Henry's Law and the Bends

Scuba divers must be very conscious of Caisson's disease, commonly called 'The Bends'.

The Bends is a nitrogen solubility problem. Since the air we breathe is 78% nitrogen, nitrogen is dissolved in all of our tissues. The amount of nitrogen dissolved is related to atmospheric pressure.

Henry's law describes the amount of dissolved nitrogen. Henry's law states that the solubility of a gas in a liquid is proportional to the pressure of the gas over the solution. Henry's law in equation form:

$$P = Hv * M$$

Where P is the partial pressure of the gas, H_v is the Henry's law proportionality constant and M is the molar concentration of the gas in solution. Table 1 contains some common Henry's law constants at 25°C.

Table 1: Molar Henry's Law Constants for Aqueous Solutions at 25°C

Gas	Constant (atm/(mol/liter))
He	2865.00
O_2	756.70
N_2	1600.00
H_2	1228.00
CO_2	29.76
NH_3	56.90

Nitrogen is 78% of the standard atmosphere. Nitrogen's partial pressure then at sea level is 78% of 1 atmosphere, or 0.78 atmospheres. The solubility of nitrogen at sea level and 25°C can be determined using Henry's Law:

$$P_{N_2} = Hv * M$$

$$M = \frac{P_{N_2}}{Hv}$$

$$M = \frac{0.78 atm.}{\frac{1600 atm.}{mol/liter}} = 4.88e-4M$$

At standard conditions, there are 0.000488 moles of nitrogen dissolved in every liter of blood. Doesn't sound like a large amount, you say? Well if that quantity were converted to a gas at those conditions, they would occupy *15 mL* for every L of blood.

$$PV = nRT$$

$$V = \frac{nRT}{P}$$

$$V = \frac{[4.88e-4\,moles] \cdot \left[0.0821\left(\frac{L * atm.}{mol * K}\right)\right] \cdot [298K]}{0.78atm.} = 0.015L * \frac{1000mL}{L} = 15ml/L$$

As the pressure of the atmosphere increases, so does the solubility of all gases. Since nitrogen is found in such a large concentration in our atmosphere, it presents a problem.

As scuba divers dive to deeper depths, the pressure of air they breathe must match the pressure of the water around them. This increase in air pressure increases the solubility of nitrogen.

Nitrogen is essentially chemically inert; it does not like to react. Therefore, the increased soluble nitrogen is not a chemical problem but a physical problem. If the high pressure making nitrogen dissolve is rapidly lowered or removed, the nitrogen becomes insoluble and returns to its gaseous state-as gas bubbles. These gas bubbles are trapped in the tissues and blood stream in a process called 'aeroembolism'. The bubbles can be transported to vital tissues such as your brain where they cause serious problems. Understanding nitrogen and its solubility are key to making sense of the phenomenon known as 'the Bends'.

In the following activity, you will investigate the amount of nitrogen dissolved in your blood as a scuba diver diving to a depth of 20 meters below the ocean surface.

Through a series of operations, you will construct and complete table two on STAT EDIT of your graphing calculator.

Table 2: Dive data.

L_1	L_2	L_3	L_4	L_5	L_6
Depth	**Total Pressure**	**Partial Pressure of Nitrogen**	**Solubility of Nitrogen**	**Partial Volume of Nitrogen**	**Total Volume of Nitrogen**
(m)	*(atm.)*	*(atm.)*	*(grams N_2/18g H_2O)*	*(mL N_2/L of blood)*	*(mL)*
0					
2					
4					
6					
8					
10					
12					
14					
16					
18					
20					

Assumptions

To simplify the calculations, we will make the following assumptions.

1. The external pressure on the diver is a function of the pressure of the atmosphere plus the pressure due to the column of water above the diver.
2. The pressure of the air used by the diver is equal to the external pressure on the diver.
3. The composition of the air in the diver's tank is identical to that found in the standard atmosphere (21% O_2, 78%N_2)
4. The water temperature remains a constant 25°C at any depth and the water density remains a constant 1,000 Kg/m^3.
5. Dissolved nitrogen remains in the blood stream and does not diffuse into any body tissue.
6. Corrections will NOT be made for physiological temperatures.

Procedure

1. Set the calculator MODE to FLOAT. Clear any data from lists 1-6 (L_1-L_6) in the STAT EDIT of your calculator.

2. Enter the depth increments into list L_1 on your calculator.

3. The total pressure at any depth is the pressure of the atmosphere plus the pressure of the water.

$$P_{total} = 1atm. + \rho gh$$

Where ρ = water's density (1,000 Kg/m^3), g = acceleration due to gravity (9.81 m/sec^2), and h = the height of the water column in meters. List L_2 is a calculation based upon list L_1. Using the above information, the equation for L_2 should be:

$$L_2 = 1atm. + (1{,}000\frac{Kg}{m^3} \cdot 9.81\frac{m}{\sec^2} \cdot L_1(m)) \cdot (\frac{1atm.}{101325Pa})$$

If you have performed the calculation correctly, list L_2 should have matching values for each L_1 value, and the value for 20 meters should be 2.94 atm.

4. Nitrogen's partial pressure is 78% of the total pressure. The equation for list L_3 is:

$$L_3 = L_2(atm.) \cdot 0.78$$

5. To determine the solubility of nitrogen, Henry's law must be applied in calculating list L_4.

$$P_{N_2} = Hv * M$$

$$M = \frac{P_{N_2}}{Hv}$$

$$L_4 = \frac{L_3(atm.)}{\frac{1600\,atm.}{mol/liter}} \cdot (\frac{28g}{1mol})$$

6. To determine nitrogen's partial molar volume we assume the diver goes from the conditions of the dive depth to standard atmospheric conditions instantaneously and the dissolved nitrogen is completely converted to gaseous nitrogen. To determine the volume of nitrogen we apply the ideal gas law taking into consideration that the amount of nitrogen converted to gas is any mass greater than its standard solubility.

$$PV = nRT$$

$$V = \frac{nRT}{P}$$

$$L5 = \frac{\left[\dfrac{L4 - 0.0137g}{28\dfrac{g}{mol}}\right]\cdot\left[0.0821\dfrac{L\cdot atm.}{mol\cdot K}\right]\cdot[298K]}{1atm.}\cdot\left[\frac{1000mL}{1L}\right]$$

7. In order to calculate the total volume of nitrogen in the diver (you), the amount of water in your blood must be determined. Using your weight in pounds, the following formula will determine the average volume of water in your blood).

$$L_{H_2O} = Weight(lb.)\cdot\frac{1Kg}{2.2lb.}\cdot\frac{0.0382L}{1Kg}$$

8. The total volume of nitrogen expanded in your bloodstream at each depth is:

$$L6 = L5\left(\frac{mL_{N_2}}{1L_{H_2O}}\right)\cdot L_{H_2O}$$

9. When your calculations are completed correctly, the first five columns of the STAT EDITor for the 20m depth should be similar to those in table 3 (*note:* some values have been rounded).

Table 3: Example Data for 20 meters depth.

L_1	L_2	L_3	L_4	L_5	L_6
Depth	**Total Pressure**	**Partial Pressure of Nitrogen**	**Solubility of Nitrogen**	**Partial Volume of Nitrogen**	**Total Volume of Nitrogen**
(m)	*(atm.)*	*(atm.)*	*(grams N_2/18g H_2O)*	*(mL N_2/L of blood)*	*(mL)*
20	2.94	2.29	0.0401	23.07	

Graphical Analysis

1. Construct a graph of solubility of nitrogen vs. depth. Calculate and record a linear regression equation to fit the graph.
2. Construct a graph of total volume of nitrogen vs. depth. Calculate and record a linear regression equation to fit the graph. Also, record the equation for two of your classmates.

Findings

1. Explain the non-zero intercept for the graph of solubility of nitrogen vs. depth. Shouldn't it be zero?
2. What is the rate of nitrogen solubility with depth?
3. Explain the similarities and differences in your linear regression equation for total volume of nitrogen vs. depth from your classmates. What would it mean if the equations were exactly the same?
4. Describe a common gas filled object whose volume is close to equal the volume of nitrogen in your blood at 20 meters depth.
5. Depths greater 30 meters, and sometimes shallower, nitrogen affects the diver's nervous system with results similar to intoxication. This is called *nitrogen narcosis*. It does not happen suddenly but increases by degrees with increasing depth. It is not a permanent or traumatic condition, but it is known to impair judgment seriously. At 30 meters, it can be very noticeable, another reason 30 meters has been established as a maximum depth for sport diving. Determine the nitrogen solubility at 30 meters.
6. A 250-pound man and his 95-pound son dive to a depth of 15 meters below sea level. Whom has the greater amount of nitrogen dissolved in their bloodstream? How much more nitrogen?
7. Who is at a greater risk of The Bends, the man, or his son?
8. Why is it that submarine workers are exempt from the effects of The Benz?
9. Why are the risks due to solubility from other atmospheric gases like oxygen (O_2) and carbon dioxide (CO_2) so much smaller than nitrogen?

Extension

Research the phenomenon called 'The Bends' (Caisson's disease) and answer the following questions with complete explanations:

What is the history behind the disease and its many names?
Is the phenomenon limited only to divers?
What are the health implications?
How is it treated?
How can it be prevented?