Recreational Scuba Diving Theoretical Nitrogen Volume (Introduction)

In Scuba Diving, dive tables and dive computers are used to determine how much nitrogen has been absorbed by the diver's body during diving. Because of the increased pressure experienced during diving, nitrogen dissolves at a faster rate into the diver's body. Too much nitrogen dissolving into tissue puts the diver at risk of decompression sickness. Theoretical nitrogen levels are calculated through dive computers and dive tables.

Dive computers measure and record the depths and pressure a diver experiences. Dive computers are the most reliable tool to record dive times. While dive computers are sometimes too costly for leisure diver's use, dive tables can be used to calculate safe dive depth and times to avoid misafe levels of nitrogen in the system. Dive tables are less accurate than dive computers because they measure the dive as if the diver was level at the bottom depth for the entire dive. When using dive tables, divers are not able to dive as deep or for as long as divers with computers.

I have my open water certification and I have only used dive tables on my dives. This has restricted the time and depth of my dives. On a recent dive I accidentally exceeded the recommended dive depth by 10 meters. I was diving with my dive buddy who was using a dive calculator. This could have potentially jeopardized my safety because the theoretical amount of nitrogen in my bloodstream was not accurately calculated. There is a large discrepancy between the time and depth that a table diver and a diver with a dive computer can dive. While it is unlikely that a greater amount of nitrogen had dissolved into my bloodstream than my dive buddy, the theoretical level of nitrogen might have been higher and my safety and subsequent dives might have been jeopardized.

By creating a formula, to determine a more accurate representation of theoretical nitrogen levels with different constants, divers will be able to dive longer and safer than if they just used a dive table. Although these theoretical calculations will not be as accurate as dive computers they will be more reliable than dive tables. Two formulas are presented. The first formula is less conservative and incorporates depth and weight of a diver and the second formula is more conservative by considering depth, weight of diver, salinity, and temperature. These variables will be used to calculate the volume of nitrogen that is dissolved within body tissue.

Creating a simplified, less conservative model:

This model only takes depth and weight of the diver into consideration. For this equation the temperature constant is 25º Celcius.

Pressure increases by 1 atm with each 10m descent. Since the density of seawater is approximately 1025 kg/m^2 to calculate L_2, Total Pressure, the following formula is used:

L_2 = 1 atm. + $(1025\frac{kg}{m^3} \cdot 9.81\frac{m}{sec^2} \cdot L_1(m)) \cdot (\frac{1atm.}{101325Pa})$

The partial pressure of N_2 is the percentage of N_2 in the air is multiplied by the atmospheric pressure units (atm.) of the water. Since the atmosphere of the earth constitutes of 78% N_2 the formula to find the partial pressure of N_2 is:

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

The solubility of N_2 is determined by using Henry's Law. Henry's Law states that the amount of a gas in a liquid is directly proportional to the partial pressure of that gas, at a constant temperature.

The formula for Henry's Law is:

$P_{N_2} = Hv \cdot M$

P_{N_2} is the partial pressure of N_2

Hv is the Henry's Law Constant

M is the molar concentration of the gas

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

When the temperature remains constant at 25º Celsius the molar concentration of N_2 is 1600.00 $(\frac{atm.}{(\frac{mol}{liter})}$). Since L_3 is the partial pressure of N_2 the equation can be rewritten as:

$$L_4 = \frac{L_3(atm.)}{(\frac{1600\ atm.}{\frac{mol}{liter}})}$$

The equation is then multiplied by $\frac{28g}{1mol}$ so that the answer is in grams of $N_2/\ 18g\ H_2O$.

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

The partial volume of N_2 is found using the ideal gas law formula PV = $n \cdot$RT

This equation can be rewritten as $V = \frac{n \cdot RT}{P}$

P is the absolute pressure of N_2 which is equal to 1 atm.

V is the volume of N_2

n is the amount of the gas which can be found using the formula $(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})$

R is the gas constant which is $(0.0821\frac{L \cdot atm.}{mol \cdot K})$ for N_2

T is the absolute temperature of N_2 is 298 K

The equation for partial volume of N_2 is:

$$L_5 = \frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}}) \cdot (0.0821\frac{L \cdot atm.}{mol \cdot K}) \cdot 298\ K}{1\ atm.}$$

The equation is then multiplied by $\frac{1000mL}{1L}$ so that it is mL of N_2 / L of blood.

$$L_5 = \frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}}) \cdot (0.0821\frac{L \cdot atm.}{mol \cdot K}) \cdot 298\ K}{1\ atm.} \cdot \frac{1000mL}{1L}$$

To find the total volume of N_2 dissolved in the bloodstream of a diver the weight in kg is needed. For every kg of weight we have 0.0382 L of blood. The equation to find the amount of blood in relation to weight is:

$$b = weight \cdot \frac{0.0382\ L}{1\ kg}$$

This equation can then be used to find the total volume is:

$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$

These equations can be used to determine total volume of N_2 in a diver's body at different depth with a constant temperature.

L_1	L_2	L_3	L_4	L_5	L_6
Depth (m)	Total Pressure (atm.)	Partial Pressure of N_2 (atm.)	Solubility of N_2 (grams N_2 / 18g H_2O)	Partial Volume of N_2 (mL N_2 / L of blood)	Total Volume of N_2 (mL)
0	1	0.78	0.1365	0	0
5	1.50	1.17	0.0204	5.87	$L_5 \cdot w + 0.224$
10	1.99	1.55	0.0272	11.8	$L_5 \cdot w + 0.450$
15	2.48	1.94	0.0340	17.7	$L_5 \cdot w + 0.677$
20	2.98	2.33	0.0407	23.6	$L_5 \cdot w + 0.903$
25	3.48	2.72	0.0475	29.5	$L_5 \cdot w + 1.13$
30	3.98	3.10	0.0543	35.5	$L_5 \cdot w + 1.35$
35	4.47	3.49	0.0611	41.4	$L_5 \cdot w + 1.58$
40	4.97	3.88	0.0678	47.3	$L_5 \cdot w + 1.81$

Line of best fit was used to calculate the relationship between Depth (m) and Partial Volume of N_2 (mL N_2 / L of blood):

$L_5 = 1.18D + -0.036$

Therefore the total volume of N_2 in a diver's body with a non constant value for depth and weight can therefore be found using the formula:

Total Volume of N_2 (mL) $= (1.18D + -0.036) \cdot (weight \cdot \frac{0.0382\,L}{1\,kg})$

Creating a more accurate, conservative model:

This model takes depth, temperature, salinity, and the weight of the diver into consideration.

Since depth is the only determinant of total pressure the same formula can be used to represent total pressure:

L_2 = 1 atm. + $((1025\frac{kg}{m^3} \cdot 9.81\frac{m}{sec^2} \cdot L_1(m)) \cdot (\frac{1atm.}{101325Pa}))$

The partial pressure of N_2 is the percentage of N_2 in the air multiplied by the atm. of the water. The atmosphere of the earth consists of 78% N_2. The formula to find the partial pressure of N_2 does not include other variables but the saturation of nitrogen in seawater is also influenced by chlorinity, salinity, and temperature.

The number of mols of N_2 in one liter of water is determined by the average saturation values of nitrogen in seawater. The salinity percentage has essentially no effect on the saturation values of N_2. By averaging the a and b values of the line of best fit found when comparing temperature, salinity, chlorinity and nitrogen saturation the effect of temperature, salinity, and chlorinity on nitrogen saturation can be determined. The average line of best fit to three significant figures in mL per L of water is $y = -0.208c + 14.1$ (mL).

SATURATION VALUES OF NITROGEN IN SEA WATER (ml/L)* FROM NORMAL DRY ATMOSPHERE (Rakestraw and Emmel, 1938b)

Chlorinity (‰)	**15**	**16**	**17**	**18**	**19**	**20**	**21**
Salinity (‰)	**27.11**	**28.91**	**30.72**	**32.52**	**34.33**	**36.11**	**37.94**
Temperature (°C)							
0	15.22	15.02	14.82	14.61	14.40	14.21	14.01
5	13.43	13.26	13.10	12.94	12.78	12.62	12.45
10	12.15	12.00	11.86	11.71	11.56	11.42	11.27
15	11.04	10.92	10.79	10.66	10.53	10.39	10.26
20	10.08	9.98	9.87	9.76	9.65	9.54	9.43
25	9.30	9.21	9.11	9.02	8.92	8.82	8.73
28	8.89	8.84	8.72	8.62	8.53	8.44	8.35

The line of best fit was found for temperature and saturation of N_2, chlorinity and saturation of N_2, salinity and saturation of N_2. The a and b values of these lines of best fit were averaged. The effect of chlorinity, salinity, and temperature to three significant figures in mL per L of water is $y = -0.208c + 14.1$ (mL).

The relationship between oxygen and temperature, chlorinity, and salinity was found using the saturation values in seawater.

SATURATION VALUES OF OXYGEN IN SEA WATER (ml/L)* FROM NORMAL DRY ATMOSPHERE (Fox, 1907)

Chlorinity (‰)	**15**	**16**	**17**	**18**	**19**	**20**
Salinity (‰)	**27.11**	**28.91**	**30.72**	**32.52**	**34.33**	**36.11**
Temperature (°C)						
−2	9.01	8.89	8.76	8.64	8.52	8.39
0	8.55	8.43	8.32	8.20	8.08	7.97
5	7.56	7.46	7.36	7.26	7.16	7.07
10	6.77	6.69	6.60	6.52	6.44	6.35
15	6.14	6.07	6.00	5.93	5.86	5.79
20	5.63	5.56	5.50	5.44	5.38	5.31
25	5.17	5.12	5.06	5.00	4.95	4.86
30	4.74	4.68	4.63	4.58	4.52	4.46

* mg-atoms of oxygen per liter = 0.08931 × ml/L.

The formula for the amount of oxygen (mL per L of water) in seawater is $y = -0.127c + 8.12\ (mL)$.

The equation of partial pressure is

$$partial\ pressure\ of\ gas = total\ pressure\ of\ all\ gases \cdot \left(\frac{number\ of\ mL\ of\ gas}{number\ of\ mL\ of\ all\ gases}\right).$$

Therefore the formula for partial pressure of N_2 is:

$$L_3 = (L_2) \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$$

With the variable c for Celsius.

The solubility of N_2 is affected by temperature. Given the data set below, the line of best fit, indicating the solubility of N_2 at various temperatures, is $y = 1.6216 \cdot 10^{-5} + -1.688 \cdot 10^{-7}c$. This equation has an r value of 0.993 indicating that there is a strong positive relationship between the points given and the linear equation.

Gas	***T*/K**	**Solubility (X_1)**
Nitrogen (N_2)	288.15	1.386×10^{-5}
$M_r = 28.0134$	293.15	1.274×10^{-5}
	298.15	1.183×10^{-5}
	303.15	1.108×10^{-5}
	308.15	1.047×10^{-5}

The product of partial pressure of N_2 and the solubility of N_2 at various temperature is the total solubility of N_2 at any given temperature.

$$L_4 = S_{N1} = K_H P_{N1} = L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$$

Since this formula has already converted mL into L and since no other determinants were taken into consideration to find the partial volume of N_2 the formula from the less conservative model can be used but instead of multiplying it my $1000mL$ it can be multiplied by 10mL:

$$L_5 = \frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}}) \cdot (0.0821 \frac{L \cdot atm}{mol \cdot K})}{1\ atm.} \cdot 10mL$$

The same is true for the total volume of N_2 dissolved in the bloodstream of a diver the weight in kg is needed. For every kg of weight we have 0.0382 L of blood. The equation to find the amount of blood in relation to weight is:

$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight\ \cdot \frac{0.0382\ L}{1\ kg})$

These equations can be used to determine total volume of N_2 in a diver's body at different depths, temperatures, salinity, and chlorinity.

L_1	L_2	L_3	L_4
Depth (m)	Total Pressure (atm.)	Partial Pressure of N_2 (atm.)	Solubility of N_2 (grams N_2 / 18gH_2O)
0	1	$(\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
5	1.50	$1.50 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
10	1.99	$1.99 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
15	2.48	$2.48 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
20	2.98	$2.98 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
25	3.48	$3.48 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
30	3.98	$3.98 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
35	4.47	$4.47 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$
40	4.97	$4.97 \cdot (\frac{-0.208c+14.1}{-0.335c+22.2})$	$L_3 \cdot ((\frac{-0.208c+14.1}{-0.335c+22.2}) \cdot 760mm\ Hg)$

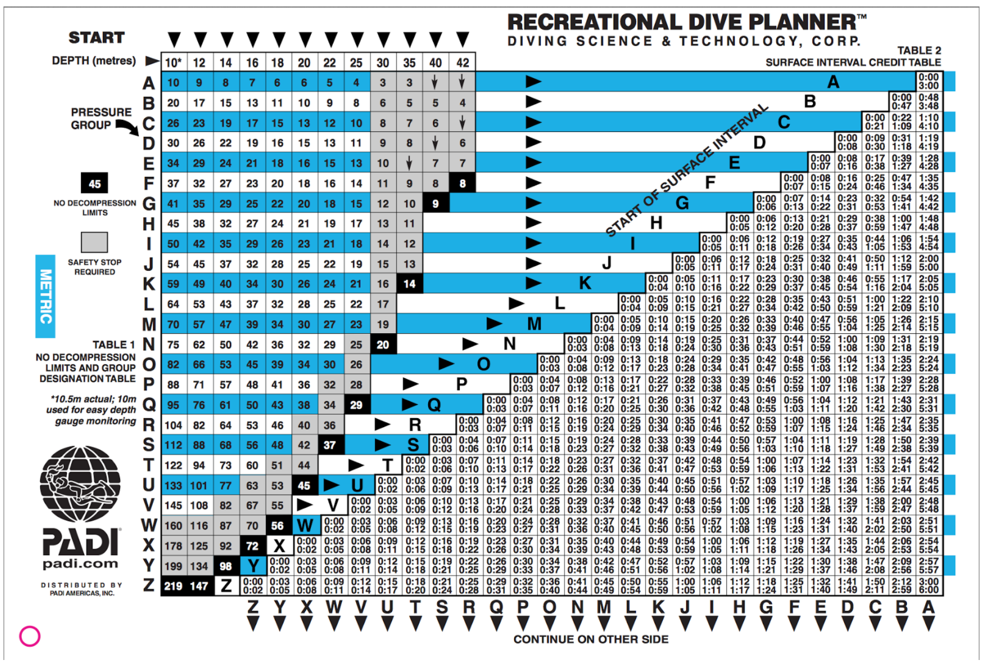
L_5	L_6
Partial Volume of N_2 (mL N_2 / L of blood)	Total Volume of N_2 (mL)
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$
$\frac{(\frac{L_4 - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot \frac{1000mL}{1L}$	$L_6 = L_5(\frac{mLN_2}{1LH_2O}) \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$

The total volume of N_2 in a diver’s body with a non constant value for depth, temperature, and weight can therefore be found using the formula:

$$V_{N_2} = \frac{(\frac{1\ atm. + ((1025\frac{kg}{m^3}\cdot 9.81\frac{m}{sec^2}\cdot D(m))\cdot(\frac{1atm.}{101325Pa}))\cdot(\frac{-0.208c+14.1}{-0.335c+22.2})\cdot((\frac{-0.208c+14.1}{-0.335c+22.2})\cdot 760mm\ Hg) - 0.0137g}{28\frac{g}{mol}})\cdot(0.0821\frac{L\cdot atm}{mol\cdot K})}{1\ atm.} \cdot 10mL \cdot (weight \cdot \frac{0.0382\ L}{1\ kg})$$

Applying the formula:

The recreational dive planner (RDP) is used to calculate the amount of nitrogen in a divers blood stream and then give the maximum time a diver has to wait between dives called a surface interval. To calculate the surface interval of a diver the depth the maximum depth and total time a diver dove is needed. The total volume of nitrogen found in a diver's body previously calculated is equal for each of the total time a diver can stay at that depth. That is the black box in the RDP called no decompression limits. The pressure groups (A-Z) represent the theoretical nitrogen level in a diver. In order to find the surface interval with the formulas calculated for theoretical nitrogen levels the exact value of the pressure groups is needed. With the average weight of a person at 188 pounds, a ratio between volume, time, and depth can be calculated.



Only the nitrogen levels corresponding with the no decompression levels could be calculated. The formula for total volume of nitrogen is used: Total Volume of N_2 (mL)

$$= (1.18D + - 0.036) \cdot (weight \cdot \frac{0.0382\,L}{1\,kg}).$$

Pressure group	F	G	K	N	Q	S	U	W	X	Y	Z

Theoretical Nitrogen Level	355 mL	339 mL	296 mL	254 mL	212 mL	186 mL	169 mL	152 mL	135 mL	118 mL	102 mL

These values are then multiplied by the $\frac{\textit{no decompression limit}}{\textit{depth}}$ to find the volume of nitrogen at different pressure groups.

Pressure group	F	G	K	N	Q	S	U	W	X	Y	Z
Theoretical Nitrogen Level	67.6 mL	79.3 mL	118 mL	169 mL	246 mL	276 mL	380 mL	473 mL	608 mL	826 mL	1250 mL

Either formula can be used to calculate the theoretical nitrogen level in order to determine the pressure group is known. If the theoretical nitrogen level is between two of the pressure group values it should be rounded up the the next pressure group.

These pressure group help determine the surface interval using the dive tables.
To support that the second formula is in fact more conservative the nitrogen levels of two randomly selected dives were calculated.

Dive 1

Depth (m)	Temperature (C)	Weight
22	19	143

Formula One	Formula Two
142 mL	159 mL

Pressure Group N	Pressure Group N

There is no pressure group difference between the two formulas. The volume of Nitrogen can not be found solely using the dive table with the data given.

Dive 2

Depth (m)	Temperature (C)	Weight
13	16	124

Formula One	Formula Two
72.5 mL	98.9 mL
Pressure Group G	Pressure Group K

There is approximately 22 minutes difference between these two pressure groups . The second formula is more conservative since it incorporates more determinants and yields a higher volume of Nitrogen.

Reflection:

I choose this topic because I have recently earned my Open Water Diver SCUBA Certification. Since I have only gone on sixteen dives in the last twelve months, I have not yet invested in a dive computer. As a table diver, I am restricted in depth and time on my dives. By creating a formula to represent the theoretical nitrogen level in my blood I should be able to safely dive past my table diver restrictions. This would be beneficial because I would be less likely to go on a dive that would put me in danger since I would be able to plan the level of nitrogen in my blood.

When researching this topic, I found that it was very difficult to account for all of the determinants in scuba diving. Most formulas available only represent values at 1 atm. which made it difficult to incorporate all of the determinants. The formula calculated is very impractical to use when diving. It is more logical to use a dive table, not the formula, since calculators are not taken onto dive boats.

I attempted to create a formula that would be very simple to use. The formula was designed to incorporate more variables than the dive table in order to calculate a more accurate representation of theoretical nitrogen levels in blood. I successfully made two formulas to represent the theoretical volume of nitrogen in blood. While these formulas are impractical to use on a scuba trip they are more conservative than theoretical levels of nitrogen found using a dive table. The use of the formulas was difficult because the dive table does not express the volume of nitrogen in the blood, it solely expresses the recommended surface interval. It was only possible to find some of the theoretical nitrogen levels which makes the models less conservative and allows for greater error. If there was a way to determine the rate for which a certain volume of nitrogen at a given depth and pressure dissolved into the bloodstream then these formulas would be able to be used. A formula that could determine this rate is from Fick's First Law but the surface area of the diver is needed along with other variables that can not be determined.

I had hoped to create a formula to represent a more accurate representation of the theoretical nitrogen levels in blood. While unsuccessful, I was able to learn more about the variables that affect scuba diving.

Conclusion:

Using a combination of the second formula and dive tables a more conservative pressure group should have been calculated. However, the theoretical nitrogen levels found are very similar and result in approximately the same amount of surface interval time. The second formula calculated is impractical for use on a scuba trip. The calculation would be difficult to find without a calculator. The first formula calculated is more practical to use but it is still not as simple as the dive table. Although these formulas offer a more accurate theoretical volume of nitrogen in blood they are impractical to use when scuba diving. The dive table allows you to find a very similar value that requires no calculations.

The only way to expand and find a more accurate representation of the pressure groups and a safe surface interval, the rate at which Nitrogen dissolves is needed. Once this is determined, the formulas can be used to determine the rate that Nitrogen dissolves. This will allow for a more accurate representation of the theoretical amount of nitrogen in the blood.

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