The Physiology of Hyperbaric Oxygen Therapy

Physics: The Gas Laws

Summary: A review of the four major gas laws that affect or explain the basic theory for the development of high blood oxygen concentrations during hyperbaric oxygen therapy (HBOT).

I. Four of the gas laws directly affect the production of high blood oxygen concentrations during HBOT:

1. Boyle's Law
2. Dalton's Law
3. Henry's Law
4. Graham's Law

Other gas laws have been developed and are utilized to explain phenomena that occur by increasing or decreasing pressure around living and non-living things.

1. Gay Lussac's Law
2. Charles' Law
3. Pascal's Law
4. General Gas Law

II. Boyle's Law

Boyles Law relates the volume and density of a gas to the pressure at a constant temperature.

Boyles Law

At a constant temperature, the <u>volume</u> of a gas is <u>inversely</u> proportional to the pressure and the <u>density</u> of a gas is <u>directly</u> proportional to the to the pressure.

1. Volume is inversely related to pressure.
   Inversely = as the pressure increases the volume of a gas decreases and as the pressure decreases the volume increases.

   a. Consequence: as you increase the pressure around a patient the volume of gas in any gas filled space in the body will decrease. Conversely, as you decrease the pressure around the patient the volume of gas in the same spaces will increase.

The volume of each alveolus will decrease as a
is pressurized in the hyperbaric chamber.

2. Density is directly related to pressure.
Directly= as the pressure increases the density of the gas molecules increases.

a. Think of the gas as many gas molecules occupying a particular volume.

b. As the pressure increases the volume of the space containing the gas molecules decreases, but it still contains the same number of gas molecules. The molecules become more tightly packed as the volume decreases. The molecules are denser, more concentrated in a smaller area.

c. Consequence: The volume of the alveolus decreases as the pressure increases around it. The oxygen molecules in the alveolus become more concentrated or denser which presents more oxygen molecules to be transferred to the blood by diffusion.
Because of Boyles Law we can provide more oxygen in the lung for transfer to the blood.

III. Dalton's Law

Dalton's Law describes the relation of the pressure of individual gases in a mixture of gases to the total pressure of the gas mixture.

Dalton's Law

The <u>total pressure</u> exerted by a <u>mixture</u> of gases is equal to the <u>sum</u> of the pressure of each <u>individual gas</u> in the mixture. The whole is equal to the sum of its parts.

1. The air we breath is a mixture of gases:
21% oxygen
78% nitrogen
1% other gases
(for practical application we ignore the 1% other gases
air is 21% oxygen, 79% nitrogen)

2. The pressure of a mixture of gases is not measured in % but in some unit of pressure such as mmHg, cmH_2O, atmospheres, barr, etc.
   To determine the pressure that each gas in a mixture exerts we can multiply the % of the gas in the mixture times the total pressure of the mixture.

   a. If we are at sea level the atmospheric pressure is 760 mmHg. The air we breath (gas mixture) has a pressure of 760 mmHg (total pressure).
      Therefore:

      The pressure of $\mathbf{O_2}$ in the air we breath
      is 760 mmHg x .21 (21%) = **159.6 mmHg**

      The pressure of **nitrogen** in the air
      is 760 mmHg x .79 (79%) = **600.4 mmHg**

      The **total pressure** of the gas
      is 159.6 + 600.4 = **760 mmHg sea level**

3. What happens if we breath a gas that is **100% oxygen** instead of 21% oxygen <u>at sea level</u>.

   a. 760 mmHg x 1.0 (100%) = 760 mmHg O_2
      The pressure of oxygen we breath in this case is now 4 times higher than if we were breathing air at sea level, 760 mmHg vs. 159.6 mmHg.

4. What happens if we increase the pressure at which we breath a gas or mixture of gases (increase the total pressure) to some pressure other than sea level (760 mmHg) as would happen while scuba diving under water or in the hyperbaric chamber.

   a. Increasing the total pressure of the mixture would increase pressure of each component gas in line with their percent of the whole.

b. At 2 atmospheres (2 ATA) of pressure (33 ft. under sea water) the pressure of air in mmHg would be:

760 mmHg (1 ATA) x 2 = 1520 mmHg

The pressure of oxygen at 2 ATA would then be:
1520 mmHg x .21 (21%) = 319.2 mmHg
This would represent twice as much oxygen than breathing air at sea level.

Breathing 100% oxyghn at 2 ATA the oxygen pressure in the inspired gas would be:

1520 mmHg x 1.0 (100%) = 1520 mmHg

This is 9.5 times more O_2 than breathing air at sea level.

5. The concentration of gases inhaled with each breath versus the concentration of gases in the alveoli of the lungs.

a. The major purpose of the respiratory track and the lungs is to transfer O_2 from the air we breath to the blood and remove CO_2 from the blood to the air we expire. The oxygen is needed by the body's tissues for cell metabolism and the by product of metabolism, CO_2, needs to be removed.

b. As we inhale atmospheric air it mixes with air coming from the alveoli of the lung which is low in O_2 and high in CO_2 . This mixing causes a dilution of the oxygen in the new inspired air. Therefore, the actual oxygen concentration in the alveolus will be less than the oxygen concentration breathed in with each breath.

c. In a patient with normal respiratory function, the pressure of oxygen in the alveolus when breathing air at sea level (760 mmHg, 21% oxygen) is approximately 100-115 mmHg. This is 44-59 mmHg less than the oxygen pressure in the atmospheric air.

d. The effect of breathing 100% oxygen at sea level (760 mmHg) on the oxygen pressure in the alveolus would be to increase the concentration, but the dilution with air coming from the alveolus would again reduce the final oxygen concentration delivered to the alveolus.
Oxygen 100% → 760 mmHg x 1.0 = 760 O_2 in the inspired air.
In the alveolus the final concentration would be Approximately 678 mmHg, 82 mmHg less.
This same affect also occurs when we place a patient in the hyperbaric chamber and administer 100% oxygen. However, because of the affects of Boyles and Dalton's Laws we can significantly increase the oxygen concentration in the alveolus.

IV. Dalton's and Boyle's Laws

Explains how a very high concentration of oxygen can be developed in the alveolus during hyperbaric oxygen therapy.

1. Dalton's Law says that we can increase the inspired concentration of oxygen if we deliver air or 100% oxygen under increased surrounding pressure.
2. Boyle's law says that as the surrounding pressure increases the volume of the alveolus will decrease, concentrating the gas molecules (↑ its density) making more molecules available per unit volume.
3. The two gas law phenomena, then, essentially provide more gas molecules to diffuse from the alveolus to the blood.

V. Grahms Law

Grahm's Law describes the relationship of the pressure (concentration) of a gas to how it moves.

Grahm's Law

Grahm's law states that oxygen and carbon dioxide (and other gases) move independently, at different rates, from an area of high pressure to an area of lower pressure.

1. In the lung gases must diffuse from the alveolus to the blood through a thin alveolar membrane, a small space between alveolus and capillary, and across the capillary cell wall. This is the same as diffusing through a semi-permeable membrane.

2. As we breath air at atmospheric pressure (at sea level) we are constantly replenishing oxygen molecules in the alveolus. As the blood passes through the various tissues oxygen is extracted from the blood. As the blood from the tissues returns to the lung its oxygen concentration is low. Consequently, the pressure (concentration) of oxygen in the alveolus constantly remains higher than that in the blood from the tissues.
   According to Grahm's Law of Diffusion, the oxygen will move from the area of higher concentration (the alveolus) to an area of lower concentration (the blood).

3. If we increase the concentration of oxygen in the alveolus, as in hyperbaric therapy(Boyle's and Dalton's laws), we will cause even more oxygen to move into the blood. Molecules of gas are very active. As we increase the concentration we increase the number of molecules hitting the semi-permeable membrane. This will increase the number that diffuse across.

4. The same law of diffusion apply at the tissue level. As the tissues use oxygen, the concentration becomes lower in the tissue than the concentration in the blood, so more oxygen diffuses from the blood to the tissues.

VI. Henry' Law

Henry's Law relates the amount of gas that can be dissolved in liquid to the pressure of the gas above the liquid.

Henry's Law

Henry's Law states that the solubility of a gas (how much is dissolved) in a liquid is directly proportional to the pressure of the gas in contact with the liquid.

1. In the case of the body the liquid is the blood. The pressure is the concentration of oxygen as it diffuses from the alveolus to the blood.

2. Following its entrance into the blood, a certain amount of oxygen is immediately combined with hemoglobin in the blood. If the patient is breathing air at sea level most of the oxygen in the blood is combined with hemoglobin. A very small amount is dissolved in the plasma.

   a. The amount of oxygen carried by hemoglobin depends on the amount of hemoglobin in the blood. In general, 100 ml (3.33oz) of blood carries approximately 20.4 ml of oxygen. Once hemoglobin is saturated with oxygen, it provides no additional oxygen for the tissues under hyperbaric conditions.

   b. A very small amount of oxygen, not combined with hemoglobin, is dissolved in the plasma when a patient breaths air at sea level (1 ATA). Approximately 100 ml (3.33 oz.) of blood has only 0.31 ml of oxygen in it at sea level.
   Under hyperbaric conditions more oxygen is available to be dissolved in the plasma governed by Henry's Law. For each 100 mmHg increase in the oxygen pressure in the alveolus another 0.31 ml of oxygen can be dissolved in the plasma. We can increase the dissolved oxygen up to 15 times normal by the use of hyperbaric therapy.

3. Consequence: Henry's Law is the reason that having a high concentration of oxygen in the alveolus will create a high concentration in the blood going to the tissues.

The Gas Laws and Hyperbaric Oxygen Therapy – Summary