DECOMPRESSION THEORY - NEO-HALDANE MODELS

This section describes the Haldane or neo-Haldane decompression theories. On each dive the divers body takes up inert gasses, like Nitrogen. After the dive the divers body is 'supersaturated' with inert gas and has to get rid of this excess gas (decompression). Decompression theories predict the inert gas uptake by the body (divided in hypothetical tissue compartments). Furthermore, they define limits (M-values) which apply to the supersaturation of each tissue compartment. If supersaturation values exceed these limits, decompression sickness (DCS) symptoms develop. The modeling of the gas uptake and these limits enable calculation of diving tables, decompression profiles and simulation by diving computers.

History

In modern diving, tables and schedules are used for estimating no- decompression limits, decompression profiles and saturation levels. Use of a diving computer during the dive is most common nowadays. Tables and computers are based on decompression theory, which describes inert gas uptake and saturation of bodily tissue when breathing compressed air (or other gas mixtures). The development of this theory was started in 1908 by John Scott Haldane c.s. Haldane, an English physiologist, described the Nitrogen saturation process by using a body model which comprises several hypothetical tissue 'compartments'. A compartment can be characterized by a variable called 'half-time', which is a measure for the rate of inert gas uptake. Theory was further developed during the years '50 and '60 by U.S. Navy. The concept of 'M-values' was developed by Robert D. Workman of the U.S. Navy Experimental Diving Unit (NEDU). In the early '70s Schreiner applied the theory to changing pressure (ascending/descending). Recently Bühlmann improved the theory and developed ZH-12L and ZH-16L model, which are quite popular in current diving computers. At this moment a lot is still unknown about the exact processes which take place during saturation and decompression. Most of the theory presented has been found empirically, i.e. by performing tests on human subjects in decompression chambers and from decompression accident statistics. Recently, a more physical approach resulted in bubble theories. These theories physically describe what is happening during decompression.

Inert gas saturation and supersaturation

When you breathe a breathing gas that contains an inert gas (gasses which do not take part in the oxidative metabolism and are not 'used' by the body) like Nitrogen (N_2) or Helium (He_2), this gas is dissolved in the blood by means of gas exchange in the lungs. Blood takes the dissolved gas to the rest of the bodily tissue. Tissue takes up dissolved gas from the blood. Gas keeps on dissolving in blood and tissue until the partial pressure of the dissolved gas is equal to the partial pressure of the gas breathed in, throughout the entire body. This is called saturation. Rates of saturation vary with different parts of the body. The nervous system and spine get saturated very fast (fast tissues), whereas fat and bones saturate very slowly (slow tissues).

When staying at sea level for a long time, like most of us do, and breathing air, again like most of us do, the entire body is saturated with Nitrogen, which makes up the air for 78%. Since at sea level air pressure is roughly 1 bar (we can neglect barometric air pressure variations, which are expressed in millibar), the partial pressure of the dissolved Nitrogen thoughout the entire body is 1 bar * 78%=0.78 bar (actually it is a bit less, as we will see later, but for the moment this will do). If a diver dives to 20 meter, he breathes air at 3 bar. Partial Nitrogen pressure in the air he breathes is 3 bar * 78% = 2.34 bar. If the diver sits down and wait for quite a long time, the diver's body gets saturated with Nitrogen at a partial pressure of 2.34 bar (the fastest tissues saturate in 25 minutes, the slowest take two and a half day to saturate). So far, so good (at least if our diver has enough air supply). If the diver goes back to the surface, however, he arrives with his body saturated with Nitrogen at a partial 2.34 bar pressure, whereas the air he breathes at the surface has a partial Nitrogen pressure of 0.78 bar. The body is supersaturated. Dissolved Nitrogen in the tissue and blood will go back to the free gas phase, in order to equalize the pressures. The Nitrogen forms micro bubbles, which are transported by the blood and removed from the body by the respiratory system. However, if to much Nitrogen goes back to the free phase, micro bubbles grow and form bubbles that may block veins and arteries. The diver gets bent and will develop decompression sickness (DCS) symptoms.

A certain amount of supersaturation is allowed, without getting bent (at least with low risk of getting bent). In fact, supersaturation (a pressure gradient) is needed in order to decompress (get rid of the excess Nitrogen). The amount of allowed supersaturation is different for various types of tissue. This is the reason the body is divided in hypothetical tissue 'compartments' in most decompression models. Each compartment is characterized by its half-time. This is the period the tissue takes a partial inert gas pressure which is half way between the partial pressure before and after a pressure change of the environment. Haldane suggested two compartments, recent theories (like ZH-16L) use up to 16 compartments. Decompression theory deals with two items:

1. Modeling the inert gas absorption in the bodily tissue
2. Estimate limits of supersaturation for each tissue, beyond which decompression sickness (DCS) symptoms develop

If these items are known, one can fill in tables, estimate no-decompression times, calculate decompression profiles, plan dives, etc.

Calculating inert gas absorption by the tissue

In this section we will derive the equations which describe inert gas uptake by bodily tissue. If you get frightened by a bit of mathematics, please skip the derivation, but have a look at the end result in the high lighted boxes (equation 8 and 13). The rate a particular tissue (compartment) takes up inert gas (i.e. the rate of change in partial pressure of that gas in the tissue) is proportional to the partial pressure difference between the gas in the lungs and the dissolved gas in the tissue. We can express this mathematically by:

$$\frac{dP_t(t)}{dt} = k[P_{alv}(t) - P_t(t)] \tag{1}$$

$P_t(t)$	Partial pressure of the gas in the particular tissue (bar)
$P_{alv}(t)$	Partial pressure of the gas in the breathing mix. To be precise: Gas exchange takes place in the lungs (alveoli). Hence, we have to consider the gas alveolar partial pressure. This pressure may be changing with time, if the diver changes depth (bar)
k	A constant depending on the type of tissue (min^{-1})
t	Time (min)

This is a differential equation which is quite familiar in physics and which applies to many processes like diffusion and heat transfer. Solving this equation requires following steps:

Step 1: Write the equation 1 to the familiar form (a.k.a. the inhomogenous differential equation):

$$\frac{dP_t(t)}{dt} + kP_t(t) = kP_{alv}(t) \tag{2}$$

Step 2: Solve the homogenous equation 3 by trying $P_{th}(t) = C_0 e^{-\lambda t}$ and solve for λ.

$$\frac{dP_{th}(t)}{dt} + kP_{th}(t) = 0 \tag{3}$$

The 'h' in P_{th} denotes that we are dealing with the homogenous equation. Substituting the solution in 3 results in $\lambda = k$. So the homogenous solution of the equation 3 is:

$$P_{th}(t) = C_0 e^{-kt} \tag{4}$$

Step 3: Find the particular solution for the inhomogenous equation 1 and solve constants using boundary conditions. In order to solve this equation, we have to know more about the partial gas pressure $P_{alv}(t)$. Two useful situations described in literature are a situation in which $P_{alv}(t)$ is constant (corresponding to remaining at a certain depth) and a situation in which $P_{alv}(t)$ varies linearly with time (corresponding to ascending/descending with constant speed). We will have a look at both situations.

Situation 1: constant ambient pressure

We look at the situation in which the alveolar partial pressure of the gas remains constant: $P_{alv}(t) = P_{alv0}$. This corresponds to a diving situation in which the diver remains at a certain depth. Equation 2 becomes:

$$\frac{dP_t(t)}{dt} + kP_t(t) = kP_{alv0} \tag{5}$$

We 'try' the solution:

$$P_t(t) = C_0 e^{-kt} + C_1 \tag{6}$$

If we subsitute solution 6 in equation 5 the e's cancel out and we are left with $C_1 = P_{alv0}$. Now we have to think of a boundary condition, in order to find C_0. We assume some partial pressure in the tissue $P_t(0) = P_{t0}$ at $t = 0$. If we substitute this into equation 6 we find that $C_0 = [P_{t0} - P_{alv0}]$. So we are left with the following equation for the partial pressure in a specific type of tissue (characterized by the constant k):

$$P_t(t) = P_{alv0} + [P_{t0} - P_{alv0}]e^{-kt} \tag{7}$$

$P_t(t)$	Partial pressure of the gas in the particular tissue (bar)
P_{t0}	Initial partial pressure of the gas in the tissue at $t = 0$ (bar)
P_{alv0}	Constant partial pressure of the gas in the breathing mix in the alveoli (bar)
k	A constant depending on the type of tissue (min^{-1})
t	Time (min)

This equation is known in literature as the *Haldane equation*. We can rewrite it a bit so that it corresponds to a form which is familiar in decompression theory literature:

$$P_t(t) = P_{t0} + [P_{alv0} - P_{t0}](1 - e^{-kt}) \tag{8}$$

Situation 2: linearly varying ambient pressure

Very few divers plunge into the deep and remain at a certain depth for a long time. For that reason we will look at the situation in which the diver ascends or descends with constant speed. This means the partial pressure of the gas he breathes varies linearly with time. Going back to equation 1 this means P_{alv}

can be writen as $P_{alv} = P_{alv0} + Rt$. P_{alv0} is the initial partial pressure of the gas in the breathing mixture at $t = 0$, and R is the change rate (in bar/minute) of the partial pressure of this gas in the alveoli. Note: R is positive for descending (pressure increase) and negative for ascending (pressure decrease). Substituting this in equation 1 gives us:

$$\frac{dP_t(t)}{dt} + kP_t(t) = kP_{alv0} + kRt \tag{9}$$

We 'try' the solution:

$$P_t(t) = C_0 e^{-kt} + C_1 t + C_2 \tag{10}$$

Substituting solution 10 in equation 9 leaves us with:

$$[kC_1 - kR]t + [C_1 + kC_2 - kP_{alv0}] = 0 \tag{11}$$

To find a solution for C_1 and C_2 that hold for every t we have to make both parts between the square brackets in equation 11 equal to 0. This results in $C_1 = R$ and $C_2 = Palv0 - R/k$. In this way we find:

$$P_t(t) = C_0 e^{-kt} + Rt + P_{alv0} - \frac{R}{k} \tag{12}$$

Again we use as boundary condition $P_t(0) = P_{t0}$ at $t = 0$ in order to find C_0. Substituting this in 12 we find $C_0 = P_{t0} - P_{alv0} + R/k$. So for the ultimate solution we find:

$$P_t(t) = P_{alv0} + R\left[t - \frac{1}{k}\right] - \left[P_{alv0} - P_{t0} - \frac{R}{k}\right] e^{-kt} \tag{13}$$

$P_t(t)$	Partial pressure of the gas in the particular tissue (bar)
P_{t0}	Initial partial pressure of the gas in the tissue at $t = 0$ (bar)
P_{alv0}	Initial (alveolar) partial pressure of the gas in the breathing mix at t=0 (bar)
k	A constant depending on the type of tissue (min^{-1})
R	Rate of change of the partial inert gas pressure in the breathing mix in the alveoli (bar/min) $R = QR_{amb}$, in which Q is the fraction of the inert gas and R_{amb} is the rate of change of the ambient pressure.
t	Time (min)

This solution was first proposed by Schreiner and hence known as the *Schreiner equation*. If we set the rate of change R to 0 (remaining at constant depth), the equation transforms in the Haldane equation 7. The Schreiner equation is excellent for application in a simulation as used in diving computers. The dive is split up in measurement (time) intervals. In an interval the depth is regarded to vary linearly. With the same frequency of measuring of the environmental pressure and performing the calculation, applying the Schreiner equation gives a more precise approximation of the actual pressure profile in the bodily tissue than the Haldane equation.

Half-times

So we see an exponential behavior. When we look at the first situation (constant depth) we have a tissue with in initial partial pressure P_{t0}. Eventually the partial pressure of gas in the tissue will reach the partial pressure of the gas in the breathing mixture P_{alv0}. We can calculate how long it takes for the partial pressure to get half way in between, i.e. $e^{-k\tau} = 1/2$. The variable τ (tau) is called the 'half-time' and is usually used for characterizing tissue (compartments). Rewriting: $-k\tau = ln(1/2) = -ln(2)$. So the relation between k and the half-time τ is:

$$\tau = \frac{ln(2)}{k} \tag{14}$$

$$k = \frac{ln(2)}{\tau} \tag{15}$$

The alveolar partial pressure

So far we did not worry about the values of P_{alv}. We will have a closer look at this alveolar partial pressure of the inert gas and how it is related to the ambient pressure. The pressure of the air (or gas mixture) the diver breathes is equal to the ambient pressure P_{amb} surrounding the diver. The ambient pressure depends on the water depth and the atmospheric pressure at the water surface. To be precise: it is equal to the atmospheric pressure (1 bar at sea level) increased with 1 bar for every ten meters depth. The partial pressure of the inert gas in the alveoli depends on several factors:

- The partial pressure (fraction Q) of the inert gas in the air or gas mixture breathed in
- The water vapor pressure. The dry air breathed in is humidified completely by the upper airways (nose, larynx, trachea). Water vapor dilutes the breathing gas. A constant vapor pressure at 37 degrees Celsius of 0.0627 bar (47 mm Hg) has to be subtracted from the ambient pressure
- Oxygen O_2 is removed from the breathing gas by respiratory gas exchange in the lungs

- Carbon Dioxide CO_2 is added to the breathing gas by gas exchange in the lungs. Since the partial pressure of CO_2 in dry air (and in common breathing mixtures) is negligible, the partial pressure of the CO_2 in the lungs will be equal to the arterial partial pressure. This pressure is 0.0534 bar (40 mm Hg).

The process of Oxygen consumption and Carbon Dioxide production is characterized by the respiratory quotient RQ, the volume ratio of Carbon Dioxide production to the Oxygen consumption. Under normal steady state conditions the lungs take up about 250 ml of Oxygen, while producing about 200 ml of Carbon Dioxide per minute, resulting in an RQ value of about 200/250=0.8. Depending on physical exertion and nutrition RQ values range from 0.7 to 1.0. Schreiner uses $RQ = 0.8$, US Navy uses $RQ = 0.9$ and Bühlmann uses $RQ = 1.0$.

The alveolar ventilation equation gives us the partial pressure of the inert gas with respect to the ambient pressure:

$$P_{alv} = \left[P_{amb} - P_{H2O} - P_{CO2} + \Delta P_{O2}\right] Q \tag{16}$$

$$P_{alv} = \left[P_{amb} - P_{H2O} + \frac{1 - RQ}{RQ} P_{CO2}\right] Q \tag{17}$$

P_{alv}	Partial pressure of the gas in the alveoli (bar)
P_{amb}	Ambient pressure, i.e. the pressure of the breathing gas(bar)
P_{H2O}	Water vapor pressure, at 37 degrees Celsius 0.0627 bar (47 mm Hg)
P_{CO2}	Carbon Dioxide pressure, we can use 0.0534 bar (40 mm Hg)
ΔP_{O2}	Decrease in partial Oxygen pressure due to gas exchange in the lungs
RQ	Respiratory quotient: ratio of Carbon Dioxide production to Oxygen consumption
Q	Fraction of inert gas in the breathing gas. For example N2 fraction in dry air is 0.78

The Schreiner RQ value is the most conservative of the three RQ values. Under equal circumstances using the Schreiner value results in the highest calculated partial alveolar pressure and hence the highest partial pressure in the tissue compartments. This leads to shorter no decompression times and hence to less risk for DCS.

Examples

We will have a look at our diver who plunges to 30 m and stays there for a while. The diver breathes compressed air and did not dive for quite a while before this dive. So at the start of the dive, all his tissue is saturated with

Nitrogen at a level that corresponds to sea level. We neglect the period of descending. In particular, we will look at two types of tissue in his body with a half time of 4 minutes (the fastest tissue) resp. 30 minutes (medium fast tissue). The ambient pressure at 30 meters is 4 bar. Equation 17 gives us a partial alveolar N_2 pressure of 3.08 bar at 30 meters and 0.736 bar at sea level, using the $RQ = 0.9$ value of the US Navy. Substituting these values in equation 7 result in 18, predicting the partial pressure in the tissues. This pressure is shown in figure 1:

$$P_{t4}(t) = 3.08 + [0.736 - 3.08]e^{-\frac{ln(2)}{4}t} \tag{18}$$

$$P_{t30}(t) = 3.08 + [0.736 - 3.08]e^{-\frac{ln(2)}{30}t} \tag{19}$$

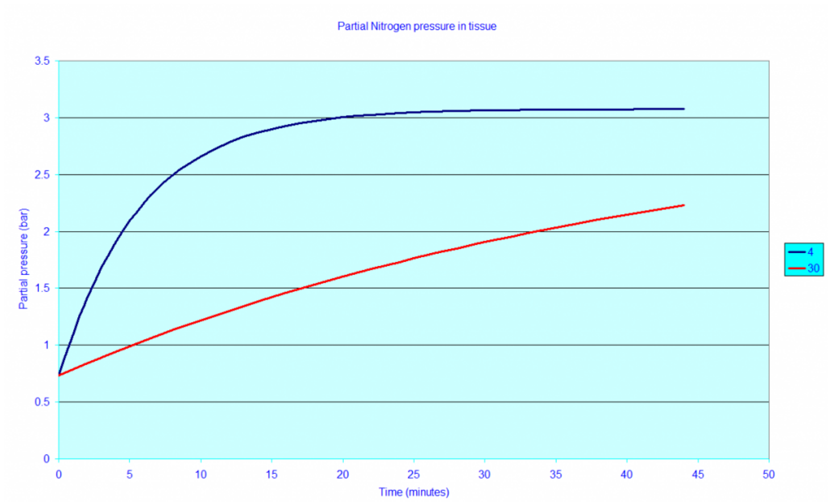

Figure 1: Partial Nitrogen pressure in tissue with half-times 4 and 30 minutes

Apparently, the faster tissue saturates much faster than the medium fast tissue. Usually, after 6 half-times the tissue is called saturated.

After 20 minutes at 30 meter our diver decides to head back to the surface at a very slow speed of -3 meter per minute (negative, since he is ascending). It takes 10 minutes to swim to the surface. The rate of change of partial alveolar pressure R is related to the change in ambient pressure R_{amb} and the fraction Q of the inertial gas by:

$$R = R_{amb}Q \tag{20}$$

In our example the ambient pressure drops -(4-1)=-3 bar in 10 minutes. This corresponds to $R_{amb} = -0.3bar/min$. The partial pressure change of the alveolar N_2 $R = -0.3 * 0.78 = -0.234 bar/min$. After 20 minutes at 30 meter, the partial N_2 pressure is given by 18 resp. 19 and is equal to 3.00 bar in the 4 min tissue and 1.60 bar in the 30 min tissue. Substituting this in equation 13 gives us equation 21 resp. 22 for the partial pressure of the N_2 in the tissues:

$$P_{t4}(t) = 3.08 - 0.234 \left[t - \frac{4}{ln(2)} \right] - \left[3.08 - 3.00 + 0.234 \frac{4}{ln(2)} \right] e^{-\frac{ln(2)}{4} t} \quad (21)$$

$$P_{t30}(t) = 3.08 - 0.234 \left[t - \frac{30}{ln(2)} \right] - \left[3.08 - 3.00 + 0.234 \frac{30}{ln(2)} \right] e^{-\frac{ln(2)}{30} t} \quad (22)$$

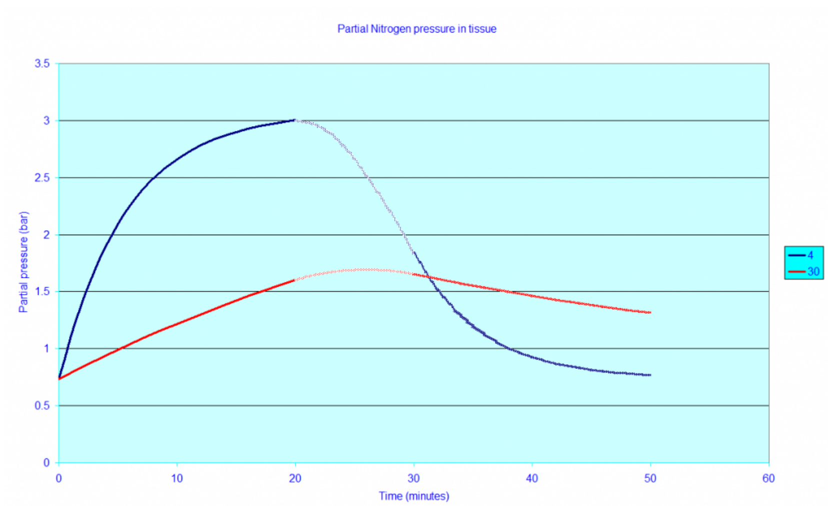

Figure 2: Partial Nitrogen pressure during and after surfacing

Figure 2 depicts the situation: the solid lines represent the period the diver is at 30 m depth. The light-colored parts in the middle of the graph (20-30 min) represent the period of ascending. The darker-coloured parts at the right represent the period after ascending, when the diver is at sea level. Using equation 7 this part has been calculated, using a N2 level in the tissues of $P_{t0-4} = 1.83 bar$ and $P_{t0-30} = 1.66 bar$ for the 4 minutes resp. 30 minutes tissue at the moment of arriving at the surface. As we can see the faster tissue saturates faster than the slower tissue. Similarly, it de-saturates faster as well, even during ascending. Since the diver ascended slowly, there is no much difference in Nitrogen levels between the tissues at the moment of arriving at the surface.

Supersaturation limits and M-Values

So we are now able to calculate inert gas levels and the amount of supersaturation in all tissue compartments of the diver. As we stated a certain amount of supersaturation is allowed, without developing DCS symptoms. In this section we will summarize various limits applying to supersaturation levels. As we will see these limits depend on:

- Type (half-time) of the tissue
- Ambient pressure, i.e. the pressure of the breathing gas (depending on depth and atmospheric pressure)

Limits according to Haldane

In 1908 Haldane presented the first model for decompression. He noticed that divers could surface from a depth of 10 meter, without developing DCS. He concluded that the pressure in the tissue can exceed the ambient pressure by a factor of 2. (Actually the factor the partial pressure of the Nitrogen in the body exceeds the ambient pressure is 0.78*2=1.56, as Workman concluded)

Haldane used this ratio to construct the first decompression tables. Up to 1960 ratio's were used. Different ratio's were defined by various scientists. In that period most of the US Navy decompression tables were calculated using this method.

Workman M-values

At longer and deeper dives, the ratio limits did not provide enough safety. Further research into supersaturation limits was performed by Robert D. Workman around 1965. Workman performed research for the U.S. Navy Experimental Diving Unit (NEDU). He found that each tissue compartment had a different partial pressure limit, above which DCS symptoms develop. He called this limiting pressure M. He found a linear relationship between this M-value and depth. Hence he defined this relationship as:

$$M = M_0 + \Delta M d \tag{23}$$

M	Partial pressure limit, for each tissue compartment (bar)
M_0	The partial pressure limit at sea level (zero depth), defined for each tissue compartment (bar)
ΔM	Increase of M per meter depth, defined for each compartment (bar/m)
d	Depth (m)

The actual Workman M-values are shown in the M-Values tables. Workman found that M values decrease with increasing half-time of the tissue compartment, indicating fast tissues can tolerate a higher supersaturation level. Using 23 we can calculate (for each tissue compartment) the minimum tolerated depth d_{min} the diver should stay at during a decompression stop, depending on the amount of supersaturation:

$$d_{min} = \frac{P_t - M_0}{\Delta M} \tag{24}$$

In order to estimate the actual depth the diver should stay below, we have to calculate the depth d_{min} for each compartment, and take the deepest depth as the limiting depth. The tissue that defines this depth is the limiting tissue.

The Bühlmann models

Bühlmann performed research to decompression from 1959 up to 1993. Like Workman he suggested a linear relationship between supersaturation limits and ambient pressure. However, his definition is somewhat different:

$$P_{t.tol.}ig = M = \frac{P_{amb}}{b} + a \tag{25}$$

$P_{t.tol.ig}$	Partial pressure limit, for each tissue compartment, equals M (bar)
P_{amb}	The ambient pressure, i.e. the pressure of the breathing gas (bar)
b	$1/b$ is the increase of the limit per unit ambient pressure (dimensionless)
a	The limit value at (theoretical) absolute 0 ambient pressure (bar)

The big difference (actually, the minor difference) between the Workman definition and the Bühlmann definition is that Workman relates M to ambient depth pressure (diving from sea level), whereas Bühlmann relates to absolute zero ambient pressure. However, in both cases, the partial pressure limit is related to ambient pressure by a linear relationship. Conversions between both definitions can be easily made, resulting in the following relationships:

$$P_{t.tol.}ig = M \tag{26}$$

$$\Delta M = \frac{1}{b} \tag{27}$$

$$M_0 = a + \frac{P_{amb\_sealevel}}{b} \quad (28)$$

In 1985 Bühlmann proposed the ZH-L12 model (ZH stands for Zürich, L for 'limits' or 'linear', and 12 for 12 pairs of M-values). In 1993 book he proposed the ZH-L16 model, which is quite popular as basis for diving computers. The coefficients of both models are presented in the tables in M-value style.

For the ZH-L16 model Bühlmann used a emperical relation for the a and b coefficient as function of the half-time τ for Nitrogen N_2:

$$a = 2bar\tau^{-\frac{1}{3}} \quad (29)$$

$$b = 1.005 - \tau^{-\frac{1}{2}} \quad (30)$$

This results in the A-series coefficients. However, these coefficients were not conservative enough, as was empirically established. So he developed the B- and C-series of coefficients for table calculations and computer calculations respectively. All three sets are presented in the tables.

Other models

DCAP (Decompression and Analysis Program) uses the M11F6 M-values, established by Bill Hamilton for the Swedish Navy. This set of M-values is used in many decompression tables used in trimix and technical diving.

The PADI Recreational Dive Planner TM uses the set of M-values developed by Raymond E. Rogers and Michael R. Powell from Diving Science and Technology Corp (DSAT). These values were extensively tested and verified, using diving experience and Doppler-monitoring (a way to detect silent bubbles in tissue).

The Recreational Dive Planner TM is a table used for no-decompression dives only. This means that for the calculation of table values no decompression stops are included: the diver can return to the surface any time. The only relevant limit M is the limit at sea level, M_0. For this model ΔM is not needed.

A comparison between the models

In the graphs below the limit M for the partial pressure of Nitrogen is plotted as function of the half-time for the different models. As we can see the limits according to the different models are comparable to each other.

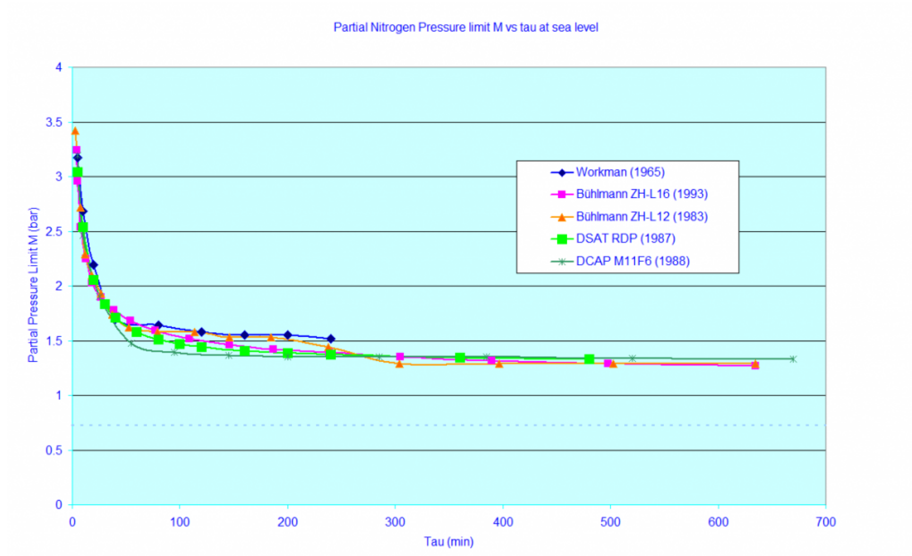

Figure 3: Partial Nitrogen pressure limit M vs. τ at sea level

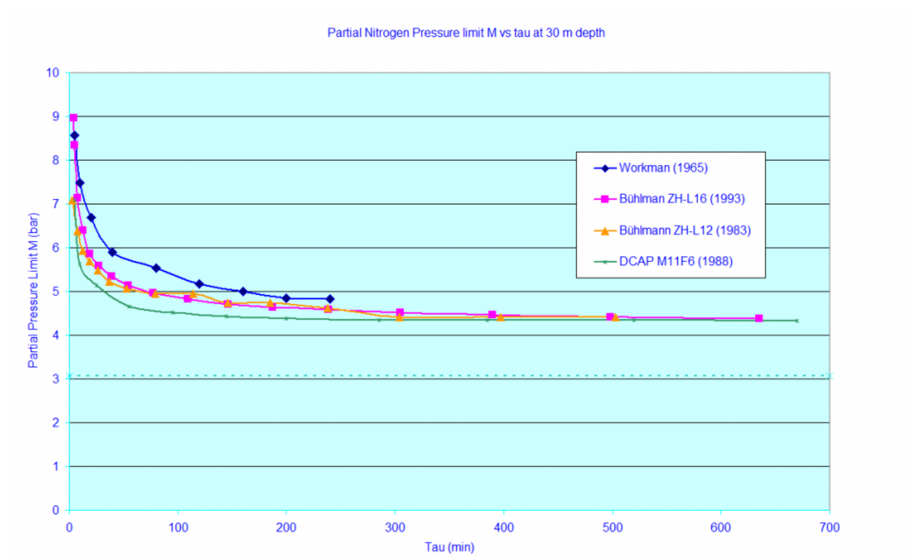

Figure 4: Partial Nitrogen pressure limit M vs. τ at 30 m

The ambient partial Nitrogen pressure is shown as a dashed line in the graphs. In fact, if the partial pressure of a tissue compartment is somewhere between the dashed line and the limit, the compartment decompresses safely. This means, the tissue gets rid of the excess Nitrogen in a controlled way. In decompression dives the diver should be as close to the limit during decompression stops in order to decompress most efficient (fast). Bühlmann expresses the position of the tissue pressure with respect to the limit as a percentage: 0% if the partial pressure of the compartment equals the ambient pressure, 100% if it equals the limiting M value.

No-decompression times

A number of tables, like the PADI RDP express no-decompression times for various depths. These are maximum times a diver can stay at this depth, being able to go to the surface without the need for decompression stops. Based on equation 8 we can calculate this time for a particular tissue compartment:

$$t_{no\_deco} = -\frac{1}{k} \ln \left(\frac{P_{no\_deco} - P_{alv0}}{P_{t0} - P_{alv0}} \right) \tag{31}$$

Of course we have to calculate this time for every tissue and take the minimum value as limit for the diver to remain at the depth. So what about P_{no_deco}. If we neglect the time the diver takes swimming to the surface, it would simply be M_0. However, as we have seen, the period the diver swims to the surface is important for decompressing as well. So we can use the Schreiner equation 13 to calculate M_{no_deco}. We assume a ascending speed of v (m/min) and we use the fact that we want to arrive at the surface with the tissue compartment partial pressure of M_0. We like to know the pressure $P_{no\_deco} = P_{t0}$ at which we have to start ascending.

$$P_{no\_deco} = \left[M_0 - P_{alv0} - R \left(t_{asc} - \frac{1}{k} \right) \right] e^{kt_{asc}} + P_{alv0} - \frac{R}{k} \tag{32}$$

In equation 31 en 32 we have:

M_0	Partial pressure limit (M-value) at sea level (bar)
t_{asc}	Time needed for ascending, $t_asc = depth/v$ (min)
p_{no_deco}	Partial pressure at which ascending has to be started (bar)
d	Depth (m)

When we use the DSAT RDP values, we find for example the smallest no-deco time of 53.9 min for the 30 minutes half-time compartment in case of a maximum depth of 20 m. The ascending speed $v = 18m/min$, $t_{asc} = 1.11min$.

More conservative limits

The limits discussed so far are actually not absolute. It merely is a solid line in a gray area. If one stays within limits, there is no guarantee that one never would develop DCS. Actual calculations can be made more conservative (include more safety) by adding extra depth, simulating asymmetrical tissue behaviour (a longer half-time for de-saturation than for saturation), adding surplus of Nitrogen, assuming a higher ascending speed, etc. Uwatec uses a Bühlmann model ZH-L8 ADT (ADT stands for adaptive), which uses 8 tissue compartment and takes into account the water temperature and the amount of work the diver performs (measured from the amount of air he uses). If the water is cold the half-time for de-saturation is longer than the half-time for saturation.