

A REVIEW OF THE GAS LAWS

by Bill Wojciechowski, MS, RRT



When performing pulmonary function testing using a body plethysmograph, do you ever think of Boyle's law? How about when you administer supplemental oxygen to a patient in the ICU, do you ever think of Dalton's law of partial pressures, Henry's law of solubility, and Graham's law of diffusion? The likelihood is you responded negatively to each of those questions. Of course, you are a competent respiratory therapist; you perform these skills and many others on a routine basis. For those of you who mow your own lawn, do you think of the Venturi principle each time you operate your lawn mower? For those of you who drive a pre-1990 (fuel injectors post-1990) vehicle, do you think of the Venturi principle each time you start the engine and depress the accelerator? Of course not, but nonetheless you are likely adept at cutting your lawn, and competent driving your pre-1990 vehicle (an assumption on my part since I lack access to your driving record).

This article is intended to serve as a refresher for some of the more common gas laws that apply to the application of respiratory therapy. Fear not. You will not be required to perform calculations. Only the qualitative aspects of gas laws will be presented.

Boyle's Law

Boyle's law states that for a given mass of gas the volume (V) and pressure (P) are inversely proportional when the temperature (T) of the gas is constant. The formula for Boyle's law is as follows:

$$k = P \times V$$

Consider a volume of gas inside a cylinder, which has an air-tight, movable piston preventing gas from escaping and entering the cylinder. When the cylinder, piston, and gas are at the same temperature, the gas molecules inside the cylinder occupy a certain volume. Based on Boyle's law, if the pressure exerted by the movable piston doubled (2P), the volume of the gas inside the cylinder would be halved (V/2). Therefore,

$$k = 2P \times V/2$$

To calculate the thoracic gas volume (VTG), the change in volume of the chest is determined. Applying Boyle's law ($P_{ibox}V_{ibox} = P_{exp}V_{exp}$), the product of the initial box (ibox) pressure and the initial box volume, both of which are known, is equated to the product of the pressure and volume of the box at the end of a chest expansion (cexp) of which only the pressure is known. The volume of the box at the end of chest expansion is computed. The difference between V_{exp} and V_{ibox} is the change in volume of the box, which is the same as the change in volume of the chest.

Applying Boyle's law again, equating the initial volume of the chest (unknown VTG) times the initial mouth pressure (known), to the sum of the initial volume of the chest (unknown VTG) and the difference between the V_{exp} and V_{ibox} times the mouth pressure during the inspiratory effort (known). Solving for the unknown volume, which is the VTG (the original volume of gas in the lungs when the shutter was closed).

Boyle's law also manifests itself during the application of hyperbaric oxygen therapy used to treat the bends or decompression sickness. Scuba divers will sometimes rapidly resurface. During this abrupt decompression gases within the vasculature and other tissues come out of solution and expand to promote a mechanical and pro-inflammatory reaction. The application of increased pressure (hyperbarism) promotes a decrease in the volume of the gas bubbles, thereby enhancing their reabsorption.

Charles' Law

Charles' law describes the direct relationship occurring between the absolute temperature and the gas volume when the mass and pressure of the gas are held constant. That is,

$$V/T = k$$

A gas volume collected in a spirometer will decrease because of the direct effect of the decreasing temperature, and because water vapor condenses as the temperature drops. To make accurate comparisons, gas volumes collected at ambient temperature pressure saturated (ATPS) conditions are corrected to those that they would occupy at body temperature pressure saturated (BTPS) conditions. ATPS to BTPS conversions are based on Charles' law.

Gay-Lussac's Law

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Gay-Lussac's law explains the direct relationship between the pressure of a gas and the absolute temperature of the gas when the mass of the gas and its volume remain constant. Gay-Lussac's law is quantitatively expressed as follows:

$$P/T = k$$

A compressed gas cylinder not in use, but containing some volume and pressure of gas represents a clinical example of Charles' law. Because that cylinder is not in use, and because its contents are not being depleted, the volume and mass of the gas inside the cylinder are constant. Therefore, the pressure and temperature are directly related. If that cylinder is stored near a source of heat, the temperature of the cylinder and its contents will increase. The pressure inside the cylinder will increase in direct proportion with the temperature.

Dalton's Law of Partial Pressures

Dalton's law of partial pressure states that the total pressure exerted by a mixture of gases is equal to the sum of the partial pressures of the constituent gases. Quantitatively, Dalton's law is,

$$PT = P1 + P2 + P3 + . . . Pn$$

In the atmosphere at sea level, the barometric pressure is generally 760 torr. Assuming no humidity, that total pressure is comprised of approximately 21% oxygen, and 79% nitrogen. Therefore, the partial pressure of the oxygen in that mixture is 760 torr times 21%, or about 160 torr. When a person breathes that air mixture, the partial pressure of the inspired oxygen is 160 torr. However, as that inspired volume of air flows through the person's upper airway and reaches the carina, it acquires 47 torr of water vapor. Consequently, at that point in the trachea, the partial pressure of the constituent gases, i.e., O₂ and N₂, change. Oxygen still comprises 21% of the mixture and N₂ 79%.

What needs to be taken into account is the 47 torr water vapor pressure that is now present. The water vapor pressure must be subtracted from the inspired barometric pressure 760 torr. After correcting for the presence of the partial pressure of water vapor (760 torr - 47 torr = 713 torr), the PO₂ in the trachea becomes approximately 150 torr (i.e., 713 torr x 0.21 = 150 torr). The change in the PO₂ from the inspired air to that in the trachea is a consequence of the addition of water vapor into the inspired gas. This example serves as an application of Dalton's law of partial pressures.

Henry's Law of Solubility

Henry's law asserts that the amount of gas that dissolves in a liquid at a certain temperature is directly proportional to the partial pressure of the gas above the surface of the liquid. In other words, the greater the number of gas molecules, or the higher partial pressure of a gas present above a liquid causes more of those gas molecules to dissolve in the liquid. Consider administering 60% oxygen to a patient via a partial rebreather mask. More O₂ molecules are entering the alveoli at this time than when room air is breathed. Consequently, as a greater partial pressure of O₂ is breathed, more nitrogen molecules are being washed out. As more O₂ molecules enter the alveoli, the partial pressure of O₂ in the alveoli increases, i.e., the partial pressure of the gas (O₂) above the surface of the liquid (blood) increases.

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