

**TOPIC 19: RESPIRATORY SYSTEM: GAS EXCHANGE AND TRANSPORT**

## I. Overview of Respiration (Fig 16.1)

- A. **External Respiration:** Entire sequence of events involved in the exchange of O<sub>2</sub> and CO<sub>2</sub> between the external environment and the cells of the body.
  1. Ventilation: exchange of air between environment & lung air sacs (alveoli)
  2. O<sub>2</sub> and CO<sub>2</sub> exchanged between alveoli and blood
  3. O<sub>2</sub> and CO<sub>2</sub> are transported by blood between lungs and tissue
  4. Exchange of O<sub>2</sub> and CO<sub>2</sub> between blood and tissues across capillaries
- B. **Internal Respiration:** Intracellular metabolic processes which use O<sub>2</sub> and produce CO<sub>2</sub> and derive energy from nutrient molecules
- C. Additional Functions of Respiratory system
  1. Route for water loss and heat elimination
  2. Enhances venous return
  3. Helps maintain acid base balance
  4. Enables vocalization
  5. Defends against inhaled pathogens
  6. Removes & modifies materials passing through pulmonary circulation

## II. Gas Exchange

- A. Physical Principles
  1. Gas flows down its pressure gradient
  2. Every gas (such as oxygen) in a mixture of gases (such as air) has a **partial pressure which is the relevant variable when determining pressure gradients** for a specific gas
  3. Partial pressure of oxygen (P<sub>O<sub>2</sub></sub>) 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 is
    - a) 100 mm Hg; this is fairly constant
    - b) Less than 160 mm Hg because
      - (1) water vapor, which exerts a partial pressure of 47 mm Hg, reduces P<sub>O<sub>2</sub></sub> to 150 mm Hg
      - (2) mixing of fresh inspired air with "old" air in lungs (lungs always have at least 1200 ml of air in them, even after max exhalation) further drops P<sub>O<sub>2</sub></sub> to 100 mm Hg
  5. Partial pressure of carbon dioxide (P<sub>CO<sub>2</sub></sub>)
    - a) 0.3 mm Hg in dry air
    - b) 40 mm Hg in alveoli because of CO<sub>2</sub> produced by tissues and brought to lungs by blood; this is fairly constant
- B. Oxygen (Fig 17.4 & 17.6)
  1. Pulmonary capillaries
    - a) P<sub>O<sub>2</sub></sub> in alveoli is 100 mm Hg; in returning ("deoxygenated") blood of systemic circulation, it is usually about 40 mm Hg
    - b) Hence a pressure gradient of 60 mm Hg exists, toward blood from alveoli, so O<sub>2</sub> diffuses from alveoli into blood
  2. Systemic capillaries

- a)  $P_{O_2}$  in blood (after oxygenation in lungs) is 100 mm Hg (ie, just what it is in the alveoli); in tissue,  $P_{O_2}$  is 40 mm Hg (although this varies quite a bit depending on amount of cellular metabolism)
  - b) Pressure gradient of 60 mm Hg exists, toward tissues from blood, so  $O_2$  diffuses from blood to tissues.
- C. Carbon Dioxide (Fig 17.4)
- 1. Pulmonary capillaries
    - a)  $P_{CO_2}$  in alveoli is 40 mm Hg; in returning ("deoxygenated") blood of systemic circulation, it is usually about 46 mm Hg
    - b) Pressure gradient of 6 mm Hg exists, toward alveoli from blood, so  $CO_2$  diffuses from blood into alveoli
  - 2. Systemic capillaries
    - a)  $P_{CO_2}$  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 (although this varies quite a bit depending on amount of cellular metabolism)
    - b) Pressure gradient of 6 mm Hg exists, toward blood from tissues, so  $CO_2$  diffuses from tissues to blood

### III. Gas Transport: Role of Hemoglobin (Hb)

- A. Oxygen-Hb binding
- 1. Each Hb molecule can bind up to 4  $O_2$  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%
  - 3. The saturation of Hb with oxygen depends on the  $P_{O_2}$  of the blood; **note that oxygen already bound to Hb does NOT contribute to  $P_{O_2}$ !!!**
  - 4. The amount of  $O_2$  bound to Hb depends on the  $P_{O_2}$ . Relationship between  $P_{O_2}$  and % Hb saturation is complex: Fig 17.8
    - a) in pulmonary capillaries,  $P_{O_2}$  is about 100 mm Hg; a large change in  $P_{O_2}$  here results in only a small change in % Hb saturation. Hence  $P_{O_2}$  can fall nearly 40% in lungs, but Hb still highly saturated. This facilitates loading of Hb with oxygen in lungs.
    - b) in systemic capillaries,  $P_{O_2}$  is about 40 mm Hg; a small change in  $P_{O_2}$  here results in a large change in % Hb saturated. Hence when  $P_{O_2}$  falls even a little in systemic capillaries, a large amount of  $O_2$  disassociates from Hb. This facilitates unloading of  $O_2$  from Hb in tissues.
  - 5. Bottom line: **Hb acts as oxygen storage location** in the blood, allowing the blood to carry much more oxygen than it could otherwise. As oxygen diffuses from the alveoli into the blood, it is loaded by Hb very rapidly; this loaded oxygen does not contribute to the blood  $P_{O_2}$ , so more oxygen enters the blood and is picked up by Hb, and so on. As oxygen diffuses from the blood into the tissues, oxygen unloads from the Hb into the blood, where it continues to diffuse into the tissues.
  - 6. Modification of  $O_2$ -Hb binding curve (Fig 17.9-17.10)
    - a) Increased metabolism leads to increase in tissue temperature, acidity,  $CO_2$ , and 2-3diphosphoglycerate (a metabolite produced

by red blood cells). 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>). Note: this is known as the “Bohr effect” when caused by increases in CO<sub>2</sub> and acid.

- 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>. In addition, Hb binds CO 240 times more readily than it does O<sub>2</sub>. These factors result in rapid death when breathing CO.

B. Carbon dioxide transported in the blood in 3 ways (Fig 17.11)

1. Dissolved in blood
  - a) About 10% of CO<sub>2</sub> transported this way
  - b) Dependent on P<sub>CO<sub>2</sub></sub>
2. Bound to Hb
  - a) About 30% of CO<sub>2</sub> bound to globin portion of Hb (not heme portion as O<sub>2</sub> does)
  - b) Reduced Hb (ie, unoxygenated) has a greater affinity for CO<sub>2</sub> than does oxygenated Hb, which facilitates Hb picking up CO<sub>2</sub> in tissue capillaries
3. As bicarbonate (HCO<sub>3</sub><sup>-</sup>)
  - a) 60% of CO<sub>2</sub> converted to HCO<sub>3</sub><sup>-</sup> and H<sup>+</sup> by the enzyme carbonic anhydrase within red blood cells (this reaction uses water also)
  - 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. This is called the **chloride shift**
  - c) The H<sup>+</sup> remaining in the red blood cells binds to Hb; again, deoxygenated Hb has a greater affinity for H<sup>+</sup> than does oxygenated Hb. This helps buffer the blood, in that if the H<sup>+</sup> left in the red blood cells were to diffuse into the plasma, it would greatly increase the acidity of the blood.
  - d) The fact that removal of O<sub>2</sub> from Hb increases the ability of Hb to pick up CO<sub>2</sub> and CO<sub>2</sub> generated H<sup>+</sup> is known as the **Haldane effect**.
  - e) these reactions are reversed once the blood reaches the pulmonary capillaries, and CO<sub>2</sub> leaves the blood and enters the alveoli
- 4.

IV. Control of Respiration: Regulation of magnitude of ventilation

A. Overview

1. P<sub>O<sub>2</sub></sub> and P<sub>CO<sub>2</sub></sub> in the blood leaving the lungs are kept fairly constant; both of these variables, plus H<sup>+</sup>, are monitored and regulated.

B. Role of decreased arterial P<sub>O<sub>2</sub></sub> in regulating ventilation (Fig 17.18)

1. Arterial P<sub>O<sub>2</sub></sub> is monitored by peripheral chemoreceptors in the carotid arteries and aortic arch.
2. These chemoreceptors are not sensitive to changes in P<sub>O<sub>2</sub></sub> from 100 mm Hg to 60 mm Hg; ie, P<sub>O<sub>2</sub></sub> can drop 40% before they will cause an increase in ventilation.

- a) Not that critical; recall that Hb is still 90% saturated at  $P_{O_2}$  of 60 mm Hg.
  3. Interesting note: these chemoreceptors monitor  $P_{O_2}$ , NOT  $O_2$  that is bound to Hb. Thus if you suffer from anemia, and so don't have enough Hb to carry  $O_2$ , the chemoreceptors do not "notice" the problem, and ventilation is not increased!
- C. Role of increased arterial  $P_{CO_2}$  in regulating ventilation (Fig 17.20)
1. Central chemoreceptors in the medulla monitor  $P_{CO_2}$  precisely
  2. An increase in  $P_{CO_2}$  results in more  $CO_2$  crossing blood brain barrier in medulla. **After**  $CO_2$  has crossed the blood brain barrier, the  $CO_2$  reacts with water to form bicarbonate and  $H^+$ ; it is the increase in  $H^+$  in the ECF of the medulla which is detected by the central chemoreceptors. They cause an increase in ventilation to blow off excess  $CO_2$  (and thereby bring in additional  $O_2$ )
  3. This system fails at very high levels of  $P_{CO_2}$  (above 80 mm Hg). Such high levels depress brain function & depress respiration, and lead to death.
- D. Role of increased arterial  $H^+$  in regulating ventilation
1.  $H^+$  can not 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.
  2. The peripheral chemoreceptors are sensitive to changes in blood  $H^+$ , and cause changes in ventilation accordingly. However, this response is minor compared to the response in the central chemoreceptors caused by  $CO_2$
  3. However, changes in blood  $H^+$  caused by factors other than increased  $CO_2$  (e.g., by diabetes) does cause a response in the peripheral chemoreceptors that changes ventilation. This is one mechanism of acid/base balance in the body, as we'll see later.