Diving at altitude:
a review of decompression strategies

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Egi SM, Brubakk AO. Diving at altitude: a review of decompression strategies. Undersea Hyperbaric Med 1995; 22(3):281-300.—Diving at altitude requires different tables from those at sea level due to the reduction in surface ambient pressure. Several algorithms extrapolating sea-level diving experimental data have been proposed to construct altitude diving tables. The rationale for these algorithms is reviewed together with the conservatism of the resulting tables and decompression computer outputs. All algorithms are based on the adaptation of critical tissue tensions to altitude. These are linear extrapolation (LEM), constant ratio translation (CRT), and constant ratio extrapolation (CRE) of maximum permissible tissue tensions (M values). Either new tables using the altitude-adapted M values were put forward or sea-level tables are to be used through an operation called correction. In this review it is shown that for a given set of M values, CRT and CRE give the same result for no-decompression-stop dives; they always yield more conservative results than LEM. When decompression stops are used, CRT is more conservative than CRE. When applied to different sets of M values, the conservatism becomes a function of bottom time, depth, and altitude. The analysis shows that the tables derived using CRT of U.S. Navy (USN) schedules and CRE Boni et al. tables give more conservative results than LEM Bühmann tables for higher altitude, longer bottom time, and deeper dives. Aviation altitude exposure decompression sickness (DCS) data are also addressed to compare different model outputs. When applied to USN and Royal Navy tables, LEM yields an altitude DCS limit of 8,581 and 8,977 m, respectively. On the other hand, the altitude limit calculated using CRE applied to USN M values and LEM Bühmann tables is found to be below 6,000 m.

altitude, decompression computer, altitude sickness, decompression tables, decompression,
hypoxia, decompression sickness boundary, oxygen window, algorithm

Metabolically inert gases such as He, N₂, and H₂ dissolve in tissues as a linear function of pressure. Upon reduction in pressure, the tension of the inert gas (Pᵣ) may exceed the ambient pressure (Pₑ) (Table 1 provides a list of variables). The supersaturated state is defined as:

\[ s = \frac{P_r}{P_e} \]  

(I)
Boycott et al. (1) postulated that there exists an allowable supersaturation ratio \( s_{aw} \) below which no symptoms of decompression sickness (DCS) will occur. Based on the observation that goats can be decompressed to half of the saturation pressure without developing DCS, these authors concluded that the allowable supersaturation ratio is 1.58. Further experiments showed that the fixed ratio principle is too conservative for shallow dives but not conservative enough for deep dives. Hawkins et al. (2) explained this by assuming the existence of multiple compartments in the body with different rates of gas exchange and supersaturation tolerances. Moreover, Van Der Aue et al. (3) observed that tolerable supersaturation ratio decreases with ambient pressure. Thus, \( s_{aw} \) will be a decreasing function of \( P_b \) (Fig. 1B) and tissue rate constant.

For a given tissue and for each \( P_b \) there exists a unique \( s_{aw} \), therefore a unique \( P_f \); so for a given \( P_b \) it is equally possible to express the symptomatic limit of DCS with the amount of dissolved (or supposed to be dissolved) gas. If the permissible amount of gas is expressed in terms of the gauge depth \( D \) instead of \( P_b \), then this is called an \( M \) value of depth \( D \) (4). The \( M \) values can be expressed in terms of the function:

\[
M(D) = a \cdot D + M_0
\]

(2)

where \( M_0 \) is the \( M \) value at surface and \( a \) is an empirical constant.
The transformation of the M values to $s_m$ can be achieved by using:

$$s_m = \frac{a \cdot D + M_0}{D + P_0}$$  \hfill (3)

where $P_0$ is the sea-level ambient pressure.

For the sake of consistency, all DCS boundary expressions presented as a function of ambient pressure are termed as M values in this text. For example, the original expression of Bühlmann’s DCS boundary is converted to M value function (appendix 1).

The concept of a straight DCS boundary is equally used in most decompression theories even if no tissue is assumed to be supersaturated (5–8). It is thus always possible to convert them to the corresponding M values. The fact that they attempt to define a tolerable amount of gas phase coming out of solution before giving rise to DCS leads in the same way to a straight DCS boundary, which defines the relationship between an allowable gas uptake and the ambient pressure (5–8). So for the sake of consistency with other non-neo-Haldanian theories, it is possible to redefine M values as the allowable gas content (dissolved + gas phase) above which symptoms of DCS will occur.

EXISTING ALTITUDE DIVING TABLES

Altitude dives require different tables from sea-level tables because the surface level $P_b$ diminishes with increasing elevation (appendix 2). The altitude $P_b$, if expressed in terms of gauge depth, corresponds to the negative part of the X axis in the M value and $s_m$ value curves (Fig. 1A, B). To define the critical tensions and tolerable supersaturation ratio in this part of the graph, either extrapolation or translation of the curves of sea-level dives is performed. These algorithms do not take into account a possible change in the gas equations or DCS boundary due to the hypoxic response of the body above 2,400 m. The time constants of the tissues are assumed to remain the same, and the critical tensions or ratios are obtained through adaptation of sea-level values. Few experiments have been done to confirm the predictions (6,9–11). There are three different principles of adaptation:

- Linear extrapolation of M values (LEM) (Fig. 2A, B) (6,9,10,12,13)
- Constant ratio translation (CRT) of M and $s_m$ values (Fig. 3A, B) (14–18)
- Constant ratio extrapolation (CRE) of $s_m$ values (Fig. 4A, B) (11)

These principles can be used to calculate new tables (9-12) or to use the existing ones through an operation called correction (6,14-18).

Linear extrapolation of M values

To find the safe surfacing value at altitude it is sufficient to extrapolate the M vs. D curve linearly (Fig. 2A). The gauge depth of the altitude surface value will be $P_a - P_b$, where $P_b$ is the surface level ambient pressure corresponding to the given altitude, $P_a$ can be found using one of the equations given in appendix 2 or can be measured directly with
FIG. 2.—When linearly extrapolated (A), M values still give a positive tolerable tension at ideal vacuum (−P₀). This corresponds to an infinite tolerable supersaturation at vacuum (B).

FIG. 3.—A, CRT of M values. After intercepting Y axis at c, Mₚ(d₀) line gives contradictory results (dashed). M₀ corresponds to sea level permissible tension, c is the M value for a depth of (P₀ − P₀) in altitude dives at Pₚ. B, critical ratios corresponding to CRT.

FIG. 4.—Extrapolation of M values (A) is done according to the sea level permissible ratio, which is assumed to remain constant for all altitudes (B). The slope of the M(D) function is equal to M₀/P₀ for all altitudes.
DIVING AT ALTITUDE

a barometer. Then, using Eq. 2, the $M_0$ value at a given altitude ($M_{a0}$) will be:

$$M_{a0} = M_0 + a \cdot (P_h - P_0)$$  \hspace{1cm} (4)

It is equally possible to calculate the $M$ value of any depth by substituting $D$ with the ambient pressure at the decompression stop expressed as gauge depth relative to sea-level pressure (Fig. 24).

This principle is used by Bühlmann (9) to devise altitude diving tables and by Hennessy (6) to calculate corrections for standard sea-level tables. To introduce a safety factor, Bühlmann tables assume that the diver is not equilibrated with the ambient pressure, whereas Hennessy introduced two separate correction formulas for sea level and altitude-equilibrated divers. Some decompression computers such as Decobrain, Aladin (12), and Scubapro DC-12 (personal communication, 1994) with altitude diving option use LEM to calculate decompression procedures. They also compute the nitrogen elimination during altitude residence.

Note that this type of extrapolation will imply greater tolerance to higher supersaturation ratios for increasing altitude, asymptotically approaching infinity at zero absolute pressure (Fig. 2B). Bell and Borgwald (14) point out that the region of extrapolation of $s_n$ values is located in a region of greatest curvature and it may be hazardous to extrapolate. In contrast, $M$ values are located on a straight line providing no obvious hazard to extrapolate. The method seems to underestimate the altitude DCS limit compared to the aviation literature (to be discussed separately).

**Constant ratio translation**

Correction terms are used to specify that sea-level tables will be used after converting the depth of the actual dive to a similar dive at sea level. The original similarity criterion was published in 1967 by Cross (16), refined by him in 1970 (17), and recognized thereafter as Cross Corrections. The same philosophy of using the sea-level tables after converting the actual depth of a dive performed at altitude is therefore grouped under correction name. In the original Cross Corrections the gauge depth of the similar dive ($P_c$) is given by:

$$P_c = P \cdot P_0/P_h$$  \hspace{1cm} (5)

where $P$ is the gauge depth of the actual dive.

The similarity requires that the diver is totally equilibrated with $P_c$. The term $P_0/P_h$ is also known as correction factor ($\alpha$). After calculating the depth of the similar dive, the standard sea-level diving tables can be used but the decompression stops should also be corrected as:

$$d_a = d/\alpha$$  \hspace{1cm} (6)

where $d$ is the sea-level decompression stop and $d_a$ is the actual stop for the altitude dive. This implies that the corresponding permissible tensions for the altitude dives should also be divided by $\alpha$:

$$M_a(d_a) = M(d)/\alpha$$  \hspace{1cm} (7)

Substituting $D$ by $d_a$ in Eq. 2 and combining Eq. 6 and 7 we find:

$$M_a(d_a) = M_0/\alpha + a \cdot d_a$$  \hspace{1cm} (8)

This is a translation of the $M(D)$ curve along the $M_0/\alpha$ line with: $d_a = D - (P_h - P_0)$ (Fig. 3A).
Another simple way of using Cross Corrections, which gives exactly the same result, is to use a capillary gauge and enter the readings of the capillary gauge directly into the sea-level tables (18).

It is somehow contradictory to adopt the old fixed ratio principle of Boycott et al. (1) for adaptation of a table that uses a depth-dependent ratio model. As a result, Cross Corrections (CRT) are self-contradictory, as they result in multiple M values corresponding to the same ambient pressure. For example, the M value of a 2-m decompression stop of an altitude dive at 81.06 kPa is different from the surface value (M_0) of the sea-level dive, although ambient pressure at the 2-m stop at 81.06 kPa (101.325 kPa absolute) is the same as sea-level surface pressure. It is possible to ensure the consistency in the graph by defining \( 0 < d_a < (P_0 - P_\alpha) \). Then M(D) will be a discontinuous function defined for all D.

Dacor Omni Pro and Oceanic DataMax Pro use this algorithm (personal communication, 1994). Both these computers follow the decompression procedures based on the CRT corrections of Bell and Borgward (14). These corrections are defined only for altitude-equilibrated divers. Unfortunately, user manuals for these decompression computers contain no warning that before any altitude dive the user should wait until all the tissues equilibrate with altitude ambient pressure.

**Constant ratio extrapolation**

The CRT correction strategy (see above), which is practiced by many diving organizations [National Association of Underwater Instructors (NAUI), COMEX, Royal Navy (RN)], is termed "Haldane altitude conversion" by Hennessy (6) indicating that the conversion criterion is based on one single allowable decompression ratio independent of ambient pressure. In fact, this is quite misleading because the definition of similar dives and the concept of CRE should be distinguished from Cross Corrections. The difference between CRE and CRT algorithm is the calculation of decompression stops. The contradiction resulting from the correction of decompression stops is also recognized by Bell and Borgward (14). They discovered that Cross Corrections lead to more conservative results, and so concluded that Cross Corrections can still be used. They pointed out that the ascent rate should also be corrected.

If the \( s_m(D) \) curve is assumed to be continuous for all altitude exposures \( s_m \) is equal to the surfacing value at sea level. The neo-Haldanian postulates should be changed with the postulates below:

\[
s_m = \begin{cases} 
\text{a decreasing function of } Pb \text{ for all } Pb > 101.325 \text{ kPa} \\
\text{constant for all } Pb < 101.325 \text{ kPa} \\
\text{a function of tissue half time}
\end{cases}
\]

In fact:

\[
s_m(D) = M_0/P_0 \text{ for } D < 0 \quad (9)
\]

For an altitude exposure the constant ratio principle implies that:

\[
s_m(D) = M_\alpha(D)/P_\alpha = M_0/P_0 \quad (10)
\]

Substituting \( P_\alpha \) using \( D = P_\alpha - P_0 \) and rearranging:

\[
M_\alpha(D) = M_0 + D \cdot M_0/P_0 \text{ for } D < 0 \quad (11)
\]
Therefore constant ratio extrapolation will give a straight DCS boundary with a slope of $M_d/P_a$ and resulting in zero tolerated tension at zero ambient pressure (at $D = -P_a$, Fig. 4A). This principle is used by Boni et al. (11) to devise a new set of altitude diving tables.

Checking the $M_d(d_s)$ function for $d_s = 0$, CRT algorithms give the same result for no-decompression-stop dives. They diverge in dives that involve decompression stops, CRT always yielding more conservative results.

Although extensively used, the authors did not specify the reason for using the old Haldanian fixed-ratio principle for only altitude dives although they accept a diminishing-ratio principle for sea-level dives. It is somehow contradictory to discard one part of the theoretical basis of a table then after some manipulations to refer back to the same table. In addition to this, the physiologic basis of the abrupt change in the slope of the $M$ value curve (Fig. 4A) or the discontinuities in the curve itself (Fig. 3A) remains unexplained.

On the other side, in his recent work Wienke (19–21) used a modified version of the varying permeability and reduced gradient bubble model (RGBM) to prove that $s_m$ is nearly constant for altitude exposures. This can partly justify the use of fixed $s_m$ values in the correction algorithms. In that case, $M(D)$ function will have a more complex expression without any discontinuity in the slope, and the CRE curve will represent the asymptote of the $M(D)$ curve for high altitudes (Fig. 5). The resulting permissible tissue tension function is an exponential extrapolation of $M$ values. Unfortunately, the curve fitting to find the bubble constants in the hypobaric region is accomplished using only one datum point which is DCS threshold in aviation. When used together with the critical tensions in the hyperbaric range, altitude DCS limit gives an $M$ value graph which is quite linear in the altitude diving range. For instance, the RGBM $M_{eq}$ value (Fig 5) for 3,000 m is 38.5 fsw. For the same altitude, LEM and CRE give 40.5 and 23.6 fsw of $M_{eq}$, respectively. Despite this, Wienke supports the use of Cross Corrections for altitude diving.

Comparison of table conservativeness

In the preceding section, three different principles of altitude adaptation algorithm are reviewed. Altitude similarity criteria are used by most of the authors to transform the dive to an equivalent sea-level dive to allow readily computed ascent schedules based on sea-level $M$ and $s_m$ values. To compare the conservatism of the resulting tables, we worked backward to calculate the equivalent $M$ and $s_m$ values at altitude. In fact, if two algorithms give a different set of $M$ values for a given altitude, the one that gives lower allowable supersaturation tensions will suggest shorter no-decompression-stop times.

![FIG. 5—Permissible tissue tensions of RGBM model. Although $M$ values are extrapolated exponentially, the curve preserves its incrementally linear value for moderate altitudes (1 fsw = 3.063 kPa).](image)
Different adaptation algorithms applied to the same model: Different algorithms applied to the same sea-level model are depicted in Fig. 6. For all depth and bottom-time combinations, CRT and CRE algorithms result in more conservative dives than LEM and the difference increases with increasing altitude (Fig. 6). For no-decompression dives, CRT and CRE algorithms yield the same result, whereas if decompression stops are involved, the CRT results are more conservative.

Different algorithms, different models: For the sake of simplicity the comparison is done only for zero decompression times. In this case, $M_{\text{al}}$ values of CRT and CRE algorithms are located on the same line. There exist four possible combinations for $M_0$ and $a$ values of each tissue of two different models as depicted in Fig. 7A–D.

Boni et al. vs. Bühlmann tables: Although the experimental basis of CRE tables of Boni et al. (11) is often used as reference for Bühlmann LEM tables (9, 10, 13), they give quite different results (Table 2A,C). As both of them share identical tissue half times and same safety factor of assuming sea-level saturation at the beginning of the dive, it is trivial to compare them on the basis of individual tissues (Table 3). Given the $M_0$ and $a$ values, the intersection point ($P_{\text{critical}}$) of the line equations of CRE and LEM methods is computed using simple analytical geometry (appendix 3). The M value plots of both algorithms on the same graph give the combination depicted in Fig. 7C,B for faster and slower tissues, respectively. Thus, for fast tissues, CRE M values will be smaller than LEM values for all altitudes (Table 3). Observe that for slower tissues, LEM gives more conservative results for altitudes with ambient pressure higher than $P_{\text{critical}}$ (Fig. 7B). Therefore, for a given dive, Boni et al. tables will be more conservative for increasing altitude. From Table 3 it can be seen that

FIG. 6—Different altitude adaptation algorithms applied to the same model.

FIG. 7—Possible combinations of CRE and LEM algorithms to applied M values of two different models. LEM is more conservative for all ambient pressures lower the $P_{\text{critical}}$ (A), higher than $P_{\text{critical}}$ (B), for all altitudes (D); in C, CRE is always more conservative.
DIVING AT ALTITUDE

Table 2: Zero Decompression Limits for Altitude Dives

A. Zero decompression of Bühlmann tables (LEM) (9)

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
<th>24</th>
<th>27</th>
<th>30</th>
<th>33</th>
<th>36</th>
<th>39</th>
<th>42</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>300</td>
<td>120</td>
<td>75</td>
<td>53</td>
<td>35</td>
<td>25</td>
<td>22</td>
<td>20</td>
<td>17</td>
<td>15</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>1,500</td>
<td>180</td>
<td>90</td>
<td>63</td>
<td>43</td>
<td>30</td>
<td>25</td>
<td>18</td>
<td>16</td>
<td>14</td>
<td>11</td>
<td>10</td>
<td>9</td>
</tr>
<tr>
<td>2,500</td>
<td>135</td>
<td>82</td>
<td>55</td>
<td>40</td>
<td>30</td>
<td>23</td>
<td>17</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>9</td>
<td>8</td>
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<tr>
<td>3,500</td>
<td>125</td>
<td>76</td>
<td>55</td>
<td>38</td>
<td>25</td>
<td>20</td>
<td>17</td>
<td>15</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>7</td>
</tr>
</tbody>
</table>

B. Zero decompression limits of USN tables as modified by Cross Corrections

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>21</th>
<th>24</th>
<th>27</th>
<th>30</th>
<th>33</th>
<th>36</th>
<th>39</th>
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<tbody>
<tr>
<td>0</td>
<td>310</td>
<td>200</td>
<td>100</td>
<td>60</td>
<td>50</td>
<td>40</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>1,500</td>
<td>272</td>
<td>104</td>
<td>63</td>
<td>46</td>
<td>33</td>
<td>24</td>
<td>17</td>
<td>12</td>
<td>10</td>
<td>8</td>
<td>7</td>
<td>6</td>
</tr>
<tr>
<td>2,500</td>
<td>185</td>
<td>77</td>
<td>51</td>
<td>35</td>
<td>24</td>
<td>17</td>
<td>12</td>
<td>9</td>
<td>8</td>
<td>7</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>3,500</td>
<td>117</td>
<td>60</td>
<td>40</td>
<td>26</td>
<td>18</td>
<td>12</td>
<td>9</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
</tbody>
</table>

C. Zero decompression limits of Boni et al. tables (CRE) (11)

<table>
<thead>
<tr>
<th>Depth, m</th>
<th>9</th>
<th>12</th>
<th>15</th>
<th>18</th>
<th>20</th>
<th>25</th>
<th>30</th>
<th>35</th>
<th>40</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>–</td>
<td>200</td>
<td>75</td>
<td>50</td>
<td>30</td>
<td>25</td>
<td>20</td>
<td>15</td>
<td>10</td>
</tr>
<tr>
<td>1,500</td>
<td>720</td>
<td>90</td>
<td>30</td>
<td>20</td>
<td>15</td>
<td>10</td>
<td>5</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>2,500</td>
<td>240</td>
<td>40</td>
<td>15</td>
<td>7</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>3,200</td>
<td>150</td>
<td>30</td>
<td>10</td>
<td>5</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
<td>–</td>
</tr>
</tbody>
</table>

*Bold numbers indicate shorter bottom times compared to Bühlmann tables.  These limits are in fact not from US Navy Diving Manual. They are calculated using CRT of US Navy M values. Offgasing during ascent is neglected.

Table 3: Conservative Altitude Range of CRE of Boni et al. Compared to LEM of Bühlmann Tables

<table>
<thead>
<tr>
<th>Half Time of the Controlling Tissue, min</th>
<th>$P_{critical}$, kPa</th>
<th>Dives Where CRE Tables are More Conservative than Bühlmann Tables</th>
</tr>
</thead>
<tbody>
<tr>
<td>5&quot;</td>
<td>–</td>
<td>all altitude dives</td>
</tr>
<tr>
<td>15&quot;</td>
<td>–</td>
<td>all altitude dives</td>
</tr>
<tr>
<td>25&quot;</td>
<td>–</td>
<td>all altitude dives</td>
</tr>
<tr>
<td>40&quot;</td>
<td>–</td>
<td>all altitude dives</td>
</tr>
<tr>
<td>53</td>
<td>93.32</td>
<td>at altitudes higher than 657 m</td>
</tr>
<tr>
<td>79</td>
<td>86.02</td>
<td>at altitudes higher than 1,307 m</td>
</tr>
<tr>
<td>146</td>
<td>90.58</td>
<td>at altitudes higher than 896 m</td>
</tr>
<tr>
<td>185</td>
<td>90.58</td>
<td>at altitudes higher than 896 m</td>
</tr>
<tr>
<td>238</td>
<td>74.17</td>
<td>at altitudes higher than 2,499 m</td>
</tr>
<tr>
<td>304</td>
<td>56.54</td>
<td>at altitudes higher than 4,681 m</td>
</tr>
<tr>
<td>395</td>
<td>56.54</td>
<td>at altitudes higher than 4,681 m</td>
</tr>
<tr>
<td>503</td>
<td>56.54</td>
<td>at altitudes higher than 4,681 m</td>
</tr>
<tr>
<td>635</td>
<td>56.54</td>
<td>at altitudes higher than 4,681 m</td>
</tr>
</tbody>
</table>

*These tissues do not exist in the original Bühlmann altitude diving tables. Instead 2.65, 7.94, 12.2, 18.5, 26.5, and 37 min tissues were used. For the sake of comparison it is possible to obtain the $M_a$ and a values of any tissue using the empirical equation derived by Bühlmann (10).
$P_{\text{critical}}$ decreases with increasing tissue half time. For a given altitude, the shallower the dive the more conservative LEM will be because slower tissues, which control zero compression times at shallower depths, have lower $P_{\text{critical}}$ (Table 3) whereas faster tissues do not have $P_{\text{critical}}$ at all (Fig. 7C). To conclude CRE, Boni et al. tables give more conservative results than Bühlmann tables for higher altitudes, longer bottom times, and deeper dives. Note that this comparison does not include computers that use the Bühlmann LEM because they calculate the offgassing at altitude, therefore their $P_{\text{critical}}$ will be higher, giving less conservative results than the Bühlmann tables (Table 2C).

Constant ratio translation USN standard air diving tables vs. Bühlmann tables and computers that use this algorithm: Two different altitude diving table applications are popular in practice: linearly extrapolated Bühlmann tables together with decompression computers using that algorithm (Decobrain, Aladin, Scubapro DC-12) and corrections using CRT principle (COMEX, RN, DICIEM, NAUI, Dacor Omni Pro, Oceanic DataMax Pro). Different decompression models use a different set of $M$ values and tissue rate constants. In fact, it is possible to use empirically derived equations to express critical tensions as a function of tissue rate constants (10,21).

The equivalent $M$ values corresponding to the original Bühlmann tables are different from LEM for the reason that all tissues are assumed to be sea-level equilibrated to introduce a safety factor (9,13). It is possible to calculate the magnitude of this safety factor in the case of altitude-equilibrated diver. The nitrogen gas exchange equation used in these models is defined as:

$$\Pi(t) = f \cdot P_0 + f \cdot (P_B - P_0) \cdot [1 - \exp(-k \cdot t)] \quad (12)$$

where $\Pi(t)$ is the tension of inert gas for a given tissue, $f$ is the fraction of $N_2$ in the alveoli, $P_B$ is the ambient pressure of the depth, $t$ is the bottom time, and $k$ is the tissue rate constant. For an altitude equilibrated diver the surface level $P_0$ is $P_h$. Substituting $P_0$ by $P_h$:

$$\Pi(t) = f \cdot P_h + f \cdot (P_B - P_h) \cdot [1 - \exp(-k \cdot t)] \quad (13)$$

If the diver is assumed to be sea-level equilibrated although he is altitude equilibrated, subtracting Eq. 13 from Eq. 12 the safety factor $Z(t)$ is calculated:

$$Z(t) = f \cdot (P_0 - P_h) \cdot \exp(-k \cdot t) \quad (14)$$

Thus, for the same fractional composition of inert gas ($f$), the safety factor $Z(t)$ depends on height ($P_h$), tissue ($k$), and bottom time ($t$). To find the graphical representation of this safety factor, Eq. 12 will be equated to Eq. 2, $\Pi(t)$ will be substituted by $\Pi_2(t) + Z(t)$ and ($P_h - P_0$) by $D$:

$$M_0 + a \cdot D = \Pi_2(t) + Z(t) \quad (15)$$

Thus:

$$M(D) = M_0 + [a + f \cdot \exp(-k \cdot t)] \cdot D \quad (16)$$

This means that the slope of the $M$ value line will increase with bottom time (Fig. 8). For a given level of supersaturation of tissue the increase of the slope of $M(D)$ by $f \cdot \exp(-k \cdot t)$ has more impact on the slow tissues. This is shown in Table 4 for $t = 1.25/k$, as this is a proved criterion for the tissue to control the zero decompression procedure of the dive (21). Then we find:

$$M(D) = M_0 + (a + 0.2263) \cdot D \quad (17)$$
DIVING AT ALTITUDE

As the decompression computers using the Bühlmann model calculate the offgassing of N\textsubscript{2} for the altitude-equilibrated diver, their M(D) function will not include this safety factor. The M value plots of both algorithms on the same graph give the combination depicted in Fig. 7B for all tissues. Again, with increasing altitude, CRE modification of USN tables becomes more conservative.

Altitude diving tables and aviation DCS data

The linear extrapolation of some of the tables is criticized by Basset (USN tables) (22) and Conkin et al. (RN tables) (23) because they do not fit the altitude exposure data of aviation and space activities, whereas some of the extrapolated tables are in close agreement with some of the thresholds cited in aviation literature (see below).

Elaborate test procedures can be applied using various data from EVA (extravehicular activity) and aviators’ DCS with different O\textsubscript{2} prebreathing mixtures and different pressure profiles (23). This, in fact, introduces an additional calculation step. The simplest way to test the performance of altitude decompression tables is to compare their model output for the threshold altitude giving rise to DCS when exposure from sea level is performed (Table 5). In each of the following models the ambient pressure (P\textsubscript{a}max) of this altitude threshold is calculated for a sea-level-equilibrated man. For CRE algorithm, P\textsubscript{a}max can be found using:

\[ s_m = M_o/P_0 = f \cdot P_0/P_{a\text{max}} \]  

(18)

For LEM algorithms we have:

\[ f \cdot P_0 = M_o + a \cdot (P_{a\text{max}} - P_0) \]  

(19)

The above equations are applied to the slowest tissue of the models to find P\textsubscript{a}max, which is then converted to altitude DCS height limit using the formula given in appendix 2. In fact, the altitude DCS boundary is determined in the aviation literature with no less inconsistency: 3,900 m Conkin et al. (23); 3,950 m Ryder et al. (24); 5,486 m Heimbach and Sheffield (25); 6,096 m Behnke et al. (26); 7,550 m Gray (27).

There are also cases in the literature in which DCS has been encountered at far less altitudes: 3,049 m, 3659 m Allan (28); 3,353 m Rayman et al. (29); 4,269 m Voge (30); 4,877 m Houston (31). In some of these cases the DCS was attributed to the presence of a recent injury and it was stressed that this has the DCS threshold-lowering effect.

The comparison given above may reflect the conservatism of the relative models, but in reality the concept of a threshold is misleading, in the sense that it points at the spontaneous occurrence of DCS above the given altitude, whereas the dynamics of bubble growth and the development of symptoms are time dependent [Yount (8) and Van Liew (32) for bubble growth, Kumar et al. (33) for development of symptoms]. So the attempt to determine a time-independent height limit is illogical. This subject is treated comprehensively in Kumar et al. (33). The time-dependent DCS limits are 3,353 m for 6 h simulated EVA (without O\textsubscript{2} prebreathing) (33) and 7,925 m for 2 h simulated EVA (without O\textsubscript{2} prebreathing) (33).

FIG. 8—Change in the slope of the M(D) function as bottom time is increased. The safety factor of assuming that all tissues are sea-level equilibrated for an altitude-equilibrated diver is equivalent to introducing a new set of M values.
Table 4: Conservative Altitude Range of CRE of USN Tables Compared to Bühlmann Tables

<table>
<thead>
<tr>
<th>Half time of the controlling tissue, min</th>
<th>USN vs. Decompression Computers, Using LEM of Bühlmann M Values</th>
<th>USN vs. Bühlmann Altitude Dive Tables</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( P_{\text{norm}} ) kPa</td>
<td>( P_{\text{norm}} ) kPa(^a)</td>
</tr>
<tr>
<td>5</td>
<td>85.01 at altitudes higher than 1,406 m</td>
<td>81.76 at altitudes higher than 1,720 m</td>
</tr>
<tr>
<td>10</td>
<td>75.38 at altitudes higher than 2,365 m</td>
<td>69.51 at altitudes higher than 3,021 m</td>
</tr>
<tr>
<td>20</td>
<td>80.45 at altitudes higher than 1,844 m</td>
<td>73.56 at altitudes higher than 2,571 m</td>
</tr>
<tr>
<td>40</td>
<td>99.6 at altitudes higher than 132 m</td>
<td>98.59 at altitudes higher than 219 m</td>
</tr>
<tr>
<td>80</td>
<td>99.6 at altitudes higher than 132 m</td>
<td>97.88 at altitudes higher than 273 m</td>
</tr>
<tr>
<td>120</td>
<td>87.74 at altitudes higher than 1,153 m</td>
<td>74.07 at altitudes higher than 2,512 m</td>
</tr>
</tbody>
</table>

\(^a\)LEM is computed taking into account the safety factor \( Z(t) \) of assuming the diver is sea level equilibrated. See appendix 3 for calculation procedure.

Table 5: Altitude Limit Giving Rise to DCS as Predicted by Different Algorithms Applied to Different Models

<table>
<thead>
<tr>
<th>Algorithm</th>
<th>Model</th>
<th>( h_{\text{max}} ) m</th>
</tr>
</thead>
<tbody>
<tr>
<td>CRE</td>
<td>Haldane (1)</td>
<td>5.524</td>
</tr>
<tr>
<td>CRE</td>
<td>USN (4)</td>
<td>5.193</td>
</tr>
<tr>
<td>CRE</td>
<td>Boni et al. (11)</td>
<td>5.120</td>
</tr>
<tr>
<td>LEM</td>
<td>USN (4)</td>
<td>8.581</td>
</tr>
<tr>
<td>LEM</td>
<td>Bühlmann (9)</td>
<td>5.332</td>
</tr>
<tr>
<td>LEM</td>
<td>Yount (8)</td>
<td>5.784</td>
</tr>
<tr>
<td>LEM</td>
<td>RN (23)</td>
<td>8.977</td>
</tr>
<tr>
<td>LEM</td>
<td>Hennessy (6)</td>
<td>5.784</td>
</tr>
<tr>
<td>RGBM*</td>
<td>Wienke (19)</td>
<td>6.838</td>
</tr>
</tbody>
</table>

\(^*\)RGBM (reduced gradient bubble model) equation (19) solved for a sea level equilibrated tissue.

Diving and Hypobaric Hypoxia

As the range of existing altitude dive tables and decompression computers extends up to 4,000 m (Table 6) the effects of hypoxia need to be considered. With increasing altitude, the pressure of inhaled \( O_2 \) decreases. It is followed by a cascade of drops in alveolar, arterial, and capillary levels of \( O_2 \). To maintain the critical \( O_2 \) pressure at which cells may function normally, a series of adaptations need to occur in the body. This has two consequences for high altitude diving:

1. If the body fails to adapt then the subject will suffer from a number of diseases, acute mountain sickness (AMS), high altitude pulmonary edema (HAPE), high altitude cerebral edema (HACE), or retinopathy (34-38). The altitude diver, like any other altitude sojourner, should follow a number of rules to adapt properly so as to avoid these diseases. A number of rules of thumb have been compiled from different authorities (35,37-41). The diver can disregard any of them at his own risk (appendix 4).

These rules do not claim to protect each climber. The susceptibility of the individual plays an important role. Bartsch et al. (42) found that the slow ascent with an average gain
DIVING AT ALTITUDE

Table 6: Altitude Limit of Decompression Computers

<table>
<thead>
<tr>
<th>Decompression Computer</th>
<th>Altitude Limit, m</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aladin Pro</td>
<td>4,000</td>
</tr>
<tr>
<td>DC-12</td>
<td>2,500</td>
</tr>
<tr>
<td>Omni Pro</td>
<td>3,000</td>
</tr>
<tr>
<td>Monitor</td>
<td>3,960</td>
</tr>
<tr>
<td>Suunto solution</td>
<td>2,400</td>
</tr>
<tr>
<td>DataMax Pro</td>
<td>4,267</td>
</tr>
</tbody>
</table>

of 500 m of altitude per day is associated with the absence of AMS and/or HAPE in non-susceptible mountaineers, but cannot prevent these illnesses in susceptible subjects. As a consequence, even if the ascent rules are followed, the climber should not forget the phrase "if in doubt go down" (40).

2. Significant changes in body parameters are necessary to adapt to low partial pressure of inhaled O2 (34,35,41,43–56). Some of these are expected to change both the time constants of tissue compartments and the threshold of DCS.

Arterial N2 tension

In some tables, the tension of inert gas in the arterial blood is assumed to be equilibrated with the fraction of the inhaled inert gas, without taking into account the presence of alveolar H2O and CO2. In extrapolating the sea-level DCS limits to altitude, this will create a problem. While calculating the gas uptakes, this error is not too large because the difference is negligible compared to applied pressure. More important, errors will occur during calculation of surface wash-outs. For altitudes above 3,000 m, calculation of arterial N2 (P_{a_n2}) as a fraction of air introduces a considerable overestimation of the N2 tension during surface washouts (Table 7). Note that the theoretical basis of Cross Corrections is also based on a fixed mole fraction of N2 in the alveoli (14), which is not correct when the altitude changes. In Bühlmann tables and decompression computers using that algorithm, only the presence of water vapor in the alveoli is taken into account, which is true for a respiratory quotient of 1. A more realistic formula taking the presence of CO2 and H2O into account is given in appendix 5.

Table 7: Overestimation of Arterial N2 Tension at Different Altitudes

<table>
<thead>
<tr>
<th>Altitude, m</th>
<th>Pa, kPa</th>
<th>( P_{a_n2} ) Calculated as %79 of Air, kPa</th>
<th>( P_{a_n2} ) Calculated from Formula in Appendix 5, kPa</th>
<th>Percent Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>101.325</td>
<td>79.993</td>
<td>76.127</td>
<td>5.11</td>
</tr>
<tr>
<td>500</td>
<td>95.192</td>
<td>75.193</td>
<td>71.327</td>
<td>5.46</td>
</tr>
<tr>
<td>1,000</td>
<td>89.459</td>
<td>70.661</td>
<td>66.794</td>
<td>5.83</td>
</tr>
<tr>
<td>1,500</td>
<td>83.993</td>
<td>66.394</td>
<td>62.528</td>
<td>6.23</td>
</tr>
<tr>
<td>2,000</td>
<td>78.926</td>
<td>63.461</td>
<td>58.528</td>
<td>6.66</td>
</tr>
<tr>
<td>2,500</td>
<td>74.26</td>
<td>58.528</td>
<td>54.795</td>
<td>7.12</td>
</tr>
<tr>
<td>3,000</td>
<td>69.727</td>
<td>55.062</td>
<td>51.195</td>
<td>7.67</td>
</tr>
<tr>
<td>3,500</td>
<td>65.461</td>
<td>51.729</td>
<td>47.729</td>
<td>8.39</td>
</tr>
<tr>
<td>4,000</td>
<td>61.595</td>
<td>48.662</td>
<td>44.663</td>
<td>9.03</td>
</tr>
</tbody>
</table>
Decrease in the oxygen window

The O₂ window is defined to be the driving force for inert gas elimination from bubbles and determines the degree of supersaturation (5,7). The O₂ window decreases with altitude (Table 8); because while alveolar partial pressure of O₂ decreases dramatically, the partial pressure of alveolar CO₂ and H₂O remain almost the same. Through acclimatization the O₂ carrying capacity of the blood increases (48) and arterial and venous levels of O₂ also increase. This is due to the increase in hemoglobin concentration and the Pₐ values (partial pressure of O₂ at which 50% of hemoglobin sites are filled). Because of the sigmoidal shape of the O₂ dissociation curve, this has more impact on the venous O₂ levels. Therefore, the O₂ window will decrease even more with acclimatization. Another implication of this hypothesis is the reduced O₂ window in the case of an altitude acclimated individual upon coming back to sea level (Table 8, altitude 0).

CONCLUSION

The common practice of divers is to use Cross Corrections together with their favorite sea-level diving tables, unless they use the Bühlmann altitude diving tables. Some decompression computers use the linear extrapolation (12). Therefore the altitude diver who uses his dive computer as a backup for a dive planned according to corrections of sea-level tables may be surprised with the large discrepancy of the results even for non-multilevel dives. For high altitude diving, the decompression computers with LEM algorithm give less conservative results.

It is shown in this review that Cross Corrections of USN tables will lead to less conservative results at low altitude compared to Bühlmann altitude diving tables. But in practical application, this depends on the interpretation of the table. For example, if the diver cannot calculate the exact depth of the similar dive, he will refer to conversion tables. For a 31-ft dive at 1,000 ft, the diver will complete the depth to the next highest depth, which is 40 ft if he uses, say, the Bell and Borgward correction table. But the situation will be different if he uses, for example, COMEX corrections which tabulate equivalent depths with 1-m increments (15). With Bell and Borgward corrections the corresponding similar depth will be 41 ft, which in turn will be converted to 50 ft while using the standard USN tables; with so much rounding-off, the Bell and Borgward corrections give a more conservative result even at low altitude compared to the linear extrapolated alternative in which only 31–40 roundings-off can be done.

Table 8: Estimation of Oxygen Window Before and After Full Acclimatization*

<table>
<thead>
<tr>
<th>Altitude, m</th>
<th>Oxygen Window, kPa (before acclimatization)</th>
<th>Oxygen Window, kPa (after acclimatization)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7.997</td>
<td>6.388</td>
</tr>
<tr>
<td>500</td>
<td>6.772</td>
<td>5.242</td>
</tr>
<tr>
<td>1,000</td>
<td>5.644</td>
<td>4.21</td>
</tr>
<tr>
<td>1,500</td>
<td>4.613</td>
<td>3.296</td>
</tr>
<tr>
<td>2,000</td>
<td>3.683</td>
<td>2.503</td>
</tr>
<tr>
<td>2,500</td>
<td>2.859</td>
<td>2.36</td>
</tr>
<tr>
<td>3,000</td>
<td>2.263</td>
<td>2.262</td>
</tr>
<tr>
<td>3,500</td>
<td>1.975</td>
<td>1.789</td>
</tr>
<tr>
<td>4,000</td>
<td>1.535</td>
<td>1.394</td>
</tr>
</tbody>
</table>

*See appendix 6 for calculations.
DIVING AT ALTITUDE

The philosophy of the comparisons is similar to the comparison of physical and chemical properties of the elements in the periodic table: that is, with some intuitive deductions along with some inconsistency arising from the switchover points between discrete identities.

As the rate constants are different in both tables, exact comparison cannot be made for the actual tables. The switchover points between different tissues may lead to some inconsistencies, and in addition we are still faced with the problem of the 10 + 10 incremental nature in the presentation of the tables. Nonetheless, Tables 2–4 and the corresponding graphic interpretations (Fig. 7A–D) allow comparison of the different tables. Instead of claiming that one table is less conservative than others, it is more logical to define the specific conditions in which the algorithm itself is more or less conservative. The comparisons given above will hold only in the case of the no-decompression-stop time calculated exactly for the depth without any rounding-off. The advantage of such comparison is that it will determine the relative performance of the decompression computers with altitude dive option. In this case, depth and time will not be rounded-off, making possible an exact comparison between different algorithms.

The theoretical basis of CRT is contradictory whereas CRE can be explained by RGBM. A decompression computer using CRT algorithm will be more conservative. As the implication of the high altitude changes of the body parameters on DCS is not determined yet, it might be useful to suggest that such a conservatism should be adopted.

Knowing that the physiologic changes involved in acclimatization follow a time course, the utopic altitude dive table would have an altitude residence time entry. At least, a coarse division between short time (up to 3 days) and long-time residence (e.g. after 10 days) should be possible after the acclimatization phase. In fact, it is equally possible to restrict the use of the tables after the acclimatization phase, where the related parameters will settle down to a greater extent and thereby get rid of the complex dynamics of the first 3 days. Some altitude diving tables are restricted for use 12–48 h after arrival, but the reason is to equilibrate the N₂ in the tissues with the ambient pressure.

The argument supporting immediate diving upon arrival is that the subject will be symptom free from AMS upon arrival until 4–6 h at altitude. Thus, if the appropriate table takes into account the residual N₂ from sea level, immediate diving followed by immediate descent to lower altitudes, if possible to sea level, may be encouraged for altitudes up to 3,000 m. At higher altitudes, DCS stress will be too high because exposure to 3,300 m (33) and 3,900 m (23) from sea level is defined as altitude DCS limit by some sources. In the case of immediate diving, the ascent rate for the last few meters of water should be extremely slow so as to avoid fast exposure to hypoxia. Long-distance surface swimming is to be avoided to prevent depletion after relatively fast transition to hypoxic medium. Safety decompression stops are advised.

Diving after full acclimatization at high altitudes (e.g., after 10 days at higher than 3,000 m) should be avoided until controlled experiments are carried out about the DCS stress induced by subclinical development of HAPE (57) and the changes in blood parameters. The decrease in the O₂ window through acclimatization must also be considered.

Even if an altitude dive table is devised that takes into account the above-cited changes together with the correct DCS boundary, for dives above 2,400 m the diver should use them with the same conservatism as in dives that involve heavy work, cold environments, or personal fitness problems. Even if the diver does not suffer from the symptoms of AMS, HAPE, and other altitude-related diseases, subclinical development is possible; in addition, the decrease in both physical and mental performance associated with altitude is reported by many sources (34–36). Increased blood flow to the brain creates an accumu-
ilation of fluid; the resulting fluid pressure can lead to headache and can impede judgment (35) which will affect the performance of the diver.

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Appendix 1
Conversion of M Values

Although the permissible tissue inert gas tension is expressed differently in Bühlmann tables, it is possible to write the corresponding M value function. The Bühlmann expression of DCS boundary is:

\[ P_e = P_a/b + c \]  \hspace{1cm} (A1)

where \( P_e \) is the maximum nitrogen tension tolerated at the ambient pressure, \( b \) and \( c \) are empirical constants \((9,10,12,13)\). \( P_a \) is the same identity as M values.

\[ P_a = M_b(D) \] and \( P_a = D + P_0 \) then:

\[ M_b(D) = (D + P_0)/b + c \]  \hspace{1cm} (A2)

where \( M_b \) is the corresponding Bühlmann M values. Separating variables:

\[ M_b(D) = D/b + P_0/b + c \]  \hspace{1cm} (A3)

then \( P_0/b + c = M_{b0} \) and \( 1/b = a \) in Eq. 2.

Appendix 2
The Elevation-Pressure Conversion

\[ P_e = P_a \cdot \exp \left[ \left( -29 \cdot h \right) / \left( 831.4 \cdot T \right) \right] \]  \hspace{1cm} (A4)

where \( T \) = temperature (Kelvin)
\( h \) = elevation (m)
\( P_a \) = ambient pressure at an elevation \( h \).

An alternative formula is given by Wienke (19):

\[ P_e = 33 \cdot \exp \left( -0.0000385 \cdot z \right) \]  \hspace{1cm} (A5)

where \( P_e \) = ambient pressure at elevation \( z \)
\( z \) = elevation (ft)

These values may differ slightly from measurements. The ambient pressure at altitude is in fact dependent on humidity, weather conditions, and latitude.

Appendix 3
Calculation of Conservative Range of CRE Tables Over LEM Tables

To calculate Tables 3 and 4, first the constants in Eq. A1 are calculated for the tissues of interest using the empirical equation proposed by Bühlmann (10):

\[ b = 2 \cdot (t_a)^{-10} \] (in bars, 1 bar = 100 kPa)  \hspace{1cm} (A6)
\[ c = 1.0005 - (t_a)^{-10} \] (unitless)  \hspace{1cm} (A7)

Bühlmann's DCS boundary expression is converted to M value format using appendix 1. The M value expression corresponding to CRE algorithm is calculated for Boni et al. (11) and USN tables.
using Eq. 11. Then the M values are plotted on the same graph. For the case depicted in Fig. 7C, M values of CRE are always smaller than LEM. For the case corresponding to Fig. 7B, intersection point (P_{atm,critical}) is calculated by equating Eq. 2 to Eq. 11. Then P_{atm,initial} is converted to elevation using the formula presented in appendix 2.

Appendix 4

Ascent Rules

Acclimatization is best ensured by slow ascent. It is a good rule to ascend no more than 600 m/day when above 2,100 m. If symptoms increase, descend a few hundred meters at night. The altitude at which one sleeps is more important than the altitude reached during the day. It is also necessary to drink more water at altitude than at sea level to compensate for the fluid loss through hyperventilation (35). Avoiding strenuous exercise for the first 2 days is helpful (37). Taking more salt than necessary causes fluid retention, perhaps enough to trigger altitude sickness (35).

Above 3,000 m, an average gain of less than 500 m/day is recommended to avoid AMS (39).

Above 3,000 m a rate of ascent of 300 m/day for two days followed by 150 m/day thereafter is recommended, but such a practice is not popular since it requires much more time for adaptation (40).

Acute mountain sickness is prevented in most cases by slow ascent, which is hard to define. The speed of ascent that is perfectly tolerable for one individual may cause HAPE in another. Above 2,500–3,000 m, the sleeping altitude should not be increased by more than 300 m/day. Adequate fluid intake must be maintained, resulting in the production of at least 1 liter of clear urine per day (38).

Above 3,500 m, a rate of ascent of 300 or 500 m/day as an average of 2 consecutive days should be maximum speed (41).

Appendix 5

Calculation of Arterial N₂ Tension

Arterial N₂ tension (P_{Atm,N₂}) is equal to alveolar partial pressure of N₂ (P_{Atm,N₂}). The partial pressures of alveolar H₂O, CO₂, and O₂ are metabolically controlled. N₂ fills the vacancy to complete the sum of the gases to ambient pressure. Thus:

\[ P_{Atm,N₂} = P_B - (P_{ACO₂} + P_{AO₂} + P_{H₂O}) \]  

(A8)

where P_{ACO₂}, P_{AO₂}, and P_{H₂O} are the alveolar partial pressures of CO₂, O₂, and H₂O respectively. P_{H₂O} is constant (6.266 kPa). P_{ACO₂} and P_{AO₂} are dependent variables. P_{ACO₂} is constant up to 3,000 m (5.333 kPa). At 3,000, 3,500, and 4,000 m the P_{ACO₂} is taken as 5.2, 4.8, and 4.66 kPa, respectively. For a given P_{ACO₂}, P_{AO₂} is found using:

\[ P_{AO₂} = P_{IO₂} - P_{ACO₂}/R + P_{ACO₂} \cdot F_{IO₂} \cdot (1 - R)/R \]  

(A9)

where P_{IO₂} is the partial pressure of inhaled gas in kPa, R is the respiratory quotient and F_{IO₂} is the fraction of O₂ in the dry air (58). In turn:

\[ P_{IO₂} = F_{IO₂} \cdot (P_B - P_{H₂O}) \]  

(A10)

Substituting P_{AO₂} with above equality one can find:

\[ P_{Atm,N₂} = F_{N₂} \cdot (P_{ACO₂} \cdot (1 - R)/R + P_B - P_{H₂O}) \]  

(A11)

where F_{N₂} (or 1 - F_{IO₂}) is the fraction of inhaled N₂ in dry air. Schreiner and Kelly (59) also proposed that the above equation (with constant P_{ACO₂}) should be used in altitude diving. Note that P_{ACO₂} values given above will decrease through acclimatization, but the sum of P_{ACO₂} and P_{AO₂} will only decrease by a negligible amount to yield 0.2–0.4 kPa higher P_{Atm,N₂} than in the above equation.
Appendix 6
Estimation of Oxygen Window for Various Altitudes

The ambient pressure is first calculated using elevation-pressure conversion formula presented in
appendix 2. \( P_{A_{o_{2}}} \) is calculated using Eq. A9. \( P_{A_{o_{2}}} \) is equilibrated with pulmonary capillaries. In the
case of acclimatization, \( P_{A_{o_{2}}} \) values are read from CO2 to O2 diagram (60). Then the fractional sat-
uration of hemoglobin (Hb) in the pulmonary capillaries is calculated using the equation:

\[
\log \left( \frac{Y}{1-Y} \right) = n \cdot \log \left( \frac{P_{o_{2}}}{P_{c_{0}}} \right)
\]  

(A12)

where \( Y \) indicates fractional saturation with oxygen, \( P_{c_{0}} \) is the PO2 for half of the Hb to be sat-
urated and \( n \) is an empirical constant. \( n \) is taken as 2.8, and values of \( P_{c_{0}} \) before and after full accl-
imatization are accepted as 26.5 and 30.6, respectively (48). The volume of \( O_{2} \) in 100 ml of blood
\( (V_{o_{2}}) \) can be found using:

\[
V_{o_{2}} = C_{h_{b}} \cdot \gamma \cdot Y
\]  

(A13)

where \( C_{h_{b}} \) is the concentration of hemoglobin (g/dl), and \( \gamma \) is the volume of \( O_{2} \) that combines to
each gram of Hb. The Hb concentration is taken as 15 g/dl before acclimatization and 22 g/dl after
acclimatization (34) and \( \gamma \) is equal to 1.34 ml/g. \( V_{c_{o_{2}}} \) (volume of \( O_{2} \) in 100 ml of capillary blood)
is calculated from Eq. A13; assuming a constant expenditure of 5 ml \( O_{2} \)/100 ml of blood, and 5%
shunt fraction, the volume of \( O_{2} \) carried by 100 ml of venous blood is found by:

\[
V_{v_{o_{2}}} = \left( 0.95 \cdot V_{c_{o_{2}}} - 5 \right) / 0.95
\]  

(A14)

where \( V_{v_{o_{2}}} \) is the volume of \( O_{2} \) in 100 ml of venous blood. Knowing \( V_{v_{o_{2}}} \), venous Hb saturation
\( (Y) \) is found using Eq. A13. Finally the Hb saturation is converted to venous level of \( O_{2} \) \( (P_{v_{o_{2}}}) \) using the
Hill equation (Eq. A12).

The \( O_{2} \) window for an altitude equilibrated diver is found using:

\[
O_{2} \text{ window} = P_{b} - (P_{v_{o_{2}}} + P_{v_{c_{o_{2}}} + P_{v_{n_{2}}} + P_{v_{h_{2}}}})
\]  

(A15)

where \( P_{v_{c_{o_{2}}} \text{ and } P_{v_{n_{2}}}} \) are the venous levels of \( CO_{2} \) and \( N_{2} \), respectively. A constant arterio-venous
difference is assumed while calculating \( P_{v_{c_{o_{2}}}} \) values. \( P_{v_{n_{2}}} \) is calculated for an altitude-equilibrated
diver using the procedure given in appendix 5 and assuming \( P_{v_{n_{2}}} = P_{A_{n_{2}}}. \)
The results are in close agreement with the estimations of Van Liew et al. (61).

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