Physical Aspects of Hyperbaric Medicine

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PHYSICAL ASPECTS OF HYPERBARIC MEDICINE

Fundamental to the safe and effective practice of hyperbaric medicine is requisite knowledge of several gas laws, appreciation of pressure definitions and the ability to convert common expressions of pressure. This knowledge also serves as a foundation for the physiology of hyperbaric oxygenation and how the hyperbaric chamber's environment generates several therapeutic mechanisms. Treatment dosing terminology is also included in this section.

Under normal environmental conditions we are exposed to the weight of earth's air atmosphere, which extends somewhat beyond 100,000 feet/30,000 meters above sea level. Ambient pressure *decreases* as one ascends, due to the decreasing weight of atmospheric air. "We live submerged at the bottom of an ocean of air." *Evangestia Torricelli, 1644* Pressure at Mount Everest's peak for example is only two fifths that of sea level. Ambient pressure *increases* as one descends, in a body of water or within a mine shaft. Because water is denser than air, increases experienced during in-water exposure are significantly greater than those encountered by miners.

Describing Pressure

Pressure is described in several forms, commonly from one of two reference points. It can be expressed with respect to a vacuum (zero pressure) and described in *absolute* terms. Alternatively, it can serve to measure differences in pressure above or below one's surroundings (ambient pressure). These values are referred to as *gauge* pressure.

Atmospheric Pressure:	Universally applied: does not register on a "standard" pressure gauge.
Absolute Pressure:	Absolute pressure gauges are zero referenced against a prefect vacuum, thereby representing the combination of atmospheric pressure and any change in ambient pressure.
Barometric Pressure:	Similar to atmospheric pressure but varies with changes in weather.
Gauge Pressure:	Chamber pressure gauges are zero referenced against ambient pressure. Gauge pressure is the difference between surrounding ambient (atmospheric) pressure and that within a pressure vessel.
Ambient Pressure:	That of the surrounding environment one is exposed to.

At sea level, pressure is referred to as 1 atmosphere absolute (1 ATA). An absolute pressure calibrated gauge will read 1.0 ATA while a standard (non-absolute) pressure gauge will read zero. Upon descent (compression), through the water or within a hyperbaric chamber, pressure increases. Next we will discuss the measured impact of pressure increases on these two gauge types.

Measuring Pressure

a. **Imperial System** (AKA British Imperial or Standard System). First defined in 1820's.

Common units of pressure are atmospheres absolute (ATA); atmospheres (atm); feet sea water (fsw); pounds per square inch gauge (psig); pounds per square inch absolute (psia), and millimeters of mercury (mmHg).

b. **Metric System.** Increasingly adopted across Europe and elsewhere during 19th century. Now commonly referred to as the 'International System of Units', or S.I. (*Le Systeme International*). S.I. adopted nearly globally as the official measurement system of weight, length, time, energy, and force.

Common units of 'hyperbaric' pressure are meters' sea water (msw); kilopascals (kPa); Bar.

Hyperbaric treatment doses (pressures) are ordered in atmospheres absolute (ATA). Multiplace hyperbaric chamber pressure gauges are calibrated in feet of sea water (fsw) here in the USA andr meters sea water (msw), elsewhere. Monoplace hyperbaric chambers pressure gauges are invariably calibrated in pounds per square inch gauge (psig). (See page 8)

Pressure Conversion Scale							
	ATA	**FSW**	**PSIG**	**PSIA**	**MMHG**	**MSW**	**KPA**
(Sea Level)	1.0	0	0	14.7	760	0	0
	2.0	33	14.7	29.4	1,520	10.1	101.35
	3.0	66	29.4	44.1	2,280	20.1	202.71
	4.0	99		58.8	3,040	30.2	304.10
	5.0	132		73.5	3,800	40.2	405.40
	6.0	165		88.2	4,560	50.3	506.77

Converting Pressure

Feet sea water (fsw) to pounds per square inch gauge (psig)

33 fsw = 1.0 atmosphere and 14.7 psi = 1.0 atmosphere

So, 33 fsw = 14.7 psi

$$1 \text{ fsw} = \frac{14.7 \text{ psi}}{33.0} = 0.445 \text{ psi}$$

Convert the following from fsw to psi 45 ______________ 60 ______________

Feet sea water (fsw) to atmospheres absolute (ATA)

33 fsw = 1.0 atmosphere

$$\text{Depth (pressure) absolute} = \frac{\text{Depth (fsw)} + 33}{33}$$

$$\frac{0 + 33}{33} = 1.0 \text{ ATA} \qquad \frac{45+33}{33} = 2.4 \text{ ATA}$$

Convert the following from fsw to ATA 60 ______________ 165 ______________

Pounds per square inch gauge (psig) to feet sea water (fsw)

14.7 psi = 1.0 atmosphere and 33.0 fsw = 1.0 atmosphere

So, 14.7psi = 33 fsw

$$1 \text{ psi} = \frac{33.0}{14.7} = 2.24 \text{ fsw}$$

Convert the following from psi to fsw 14.7 ______________ 29.4 ______________

Pounds per square inch gauge (psig) to atmospheres absolute (ATA)

14.7 psi = 1.0 atmosphere

$$\text{Pressure Absolute} = \frac{\text{Pressure} + 14.7}{14.7}$$

$$\frac{0 + 14.7}{14.7} = 1.0 \text{ ATA} \qquad \frac{14.7 + 14.7}{14.7} = 2.0 \text{ ATA}$$

Convert the following from psi to ATA 20.6 ____________ 29.4 ____________

Key Gas Laws Related to the Practice Hyperbaric Medicine

A. **Boyle's Law** *(Sir Robert Boyle; English chemist and physicist 1627-1691)*

<u>Encyclopedic definition:</u> *"For a fixed mass of an ideal gas at a fixed temperature, the product of pressure and volume is a constant"*

<u>Lay definition:</u> *"A directly proportional inverse relationship exists between pressure and volume"*

The role of Boyle's Law in hyperbaric medicine:

i. Therapeutic for accidents and events that produce intravascular and/or other embolic gas

a. Decompression sickness
b. Decompression – induced arterial gas embolism
c. Iatrogenic arterial gas embolism
d. Pneumotosis cystoides intestinalis (O*ff label)*

ii. A complicating event in hyperbaric medicine

A. Ear, sinus, dental barotrauma
B. Pulmonary barotrauma
C. Damage to equipment and medical devices involving enclosed gas-filled spaces

One mathematical expression (vs. P1V1 = P2V2) for Boyle's Law is:

PV = K where **P** is the pressure of the gas* **V** is the volume of the gas **K** is the constant

**Must be expressed in absolute form*

If temperature remains constant the computed value of **K** will not change as pressure and volume change

Example 1

A lifting balloon is inflated to 4 liters of volume while at 150 feet below the ocean surface and sealed. What would be the resulting volume expansion if the balloon ascends to 100 feet?

Before:

$$\mathbf{P} = \frac{150 + 33}{33} = 5.55$$

	P	x	**V**	=	**K**
=	5.55	x	4	=	**22.2**

After:

$$\mathbf{P} = \frac{100 + 33}{33} = 4.03$$

	P	x	**V**	=	**K**
=	4.03	x	?	=	**22.2**

$$= \frac{\mathbf{22.2}}{4.03} = 5.5 \text{ liters}$$

Example 2

A hyperbaric patient is compressed from sea level (1.0 ATA) to 2.4 ATA. Their initial middle ear volume is a nominal 1.0. In the absence of middle ear pressure equalization during compression (sedated), what would be the resulting middle ear volume upon arrival at 2.4 ATA?

	P	x	V	=	K
Before:	1.0	x	1.0	=	1.0

	P	x	V	=	K
After:	2.4	x	?	=	1.0

$$= \frac{1.0}{2.4} = 0.41$$

B. Dalton's Law (*John Dalton; English chemist, meteorologist, physicist 1766-1844)*

<u>Encyclopedic definition</u>: *"Total pressure exerted by gaseous mixture is equal to the sum of the partial pressures of each individual component of that mixture"*

<u>Lay definition:</u> *As above!*

Mathematical expression of Dalton's Law:

P total = p1+p2+p3…

Pressure (expressed as absolute) multiplied by gas in question (expressed in decimal form) equals partial pressure of a given gas

Under normal atmospheric air/sea level pressure conditions:

P total = 1.0 ATA or 760 mmHg

<u>What is the partial pressure of oxygen expressed in mmHg at sea level?</u>

760 mmHg absolute pressure; oxygen is 21%: therefore, 760 x 0.21 = 160 mmHg

<u>What is the partial pressure of nitrogen in mmHg at sea level?</u>

760 x 0.78 = 593 mmHg

<u>What is the partial pressure of oxygen in air at 3.0 ATA?</u>

760 x 3 x 0.21 = 479 mmHg (equivalent of breathing 63% oxygen at sea level (1.0 ATA)

Determine the partial pressures of oxygen and nitrogen under air breathing conditions at 2.5 ATA

0_2___________ N_2__________

Role of Dalton's Law in hyperbaric medicine: Describes process whereby high oxygen pressures are delivered to the lungs during increases in ambient chamber pressure.

C. Henry's Law (*William Henry; English chemist 1775-1836)*

<u>*Encyclopedic definition:*</u> *"At constant temperature, the amount of a given gas dissolved in a given type and volume of liquid is directly proportional to the partial pressure of that gas in equilibrium with that liquid"*

<u>*Lay definition:*</u> *"A gas will dissolve into a liquid in direct proportion to its partial pressure"*

Mathematical expression of Henry's Law:

C = kP

where:
C = concentration of dissolved gas
k = Henry's Law constant
P = partial pressure of the gas

Role of Henry's Law in Hyperbaric Medicine: Explains the process whereby the high oxygen pressures delivered to the lung (Dalton's Law) diffuse (transfer) in direct proportion to its partial pressure into blood and on to tissues. Full saturation of blood and tissues at any new ambient pressure takes in the order of 12-18 hours to occur.

D. Gay-Lussac's Law (*Joseph Louis Gay-Lussac; French chemist 1778-1850)*

<u>*Encyclopedic definition:*</u> *"If volume is fixed (hyperbaric chamber), pressure is directly proportional to its temperature, in Kelvins."*

Mathematical expression of Gay-Lussac's Law:

$$\frac{P_1}{T_1} = \frac{P_2}{T_2} \quad \text{or} \quad P_1 T_2 = P_2 T_1$$

T_1 = initial temperate (absolute)
T_2 = final temperate (absolute)
P_1 = initial pressure (absolute)
P_2 = final pressure (absolute)

Role of Gay-Lussac's Law in hyperbaric medicine:

In a chamber's fixed volume, as pressure is increased a corresponding and proportional increase in ambient temperature occurs, the degree of which depends upon pressurization rate. Patients will sense a slight warming. Once at treatment pressure, temperature equilibrates with ambient surroundings. As the chamber is decompressed there is a corresponding fall in chamber temperature.

E. Charles's Law (Jacques Charles; French scientist, mathematician, balloonist 1746-1823, with apologies to Guy-Lussac who confirmed this discovery but credited it to early work by Charles)

<u>*Encyclopedic definition*</u>:

"The volume occupied by a fixed amount of gas is directly proportional to its absolute temperature, if the pressure remains constant"

Mathematical expression of Charles Law

$$\frac{V1}{T1} = \frac{V2}{T2}$$

This law describes how a gas expands as temperature increases; conversely a decrease in temperature will lead to a decrease in volume.

Charles Law relates more to undersea activities

F. Pascal's Law (*Blaise Pascal; French mathematician, physicist, inventor 1778-1850)*

Encyclopedic definition:

"A confined fluid transmits externally applied pressure uniformly in all directions without change in magnitude"

$P_1 = P_2$ (since pressures are equal throughout)

Role of Pascal's Law in hyperbaric medicine: As body tissues are incompressible, those who undergo compression/decompression do not sense changes. Pressure *'damage'* is sensed if air containing spaces don't communicate externally.

Calibration to Ambient Oxygen Pressure

Normally, only change in barometric pressure is of practical importance when calculating calibration value of indoor environment. (Assumes stable humidity).

The following represents the transcutaneous oxygen monitor's barometric calibration process:

Where:

PO_2 : is the calibration value

B : is the barometric pressure (mmHg)

XO_2 : is the fraction of oxygen in atmospheric air; *normally given as 0.2093*

In US, barometric pressure commonly expressed in inches Hg. To convert to mmHg, the value recorded on the monitor:

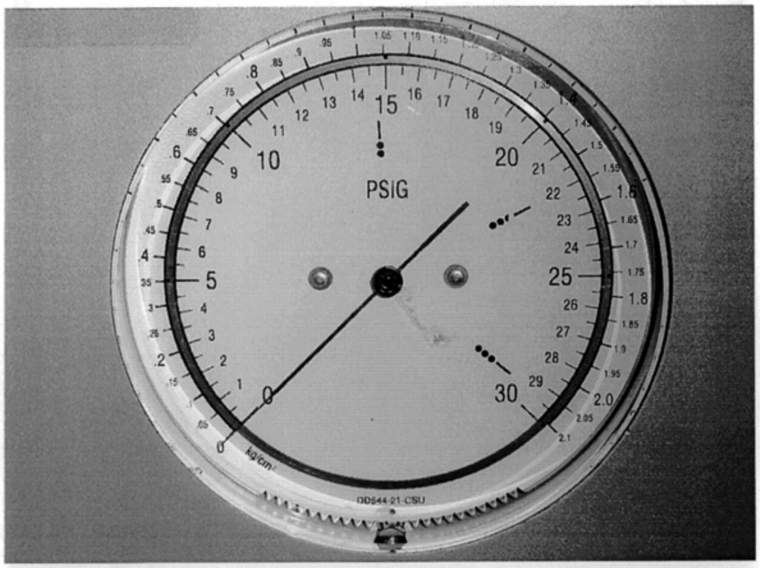
I. Multiply barometric pressure (inches) by 25.40 to become mmHg

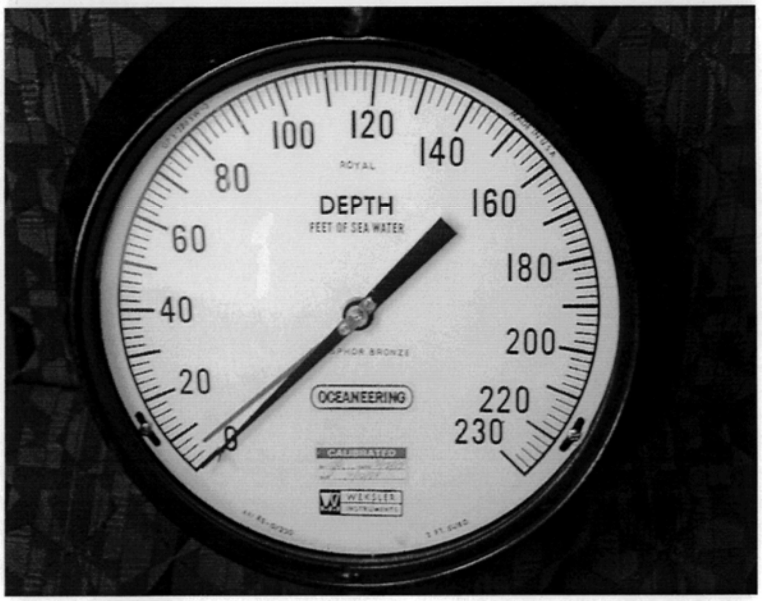
II. Multiple mmHg by 0.2093

Example

Barometric pressure is 30.26 inches; *therefore,* 30.26 x 25.40 x 0.2093 = 160.9 mmHg

Several apps available…auto conversion


PSIG
0
5
10
15
20
25
30
kg/cm


ROYAL
DEPTH
FEET OF SEA WATER
0
20
40
60
80
100
120
140
160
180
200
220
230
OCEANEERING
CALIBRATED
WEKSLER INSTRUMENTS


OXYGEN
ft. sea water
m. sea water
0
40
80
120
160
200
230
10
20
30
40
50
60
70

SUMMARY
CALCULATIONS & GAS LAWS

FSW to PSI**<u>G</u>** = depth (fsw) x 0.445
FSW to PSI**<u>A</u>** = depth (fsw) x 0.445 + 14.7
FSW to Absolute Pressure = $\frac{\textbf{FSW + 33}}{\textbf{33}}$

PSIG to FSW = psig x 2.24
PSIG to PSIA = psig + 14.7
PSIG to Absolute Pressure = $\frac{\textbf{PSIG + 14.7}}{\textbf{14.7}}$

BOYLE'S LAW (Pressure-Volume Law)

- Pressure (absolute) x Volume = Constant

$$\mathbf{P} \times \mathbf{V} = \mathbf{K}$$

DALTON'S LAW (Partial Pressure Law)

- Pressure (absolute) x gas in question (decimal)
  = partial pressure of that gas

HENRY'S LAW (Solubility Law)

- Gas dissolves a liquid in direct proportion to its partial pressure

GAY-LUSSAC'S LAW (Temperature Law)

- Changes in temperature and pressure are directly proportional

TCOM BAROMETER CALIBRATION

- Barometric pressure (mmHg) x 0.2093 (or 0.21)
  Inches to mmHg x 25.4