Gas Partial Pressures

Prior to any further presentation and discussion of pulmonary physiology, the physical laws governing the movement and concentration of gases must be presented (my job) and understood (each of mine, your instructor's and your jobs)! Central to these topics and tasks is the concept of gas partial pressures. This concept may be totally foreign to you. After-all, when concerned with concentrations, mainstream examples or applications deal with particles or molecules in solution. This is a concept that is relatively easy to learn, as you can often visual detect changing concentrations based on changes in color intensity, or opaqueness, or viscosity. We can also taste when more or less salt or sugar is in a food item, regardless of whether the food is a solid or a liquid. Perceiving x amount of something in Y amount of another thing seems to work well for our brains. For gases, this is a bit different. This is because gas volumes vary so much with temperature and pressure, and therefore expression of concentrations of gases cannot be accomplished based on total gas volume. This is where pressure becomes so important. Gas concentrations are a special type of concentration based on the pressure a given gas makes up of the total gas mixture composition. The presence of a gas in a mixture therefore accounts for a part of the total pressure. At sea level, this total pressure approximates 760 mmHg. For air, oxygen makes up 159 mmHg of this 760 total, which means there is a partial pressure for oxygen (PO_2) of 159 mmHg. This computes to a O_2 gas fraction of 159/760 = 0.2095. Thus, for pulmonology, gas concentrations are quantified by partial pressures, or the part of the total pressure of a gas mixture caused by the specific gas at question.

Air Gas Partial Pressures

The **atmospheric air** inhaled into the lungs consists of certain gases, as presented in Table 1. As shown, 99.06% of air is comprised of **nitrogen** (N_2; 78.08%), **oxygen** (O_2; 20.95%), and **carbon dioxide** (CO_2; 0.031%) (78.08+20.95+0.031=99.06%). Gases are not expressed as concentrations. Rather, the driving force for gas diffusion is the gas pressure. As each gas of concern (N_2, O_2, CO_2) is part of atmospheric air, its presence or effective concentration can be expressed as the pressure it makes up of the total atmospheric air pressure. This is termed a gas **partial pressure**, and is computed as a simple product of the gas fraction and total atmospheric pressure (Table 1 and Equation 1). This means that a gas partial pressure is dependent on two variables; 1) the gas fraction, which is a constant for unpolluted air, and 2) the barometric pressure, which is influenced by altitude and weather.

It is very important to note that the calculations of Equation 1 are only accurate for air that has no **water vapor pressure** (dry air), which means **relative humidity** is zero. The reason why this is important was also explained in the Section on Calorimetry. As repetition is good for learning, here we go again!

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Table 1. Standard gas fractions for clean air.

Gas	Symbol	% by Volume
Nitrogen	N_2	78.08
Oxygen	O_2	20.95
Argon	**Ar**	0.93
Carbon dioxide	CO_2	0.031
Neon	**Ne**	0.0018
Helium	**He**	0.00052
Methane	CH_4	0.0002
Krypton	**Kr**	0.00011
Nitrous oxide	N_2O	0.00005
Hydrogen	H_2	0.00005
Xenon	**Xe**	0.000008
Ozone	O_3	0.000002
Radon	**Rn**	trace
Other	----	0.00426

CRC Handbook of Chemistry and Physics (1997)

$$Gas\ partial\ pressure\,(P_{gas};\, mmHg) = gas\ fraction \times barometric\ pressure\,(mmHg)$$

$$P_{N2} = 0.7808 \times 760 = 593.408\ mmHg$$
$$P_{O2} = 0.2095 \times 760 = 159.22\ mmHg$$
$$P_{CO2} = 0.000314 \times 760 = 0.2386\ mmHg$$

Equation 1

Water vapor is also a gas, which means that it takes up part of the total atmospheric air pressure, or as you will also learn here, lung air pressure. This means that to calculate accurate values for our three physiological gas partial pressures, the water vapor pressure must first be subtracted from the air pressure. This adjusted air pressure is then used to calculate the gas partial pressures.

Air water vapor pressure is not easy to measure, unless you get it directly from a commercial weather station. Air water vapor pressure is influenced by air temperature and relative humidity, which means that air temperature and relative humidity need to be known to compute water vapor pressure. Refer back to the topic on indirect calorimetry to get added details on relative humidity.

Alveolar Gas Partial Pressures

The important physiological gas partial pressures are not that of air, but rather that for air in the lung, termed alveolar air, resulting in **alveolar gas partial pressures** (P_Agas). As body temperature is typically a constant at 37 ºC, unless hypo- or hyperthermic, and relative humidity is 100% for air inside the lungs, the water vapor pressure is assumed to be a constant for most exercise conditions, which for 37 ºC is 47 mmHg water vapor pressure. A list of water vapor pressures for specific temperatures for saturated air (100 % relative humidity) is presented in Table 2.

Table 2. Air water vapor pressures for saturated air at different temperatures.

Temperature (°F)	**Temperature (°C)**	**P_{H2O} (mmHg)**
57.2	**14**	21.9
59	**15**	13.5
60.8	**16**	14.1
62.6	**17**	14.9
64.4	**18**	15.5
66.2	**19**	16.5
68	**20**	17.5
69.8	**21**	18.7
71.6	**22**	19.8
73.4	**23**	21.1
75.2	**24**	22.4
77	**25**	23.8
78.8	**26**	25.2
80.6	**27**	26.7
82.4	**28**	28.3
84.2	**29**	30.0
86	**30**	31.8
87.8	**31**	33.7
89.6	**32**	35.7
91.4	**33**	37.7
93.2	**34**	39.9
95	**35**	42.2
96.8	**36**	44.6
98.6	**37**	47.1
100.4	**38**	49.4
102.2	**39**	52.0
104	**40**	54.7

$P_{H2O} = (13.955 - (0.6584 \times T)) + (0.0419 \times T^2)$

Thus, to compute alveolar gas partial pressures, you need to know the atmospheric pressure, that saturated air at 37 ºC has 47 mmHg water vapor pressure, and the alveolar gas fraction. Equation 2 presents the formula for computing barometric pressure from altitude. I recommend that you memorize this equation.

$$P_B\ (mmHg) = 760 \times \left(e^{-(m/7924)}\right) \qquad \text{Equation 2}$$

Table 3 presents the known alveolar gas fractions in the lung at sea level and 1 mile above sea level (5,280 ft or 1,610 m) , and with normal ventilation. Note that excess ventilation (**hyperventilation**) or under ventilation (**hypoventilation**) for a given metabolic demand of the body will change these fractions. For example, hyperventilation would raise PAO_2 and lower $PACO_2$. Conversely, hypoventilation would raise $PACO_2$ and lower PAO_2. Why are there these changes? Well, hyperventilation brings more atmospheric air into the lung than is needed for external respiration to maintain peak blood oxygen content. Thus, the excess oxygen from the excess inhaled air causes alveolar air to be more like atmospheric air, which means having a higher PO_2 and lower PCO_2 than is typical for the lung. Hypoventilation works in the opposite direction. When ventilation is inadequate to meet the metabolic needs of the body, insufficient O_2 is available to sustain peak blood oxygen content and PAO_2 falls. Inadequate ventilation also means a reduced capacity to clear CO_2 from the body and lung, raising $PACO_2$.

Table 3. Alveolar gas partial pressures and fractions for conditions of sea level and 1,610 m above sea level.

	Sea Level P_B=760 mmHg P_B-47=713 * 0.9906 = 706.3			5,280 ft (1,610 m) P_B=620 mmHg P_B-47=573 * 0.9906 = 567.6
Gas	Air Fraction	Alveolar Fraction	$P_A$gas (mmHg)	$P_A$gas (mmHg)
Nitrogen	0.78084	0.7868	**561**	447
Oxygen	0.209476	0.1472	**104**	84
Carbon Dioxide	0.000314	0.0566	**40**	32

The data of alveolar partial pressures at any barometric pressure (altitude) can be calculated from memorizing the bold values.

As indicated at the foot of Table 3, all alveolar data can be completed for this table from simply knowing PAO_2 and $PACO_2$ at sea level. From these values, the alveolar gas fractions can be computed from the known barometric pressure adjusted for lung water vapor. The nitrogen values can then be calculated assuming 99.06% of lung air is nitrogen plus oxygen plus carbon dioxide. The alveolar gas fractions can then be applied to the altitude condition and the new barometric pressure adjusted for lung water vapor, which remains 47 mmHg.

Note that some of these alveolar partial pressures will differ to what is presented in other exercise physiology textbooks. My data research for this book has shown, as I previously explained in the Section on “Indirect Calorimetry”, that atmospheric air is not 79.03% N_2, 20.93% O_2, and 0.03% CO_2. These values have been used in past exercise physiology pulmonary presentation because the Argon content of air has been ignored and factored into the nitrogen value. I have decided not to do this, and present real numbers from the CRC Handbook of Chemistry and Physics (1997). The adjustments in the data are not large, but at least they are factually correct!

As will be explained in the next Topic, these alveolar gas partial pressures dictate changes in each of blood O_2 and CO_2 partial pressures.

Tidal Changes in Expired Gas Fractions and Partial Pressures

I wanted to explain a few more advanced issues about gas partial pressures and ventilation. Remember that the conducting zone of the lung provides an anatomical dead space, where there is no gas exchange. Also remember that after an exhalation, the air in the anatomical dead space consists of air that is reflective of alveolar gas conditions as it as the air that was the last to leave the respiratory zone of the lung. We call such air **end-tidal air**, and **end-tidal gas fractions** are measured at the mouth through ports within the mouthpiece apparatus used in indirect calorimetry or spirometry.

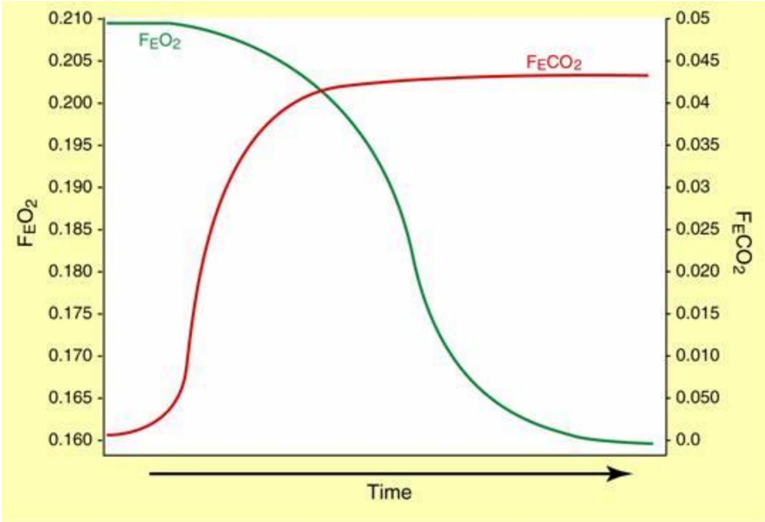

Figure 1. Changes in the O_2 and CO_2 fractions in expired air during a normal breathing cycle.

Figure 1 provides the data from changes in expired air gas fractions during a normal exhalation. Note the changes in end-tidal gas fractions from the start of expiration to the end of expiration. The oxygen content of expired air gradually decreases through the exhalation until end-tidal air is reached and the O_2 fraction becomes stable. The opposite is true for CO_2, where the CO_2 fraction increases and becomes stable for end-tidal air. As previously stated, end tidal gas fractions can be used to estimate alveolar gas fractions, but only in individuals with normal, non-diseased, lungs. I hope you are also aware that the two gas responses (O_2 and CO_2) differ in their kinetics. Look at the figure. Which gas has a more rapid change to the end-tidal condition? It should be obvious – CO_2 at close to double the rate response, which means in half the time. This issue has tremendous relevance to the physiological consequences of changing O_2 or CO_2 partial pressures in the air we breathe, and these issues will be addressed again in other Topics in this section, as well as in the content within the Section on environmental physiology.

Glossary Words

atmospheric air refers to air from unpolluted air.

nitrogen (N_2) is the main gas from atmospheric air, comprising 78.08 % of the total pressure.

oxygen (O_2) is the main gas from atmospheric air essential for life, comprising 20.95 % of the total pressure.

carbon dioxide (CO_2) is a biological relevant gas found in low concentrations in atmospheric air, comprising 0.031 % of the total pressure.

partial pressure refers to the pressure a specific gas from a mix of gases provides to the total gas pressure.

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relative humidity refers to the relative (%) water vapor content in a sample of air of a known temperature compared to what the air could hold at that temperature if completely saturated with water vapor.

alveolar gas partial pressure the partial pressure of a specific gas in alveolar air.

hyperventilation is a larger than typical ventilation for a specific condition.

hypoventilation is a lower than typical ventilation for a specific condition.

end tidal air refers to air measured at the end of an expiration.

end tidal gas fractions refers to expired air gas fractions sampled at the end of an expiration.