

High Altitude Diving Depths

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Short title: Diving in mountain lakes

Abstract

In order to make any sea level dive table usable during high altitude diving, a new conversion factor is created. We introduce the *Standardized Equivalent Sea Depth (SESD)*, which allows conversion of the *Actual Lake Diving Depth (ALDD)* to an equivalent sea dive depth.

SESD is defined as the sea depth in meters or feet for a standardized sea dive, equivalent to a mountain lake dive at any altitude, such that:

$$\text{SESD} = \text{ALDD} * [\text{Nitrogen ratio}] * [\text{Water density ratio}]$$

$$\text{SESD} = \text{ALDD} * [(760 - 47) / (P_B - 47)] * [1000 / 1033]$$

$$\text{SESD} = \text{ALDD} * [\text{SESD factor}]$$

Mountain lakes contain fresh water with a relative density that can be standardized to 1000 kg m^{-3} , and sea water can likewise be standardized to a relative density of 1033 kg m^{-3} , at the general gravity of 9.80665 m s^{-2} . The *Water density ratio* (1000/1033) refers to the fresh lake water and the standardized sea water densities.

Following calculation of the SESD factor, we recommend the use of our simplified diving table or any acceptable sea level dive table with 2 fundamental guidelines:

1. The classical decompression stages (30, 20 and 10 feet or 9, 6 and 3 m) are corrected to the altitude lake level, dividing the stage depth by the SESD factor.
2. Likewise, the *Lake ascent rate* during diving is equal to the *Sea ascent rate* divided by the SESD factor.

Key words

Decompression sickness; Dive Tables; High altitude diving; Water density.

Introduction

A relatively higher risk of developing decompression sickness (DCS) is probably present when diving in mountain lakes in contrast to the sea.

Bell and Borgwardt (1976) converted the diving depth at altitude to an equivalent depth in the sea. Previous conversions were entirely based on the ratio of the atmospheric pressure at altitude to that at sea level. The difference in density between fresh and salt water was not included in the correction. Bell and Borgwardt (1976) adjusted the ascent rate in the Cross tables and dived in lake Tahoe without DCS.

Boëni, Schibli, Nussberger et al (1976) developed altitude decompression tables and performed wet dives up to 2000 m above sea level in the Swiss mountains without DCS.

Hennesy (1977) proposed formulas for converting standard air decompression tables for no-stop diving at altitude. Predictions were in agreement with the Swiss diving tables, that are available in Buhlman's book (1984) and at the internet (2005).

Sahni, Dhall and Chatterjee (1991) converted depths at altitude to depths at sea level and used the Royal Navy Air Tables. They concluded that equivalent air depths applied to Royal Navy tables is a safe method for diving at altitude.

None of these strategies are easy to use for the recreational diver. The purpose of the present report was to develop a scientifically based and practical model for dive tables used at high altitude.

Methods

An essential determinant for N₂ exchange between the body and the surrounding breathing medium is the N₂ tension in the water vapor-saturated, tracheal air (P_{IN2}). This value is a feeding pressure to the body during loading and a receiving pressure during unloading of the body from N₂. In both cases the body can be considered a black box as far as the model is concerned. At any altitude above sea level, the barometric pressure (P_B) is below 1 atmospheres absolute pressure (P_B < 760 Torr). The effect of the tracheal water vapor pressure increases with increasing altitude, therefore this constant (47 Torr or 6.3 kPa) value must be included in the model. The ratio between the inspired tracheal N₂ tension at any P_B and that at sea level (1 atm abs) must be:

$$F_{IN2} (P_B - 47) / F_{IN2} (760 - 47)$$

using the unit Torr (= mmHg). The dry, inspired Nitrogen fraction (F_{IN2}) is constant and eliminated, resulting in:

$$(P_B - 47) / (760 - 47)$$

This is actually equal to the *Nitrogen tension ratio* for loading as well as for unloading the body from N₂ at any typical altitude-P_B relative to sea level (760 Torr). The partial pressure of saturated water vapour at body temperature – constantly equal to 6.3 kPa or 47 Torr as long as the body temperature remains normal - obviously plays a larger role at increasing altitude. For example, at 470 mmHg of P_B, the water vapour pressure (47 Torr at 37 °C) amounts to 10 %.

Most mountain lakes contain fresh water with a relative density that can be standardized to 1000 kg m⁻³, and seawater can likewise be standardized to a relative density of 1033 kg m⁻³, at the general gravity of 9.80665 m s⁻². With fresh water and standardized seawater

the *Water density ratio* is (1000/1033). The difference in relative density of lake water and seawater also affects the size of the inspired nitrogen pressure.

Adaptation of the diver to altitude

A diver spending more than one day following arrival to altitude, will be more or less adapted to the environment including the low partial pressure of nitrogen in the inspired air of the trachea.

Standardized Equivalent Sea Depth (SESD)

In order to make sea level diving tables usable during high altitude diving, a new terminology for comparison purposes is created. It must be an acceptable strategy to develop an accurate *correction factor*, so it is possible to convert the *actual lake diving depth* (ALDD) to an equivalent sea dive depth. The risk of contacting DCS increases during ascent following exposure to a higher partial pressure of nitrogen due to the dive. This is because such a rise leads to a proportional rise in the nitrogen gradient between the body and the environment, hereby increasing the body load of nitrogen compared to that at the surface of the lake. This is a relativity model describing loading and de-loading of nitrogen.

SESD is defined as the sea depth in meters (m or msw) for a standardized sea dive, equivalent to a mountain lake dive at any altitude. The sea dive is standardized in air saturated salt seawater with a relative density of 1033 kg m^{-3} , at the general gravity of 9.80665 m s^{-2} . Hereby, a standardized 10 m seawater column corresponds to 1

atmosphere. With fresh water and standardized seawater the *Water density ratio* is (1000/1033) – as developed above.

Calculation of the SESD factor

The actual lake diving depth (ALDD) is converted to SESD by correction for the relative change in typical barometric pressure (P_B Torr) at altitude compared to 760 Torr, and thus the relative change in nitrogen pressure in the inspired air $(760 - 47)/(P_B - 47)$. This is therefore equal to the true inspired *nitrogen ratio*.

$$\text{SESD} = \text{ALDD} * [\text{Nitrogen ratio}] * [\text{Water density ratio}]$$

$$\text{SESD} = \text{ALDD} * [(760 - 47)/(P_B - 47)] * [1000/1033]$$

$$\text{SESD} = \text{ALDD} * [\text{SESD factor}]$$

Calculation of the rate of descent and ascent

The rate of ascent/descent from a standard sea dive table is called *Sea rate*. - Feet (yards) are transferred to meters. - Now the *Lake ascent rate* is equal to the *Sea ascent rate* divided by the SESD factor.

Decompression Stages

Assuming the classical sea level decompression stages to be valid, we need to compensate for the relative pressure changes at altitude. Therefore, the classical sea level decompression stages must be recalculated dividing by the SESD factor.

Results

Modified US Navy dive tables

Now a suitable dive table for sea diving can be followed. We have chosen to modify the US Navy dive table shown below (US Navy Diving Manual 1963). This table is running to a maximum of 60 m at sea level (Table 1), because it is for Navy and professional divers. In fact 100 fsw (equivalent to around 30 m) is considered the max depth for recreational and sport diving (Kizer 2001).

Table 1. The depth is converted from “unified feet” to meters and rounded-off. The diving time is the period from the diver leaves the water surface until the time when he starts to ascend from the bottom. The recommended Total Ascent Period (rounded-off) from depth is based on the maximal allowable ascent rate of 30 feet/min (9 m/min) including necessary stage stops. It is recommended to stop always for an extra 1 minute at the last decompression stage (with an extra SCUBA apparatus) to obtain proper off-gassing. This table only allows one dive per day.

Table 1. Modified US Navy Dive Table for standard dives at sea level
Zubieta & Paulev.

Diving Depth		Diving time	Decompression Stages			Total Ascent Period
Feet	Meters	minutes	30 ft=9 m	20 ft=6 m	10ft=3 m	Minutes
35	11	310			1	2
		320			2	3
40	12	200			1	2
		210			2	3
		230			7	8
50	15	100			1	3
		110			3	5
		120			5	7
60	18	60			1	3
		70			2	4
		80			7	9
70	21	50			1	3
		60			8	10
		70			14	16
80	24	40			1	4
		50			10	13
		60			17	20
90	27	30			1	4
		40			7	10
		50			18	21
100	30	25			1	4
		30			3	6
		40			15	18
110	34	20			1	5
		25			3	7
		30			7	11
120	37	15			1	5
		20			2	6
		25			6	10
130	40	10			1	5
		15			2	6
		20			4	8
140	43	10			1	6
		15			2	7
		20			6	11
150	46	5			1	6
		10			2	7
		15			3	8
		20		2	7	14
160	49	5			1	6
		10			2	7
		15		1	4	10
		20		3	11	19
170	52	5			1	7
		10			2	8
		15		2	5	13
		20		4	15	19
180	55	5			1	7
		10			3	9
		15		3	6	15
		20	1	5	17	29
190	58	5			1	7
		10		1	3	10
		15		4	7	17
		20	2	6	20	34

In order to reduce the risk of DCS further, we suggest to stop at the last decompression stage (3 m for sea diving) for 1 min after any dive, since bubbles have been recorded with ultrasound even from a saturation dive below 5 m. The modified US Navy dive table shown below is running to a maximum of 60 m (190 ft or 57.9 m in Table 1). Recall as mentioned above, recreational diving is recommended down to 100 fsw or 30 m of depth.

Specific mountain lakes

LAKE NYASA

Lake Nyasa – with a surface area of 6,400 km² - is located at an altitude of 500 m (1641 ft) corresponding to a typical barometric pressure of 715 Torr.

The SESD factor, in this case, is equal to $[(760 - 47)/(715 - 47)] * [1000/1033]$ or 1.03. Obviously, there is no need for any correction, and any sea level dive table can be used, just like the modified US Navy dive table presented in Table 1.

LAKE TITICACA

At the surface of the Titicaca Lake, the largest navigable high altitude lake in the world, located in Bolivia and Peru at 3810 m, there is a typical P_B of 480 Torr. Let us consider an actual lake dive to a depth of 38 m:

$$SESD = 38 * [(760 - 47)/(480 - 47)] * [1000/1033]$$

$$SESD = 38 * [1.6466] * [0.968]$$

$$SESD = ALDD * [SESD \text{ factor}]$$

$$SESD = 38 * 1.594 = 60.6 \text{ m seawater.}$$

At Titicaca the SESD factor is therefore equal to 1.594.

We have chosen to recalculate the classical decompression stages (3, 6 and 9 m corresponding to 10, 20 and 30 ft of depth) by division with the value of the SESD factor.

At Lake Titicaca the 3 calculated stages are 2, 4 and 6 m of depth.

Notice that a 38 m Titicaca dive is as dangerous as a 60 m sea dive due to the larger relative pressure exposure. The limit depth for compressed air dives is 60 meters at sea level or any comparable altitude dive.

A new dive Table for Lake Titicaca (Table 2) is developed on the basis of Table 1. The maximally recommended dive depth is 36 m or 119 ft and only for a short period.

Table 2. The Total Ascent Period recommended is based on the maximal allowable ascent rate of 19 feet/min (6 m/min) from depth and includes necessary decompression stage stops. It is recommended to always stop during 1 minute at the last stage to obtain proper off-gassing. This table only allows one dive per day.

Table 2. Modified US Navy Dive Table for Lake Titicaca (3810 m; standard dives with compressed air). Zubieta & Paulev.

Diving Depth		Diving time	Decompression Stages			Total Ascent Period
Feet	Meters	minutes	19 ft=6 m	13 ft=4 m	6 ft=2 m	Minutes
22	7	310			1	2
		320			2	3
25	8	200			1	2
		210			2	3
		230			7	8
31	10	100			1	3
		110			3	5
		120			5	7
38	12	60			1	3
		70			2	4
		80			7	9
44	13	50			1	3
		60			8	10
		70			14	16
50	15	40			1	4
		50			10	13
		60			17	20
56	17	30			1	4
		40			7	10
		50			18	21
63	19	25			1	4
		30			3	6
		40			15	18
69	21	20			1	5
		25			3	7
		30			7	11
75	23	15			1	5
		20			2	6
		25			6	10
82	25	10			1	5
		15			2	6
		20			4	8
88	27	10			1	6
		15			2	7
		20			6	11
94	29	5			1	6
		10			2	7
		15			3	8
		20		2	7	14
100	31	5			1	6
		10			2	7
		15		1	4	10
		20		3	11	19
107	33	5			1	7
		10			2	8
		15		2	5	13
		20		4	15	25
113	34	5			1	7
		10			3	9
		15		3	6	15
		20	1	5	17	29
119	36	5			1	7
		10		1	3	10
		15		4	7	17
		20	2	6	20	34

LAKE TSO MORARI

Lake Tso Morari is located in the Ladakh region of the Himalayas at an altitude of 4900 m. corresponding to a typical barometric pressure of 451 Torr.

Here, the SESD factor is equal to $[(760 - 47)/(451 - 47)] * [1000/1033]$ or 1.709. A dive at Lake Tso Morari of 35 m corresponds to an sea dive of 60 m. The maximal depth of this lake is said to be 30-35 m. A dive table for this lake can be developed.

Discussion

A recent review suggests the use of staged decompression for the reduction of decompression sickness for non-decompression dives (Gordon 1996). In order to reduce the risk of DCS further, we suggest to use an extra stop at the last decompression stage (3 m for sea diving) for 1 min also after non-decompression dives. Bubbles have been recorded with ultrasound even from a saturation dive to less than 5 m.

The values in m for the former US yard and the imperial yard are both so close to the value for the unified yard (0.9144) – and thus the “unified foot “ used in this report - that the minor conversion differences between feet and meters for dives up to 60 m are immaterial.

Previous models differ from ours in the following way: First, the effect of the water vapour pressure in the inspired tracheal air was not included. This factor increases in importance with altitude. Second, the difference between the density of fresh water and

sea water were not included. Third, the decompression stops are not corrected for use at altitude. Fourth, the ascent rate at altitude is not corrected either.

The Buhlmann altitude diving tables (2005) are divided into groups covering 0-700 m and 700-2500 m. They present extended details which seem difficult for a practical dive.

Our model – and hereby our tables – assume that the body is a black box, so we need not consider maximum allowable nitrogen tissue tensions for a single dive per day on compressed air. The dive table presented here for Lake Titicaca is based on the US Navy sea dive table adapted and modified by us, and it is being tested at the High Altitude Naval Diving School at Lake Titicaca, Bolivia (3800 m).

Noteworthy is the fact that the Total Ascent Period remains the same for comparable dive depths in all our tables - a result of the correct mathematical procedure. The numerator (diving depth) and the denominator (ascent rate) are both subjected to the SESD correction.

Recommendations

1. Any compressed air dive up to a maximum of 60 meters at sea level (or any comparable altitude dive) should always stop the ascent at the last stage for 1 minute for proper off gassing. - The classical decompression stages (30, 20 and 10 feet or 9, 6 and 3 m) are corrected to the lake altitude level by dividing the stage value with the SESD factor.
2. The ascent rate at altitude is crucial and should always be slower than at sea level. The *Lake ascent rate* is equal to the *Sea ascent rate* divided by the SESD factor.

Precautions

These equations and calculations must be used as guidelines only. An sea dive depth of 60 m is generally agreed to be the limit for professional compressed air dives.

Diving requires knowledge and several variables must not be overlooked: Adequate and quality equipment, diver's health condition and body temperature, quality compressed air etc. Hence we assume no responsibility. If suspicion of DCS occurs, use supplementary oxygen on open mask during transportation to a recompression chamber for proper treatment.

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