (e.g. inhaling helium) → ↓ resistance

BREATHING CYCLE

osms.it/breathing-cycle

- Normal, quiet breathing phases
  - Rest (period between breaths), inspiration, expiration
- Involves changes in air volume, intrapleural pressure, alveolar pressure
- Affected by respiratory system's resistance, compliance

Rest

- Alveolar pressure (P_{alv}) = atmospheric pressure (P_{atm}) = 0
- No air movement in/out of lungs
  - Due to pressure gradient's absence
- Air volume in lungs = FRV
- Intrapleural pressure = -0.5cm0.2in $H_2 0$
  - Transmural pressure gradient (intrapleural pressure always less than alveolar pressure) keeps lungs inflated
- Diaphragm relaxed

Inspiration

- Active process (requires muscle activity)
- Diaphragm (major inspiratory muscle; innervated by phrenic nerve) contracts, moves downward; external intercostal muscles contract (innervated by intercostal nerves) contract, elevate ribs outward, upward → enlarge thoracic cavity → ↑ lung volume → ↓ pressure in lungs (P_{alv} = -1cm/0.39in $H_2 0$)
  - *Boyle's law (P = k/V):* gas pressure (P) in container (thorax, alveoli) at constant temperature (k) inversely proportional to volume (V)
- Pressure gradient causes air to flow into lungs until $P_{alv} = P_{atm}$ at inspiration's end
- Volume in lungs = FRC + VT
- Intrapleural pressure = -8cm/3.1in $H_2 0$ at expiration's end

Expiration

- Passive process
- Elastic forces of lungs compress alveolar air volume → ↑ pressure in lungs → $P_{alv} > P_{atm}$ → pressure gradient causes air to flow out of lungs until $P_{alv} = P_{atm}$ at inspiration's end
- Diaphragm, external intercostal muscles relax → ↓ thoracic cavity size → ↓ lung volume → ↑ pressure in lungs
- V_T expired → lung volume = FRC