

# **RESPIRATORY MECHANICS AND GAS EXCHANGE**

## **Respiratory System I-III (Topics 26-29)**

### **I Respiration**

- A Internal Respiration:** Intracellular metabolic processes carried out in the mitochondria which use  $O_2$  and produce  $CO_2$
- B External Respiration:** entire sequence of events involved in the exchange of  $O_2$  and  $CO_2$  between the external environment and the cells of the body.
  - 1 Ventilation: exchange of air between environment and alveoli of lungs
  - 2  $O_2$  and  $CO_2$  exchanged between alveoli and blood
  - 3  $O_2$  and  $CO_2$  are transported by blood between lungs and tissue
  - 4 Exchange of  $O_2$  and  $CO_2$  between blood and tissues across capillaries

### **II Review Structure of Respiratory system**

- A Airways:** Tubes that carry air between environment & alveoli
  - 1 from trachea through right and left bronchi (rigid cartilage)
  - 2 bronchi branch into bronchioles (smooth muscle)
- B Alveoli**
  - 1 Clusters of thin walled, inflatable, grapelike sacs at the terminal branches of the bronchioles
  - 2 Surrounded by pulmonary capillaries
  - 3 NOTE: thin walls and huge surface area of all alveoli

## C Lungs and Chest cavity

- 1 Two lungs, each supplied by one of the bronchi; lungs occupy most of chest cavity
- 2 Lungs contain lots of elastic connective tissue
- 3 Diaphragm forms the floor of the chest cavity.
- 4 Pleural sac separates each lung from the thoracic wall and other structures. Pleural sac contains intrapleural fluid

## D Pressure Considerations

- 1 Air moves from a region of high pressure to low pressure; it flows down a pressure gradient. Air flows in and out of the lungs by reversing pressure gradients between lungs and environment.
- 2 Important pressures related to respiration
  - a Atmospheric (barometric) pressure: pressure exerted by weight of air in atmosphere on objects on earth ' s surface.
  - b Intra-alveolar pressure (sometimes called intrapulmonary pressure) is the pressure within the alveoli.
  - c Intrapleural pressure (also called intrathoracic pressure) is the pressure exerted outside the lungs within the thoracic cavity.
  - d The intrapleural pressure is 756 mm Hg and the intra-alveolar pressure is 760 mm Hg when equilibrated with atmospheric pressure. This transmural pressure gradient across the lung wall is crucial in expanding the lung to fill the chest cavity.

- e Although elastic lungs 'want' to collapse, they don't because of this transmural pressure gradient

### III Respiratory Cycle

- A Respiration works by changing the volume of the chest cavity
- B Before the start of inspiration, respiratory muscles are relaxed, intra-alveolar pressure = atmospheric pressure, and no air is flowing.
- C At onset of inspiration, inspiratory muscles (primarily the diaphragm) contract, which results in enlargement of the thoracic cavity.
- D As the thoracic cavity enlarges, the lungs are forced to expand to fill the larger cavity.
- E Because the intra-alveolar pressure is less than atmospheric pressure, air follows its pressure gradient and flows into the lungs until no further gradient exists
- F Therefore, lung expansion is not caused by movement of air into the lungs
- G Deeper inspirations are accomplished by contracting inspiratory muscles more forcefully, and by using accessory inspiratory muscles to enlarge the chest cavity further.
- H At the end of inspiration, the inspiratory muscles relax, the chest cavity returns to original size, and the lungs return to original size.
- I Although at rest expiration is a passive process, during exercise it is an active process and expiratory muscles (primarily abdominal muscles) contract to decrease the size of the chest cavity during expiration.

## IV Elasticity of Lungs

- A Part of what makes lungs elastic is the alveolar surface tension displayed by the thin layer of liquid that lines each alveolus.
- B Problem: if this thin layer of liquid is ONLY water, the surface tension would be great
- C Solution: Pulmonary surfactant, a complex mixture of lipids and proteins secreted by alveolar cells, which reduces alveolar surface tension.

## V Gas Exchange

### A Physical Considerations

- 1 Gas flows down its pressure gradient
- 2 Every gas in a mixture of gases has a partial pressure
- 3 Partial pressure of oxygen ( $P_{O_2}$ ) in dry atmospheric air at sea level
  - a atmospheric pressure = 760 mm Hg
  - b oxygen makes up 21% of air
  - c partial pressure of oxygen:  $.21 \times 760 \text{ mm Hg} = 160 \text{ mm Hg}$
- 4 Partial pressure of oxygen in alveoli
  - a is 100 mm Hg; this is fairly constant
  - b Less than 160 mm Hg because
    - i alveolar air contains more water vapor
    - ii mixing of fresh inspired air with 'old' air in lungs (lungs always some air in them, even after max exhalation)
- 5 Partial pressure of carbon dioxide ( $P_{CO_2}$ )
  - a 0.03 mm Hg in dry air
  - b 40 mm Hg in alveoli because of  $CO_2$  produced by tissues & delivered to lungs; this is fairly constant

## B Exchange of oxygen and carbon dioxide

- 1 Pulmonary capillaries (as they approach alveoli)
  - a  $P_{O_2}$  in alveoli is 100 mm Hg; in blood arriving from systemic circulation, it is usually about 40 mm Hg
  - b Pressure gradient exists, toward blood from alveoli
  - c  $P_{CO_2}$  in alveoli is 40 mm Hg; in blood arriving from systemic circulation, it is usually about 46 mm Hg
  - d Pressure gradient exists, toward alveoli from blood, so  $CO_2$  diffuses from blood into alveoli
- 2 Systemic capillaries (as they enter tissues)
  - a  $P_{O_2}$  in blood (after oxygenation in lungs) is 100 mm Hg (that is, just what it is in the alveoli); in tissue,  $P_{O_2}$  is 40 mm Hg (although this varies)
  - b Pressure gradient exists so  $O_2$  diffuses from blood to tissues.
  - c  $P_{CO_2}$  in blood (after visit to lungs) is 40 mm Hg (ie, just what it is in the alveoli); in tissue,  $P_{CO_2}$  is about 46 mm Hg so  $CO_2$  diffuses from tissues to blood

# GAS TRANSPORT AND CONTROL OF RESPIRATION

## I Gas Transport: Role of Hemoglobin (Hb)

### A Oxygen-Hb binding

- 1 Each Hb molecule can bind up to 4 O<sub>2</sub> molecules; when it is carrying 4 oxygens, it is said to be fully saturated
- 2 Percent Hb saturation is a measure of the extent to which the Hb present is combined with oxygen, and can vary from 0 to 100%
- 4 The saturation of Hb with oxygen depends on the **P<sub>O2</sub> of the blood; note that oxygen already bound to Hb does NOT contribute to P<sub>O2</sub>**
- 5 Relationship between P<sub>O2</sub> and % Hb saturation is complex:
  - a at alveoli, P<sub>O2</sub> is about 100 mm Hg; a large change in P<sub>O2</sub> here results in only a small change in % Hb saturation. Therefore P<sub>O2</sub> can fall nearly 40% in lungs, but Hb still highly saturated. **This facilitates loading of Hb with oxygen in lungs.**
  - b in tissues, P<sub>O2</sub> is about 40 mm Hg; a small change in P<sub>O2</sub> here results in a large change in % Hb saturated. Hence when P<sub>O2</sub> falls even a little in systemic capillaries, a large amount of O<sub>2</sub> dissociates from Hb. **This facilitates unloading of O<sub>2</sub> from Hb in tissues.**
- 6 Therefore Hb acts as oxygen storage location in the blood, allowing the blood to carry much more oxygen than it could otherwise.

## 7 Modification of O<sub>2</sub>-Hb curve.

- a Increased metabolism leads to increase in tissue temperature, acidity, and CO<sub>2</sub>. An increase in all these variables 'right shifts' the O<sub>2</sub>-Hb curve, which results in more unloading of oxygen for a given P<sub>O<sub>2</sub></sub> (ie, Hb delivers more O<sub>2</sub> to the tissues at lower P<sub>O<sub>2</sub></sub>). (= **Bohr effect**)
- b Carbon monoxide 'left shifts' the O<sub>2</sub>-Hb curve, so that less oxygen is delivered to tissues for a given level of P<sub>O<sub>2</sub></sub>.

## B Carbon dioxide transport in the blood in 3 forms

- 1 10% is dissolved in plasma
- 2 30% is Bound to Hb
  - a bound to globin portion of Hb (not heme portion as O<sub>2</sub> is)
  - b Unoxygenated Hb binds tighter to CO<sub>2</sub> than does oxygenated Hb, which facilitates Hb picking up CO<sub>2</sub> in the tissue capillaries (= Haldane effect)
- 3 60% is transported as bicarbonate
  - a  $\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{H}^+$  by carbonic anhydrase (CA) within the red blood cells
  - b HCO<sub>3</sub><sup>-</sup> then diffuses out of the red blood cells, and Cl<sup>-</sup> diffuses into the red blood cells to restore the electrical gradient. **Chloride Shift**
  - c The H<sup>+</sup> remaining in the red blood cells binds to Hb; this helps buffer the plasma (prevents plasma from being too acidic)

- d these reactions are reversed once the blood reaches the pulmonary capillaries, and CO<sub>2</sub> leaves the blood and enters the alveoli

## II Control of Airway Resistance

- A Similar to the cardiovascular system, resistance plays a role in determining airflow rates
- B Parasympathetic stimulation causes bronchoconstriction.
- C Sympathetic stimulation causes bronchodilation.
- D Local factors: Matching blood flow and air flow: Need to have a good match between air flow and blood flow in the alveoli to avoid buildup of CO<sub>2</sub> or lack of O<sub>2</sub>
  - 1 Blood flow > Airflow (as when bronchiole constricts or alveolus collapses)
    - a CO<sub>2</sub> buildup in alveolus, too little O<sub>2</sub> for blood to pick up.
    - b Local control: the buildup of CO<sub>2</sub> and lack of O<sub>2</sub> cause
      - i vasoconstriction to reduce blood flow
  - 2 Blood flow < Airflow (as when capillaries collapse)
    - a Too little CO<sub>2</sub> buildup in alveolus, too much O<sub>2</sub> for blood to pick it all up
    - b Local control: the lack of CO<sub>2</sub> and buildup of O<sub>2</sub> cause
      - i bronchoconstriction to decrease airflow

## III Control of Respiration: Rhythmic breathing pattern

- A Recall that the heart was autorythmic, and that input from the nervous system was only required to modify the rate and strength of cardiac contraction. This is NOT the case in the lungs; CNS input is REQUIRED for breathing to occur at all.

B Various parts of brain stem are involved in control of rhythmic breathing

#### IV Control of Respiration: Regulation of magnitude of ventilation

A  $P_{O_2}$  and  $P_{CO_2}$  and  $H^+$  all contribute in some way to regulation of ventilation

B Role of decreased arterial  $P_{O_2}$  in regulating ventilation

- 1 Arterial  $P_{O_2}$  is monitored by peripheral chemoreceptors
- 2 These chemoreceptors are not sensitive to changes in  $P_{O_2}$  from 100 mm Hg to 60 mm Hg; ie,  $P_{O_2}$  can drop 40% before they will cause an increase in ventilation.
- 3 These go into effect only in 'emergencies'

C Role of increased arterial  $P_{CO_2}$  in regulating ventilation (the most important mechanism)

- 1 Central chemoreceptors in the medulla monitor  $P_{CO_2}$
- 2 An increase in  $P_{CO_2}$  results in more  $CO_2$  crossing blood brain barrier in medulla. Once across the blood brain barrier, the  $CO_2$  reacts with water to form bicarbonate and  $H^+$ ; **it is the increase in  $H^+$  in the medulla which is detected by the central chemoreceptors.**
- 3  $H^+$  cannot cross the blood brain barrier, so the increase in blood  $H^+$  that accompanies an increase in blood  $P_{CO_2}$  does not affect central chemoreceptors.
- 4 The peripheral chemoreceptors are sensitive to changes in blood  $H^+$ , and cause changes in ventilation accordingly. This response is generally minor compared to the response in the central chemoreceptors caused by  $CO_2$

D Voluntary control: of respiratory muscles by motor neurons

# HIGH ALTITUDE PHYSIOLOGY

## I General High Altitude Considerations

- A Low Atmospheric Pressure means less  $O_2$  in air
- B Low  $O_2$  in atmosphere means less  $O_2$  in blood
  - 1 affects Hb saturation
  - 2 sensed by kidneys B affects RBC production
  - 3 sensed by peripheral chemoreceptors (when very low)
    - : affects ventilation and heart rate

## II 5,000 - 10,000 ft

- A Up to 10,000 ft, hemoglobin still 100% saturated
- B Low blood  $P_{O_2}$  sensed in kidneys causes release of erythropoietin, which causes more RBCs to be generated in bone marrow
- C No major effects on ventilation and heart rate
- D Altitudes can be negotiated safely by ascending slowly and allowing time for acclimation

## III 10,000 - 17,000 ft

- A Above 10,000 ft, Hb is no longer 100% saturated,  $P_{O_2}$  in pulmonary capillaries (as they leave lungs) can drop; begins to favor unloading of Hb

B Continued generation of additional RBCs

- 1 blood becomes more viscous
- 2 increase in peripheral resistance, therefore increase in mean arterial b.p.

C Decreased  $P_{O_2}$  now sufficient to stimulate peripheral chemoreceptors

- 1 Increased ventilation
  - a High ventilation blows off more  $CO_2$ 
    - i Less blood  $CO_2$  means less blood  $HCO_3^- + H^+$
    - ii Blood becomes more alkaline
- 2 Increased resting heart rate

D These altitudes can also be negotiated safely; more danger if ascent is rapid (Acute Mountain Sickness)

- 1 Headache
- 2 Fatigue
- 3 Nausea, loss of appetite
- 4 Insomnia

IV 17,000 - 26,000 ft

A At 17,000 ft,  $P_{O_2}$  atmosphere = 90 mmHg,  $P_{O_2}$  alveoli = 50 mmHg, Hb saturation declines precipitously

B Once beyond 17,000 ft, body can still acclimate

- 1 Still more RBCs
- 2 Higher resting ventilation and heart rates

## C But physical deterioration begins

- 1 stress response: adrenal cortex releases more cortisol, causes
  - a tissue 'wasting' : body uses it's own tissues for fuel
  - b immune system depression : more susceptible to infection
  
- 2 More dangerous symptoms : mechanism still under investigation!
  - a high altitude pulmonary edema (HAPE)
    - i because of low pulmonary O<sub>2</sub> (lungs want to match blood flow to air flow), many pulmonary arterioles constrict
    - ii result is high pulmonary blood pressure
    - iii pulmonary vasoconstriction is 'uneven' -- some blood vessels burst, and alveoli fill with blood
    - iv victim rapidly loses any remaining gas exchange capacity
  - b high altitude cerebral edema (HACE) : several possible mechanisms
  - c brain hypoxia in general : cognitive functions impaired

## V Over 26,000 ft = The Death Zone

- A Cannot possibly acclimate to this
- B Rapid physical deterioration
- C Resting heart rate continues to increase
  - a Maximum heart rate continues to decline (heart is also O<sub>2</sub> starved and cannot work as efficiently)

b As altitude increases, these two get closer and closer together

D Cognitive function seriously impaired (26,000 - 29,000 ft)