Equivalent air depth: fact or fiction

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Berghage, T. E., and T. M. McCracken. 1979. Equivalent air depth: fact or fiction. Undersea Biomed. Res. 6(4): 379–384.—In mixed-gas diving theory, the equivalent air depth (EAD) concept suggests that oxygen does not contribute to the total tissue gas tension and can therefore be disregarded in calculations of the decompression process. The validity of this assumption has been experimentally tested by exposing 365 rats to various partial pressures of oxygen for various lengths of time. If the EAD assumption is correct, under a constant exposure pressure each incremental change in the oxygen partial pressure would produce a corresponding incremental change in pressure reduction tolerance. Results of this study suggest that the EAD concept does not adequately describe the decompression advantage obtained from breathing elevated oxygen partial pressures. The authors suggest that the effects of breathing oxygen vary in a nonlinear fashion across the range from anoxia to oxygen toxicity, and that a simple inert gas replacement concept is no longer tenable.

decompression theory
equivalent air depth
decompression schedules

Equivalent air depths (EAD’s) are theoretical constructs used in the U.S. Navy Diving Manual (1977) to determine the air decompression schedules to be used during nitrogen-oxygen mixed-gas dives. The EAD concept assumes that oxygen does not contribute to the total tissue gas tension, and that only the partial pressure of the inert gas need be considered in decompression calculations. This concept was recognized by Haldane and Priestley (1935), although it was not part of their original model.

An EAD is a theoretical depth at which the air breathed has a nitrogen partial pressure equivalent to that of the actual diving depth. An example of this conversion is as follows:

Actual dive depth: 99 fsw (4 ATA)
Breathing gas mixture at 99 fsw (4 ATA): Oxygen 38% (1.5 ATA); Nitrogen 62% (2.5 ATA)
Depth for decompression calculation: 71.5 fsw (3.16 ATA)
Fig. 1. Relationship between partial pressure of inert gas and percentage of mice with serious decompression sickness for various oxygen exposures (Berghage et al. 1973).

\[
EAD = \frac{\text{nitrogen partial pressure}}{\text{nitrogen content in air}} = \frac{2.5}{0.79} = \frac{3.16 \text{ ATA}}{71.5 \text{ fswg}}
\]

Using this principle, one should be able to manipulate the decompression requirements within the oxygen anoxic-toxic limits. If the total exposure pressure is constant, every one-atmosphere increase in the oxygen partial pressure should produce a corresponding one-atmosphere improvement in the pressure reduction tolerance. This should be true for both nitrogen-oxygen and helium-oxygen breathing mixtures.

Hempleman (1963) reported on the results of a goat experiment in which the improvement in pressure reduction tolerance was almost equal to the amount of inert gas replaced by oxygen. After breathing air enriched with 0.45 atm of oxygen for 18 min, the average improvement in pressure reduction tolerance was 0.42 atm. After a 180-min exposure to the same enriched mixture, the pressure reduction tolerance was improved by 0.38 atm. According to the EAD concept, these results are what one would expect statistically. Despite such supportive experimental results, it is obvious that there are limits to the decompression improvements that can be expected through the use of oxygen.

Current operational evidence raises questions concerning the adequacy of the EAD concept. For example, it is known that in human saturation diving, the incidence of decompression sickness varies, depending on whether the divers are breathing 0.3 or 0.4 atmospheres of oxygen, even though the inert gas pressure can be very high. A study by Berghage, Conda, and Armstrong (1973) has also demonstrated experimentally that oxygen interacts with pressure. As shown in Fig. 1, exposures to the same inert gas partial pressure produced significantly different results, depending on the oxygen level in the breathing medium. To explore these results more systematically, we replaced the inert gas with oxygen in quantifiable increments to determine if the pressure reduction threshold increased in a corresponding fashion.
TABLE 1
EXPERIMENTAL CONDITIONS AND RESULTS

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<tr>
<th>Oxygen Partial Pressure, ATA</th>
<th>Exposure Time, min</th>
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<tr>
<td>Wt</td>
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<td>232.4</td>
<td>218.2</td>
<td>233.2</td>
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<tr>
<td>( r )</td>
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<td>.92</td>
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<tr>
<td>( ED_{50} )</td>
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<td>10.8</td>
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<td>( ED_{50} )</td>
<td>13.4</td>
<td>12.2</td>
<td>12.0</td>
<td>12.2</td>
<td>11.4</td>
<td>11.7</td>
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\( n \) = Number of animals used to determine the \( ED_{50} \); \( Wt \) = mean weight of the animals; \( r \) = correlation coefficient for the least-squares best-fit line used to determine the \( ED_{50} \); \( ED_{50} \) = pressure reduction in atmospheres that will produce a 50% bends incidence.

METHOD

The study employed 18 experimental conditions; subjects were 365 male albino rats (Tac: N(SD)FBR, Sprague-Dawley derived). The animals were housed in groups of five. Their mean and standard deviation free-feeding weight at the time of the experiment was 232.4 \( \pm \) 37.1 g. The mean weights of the animals for each experimental condition are shown in Table 1.

The experimental exposures were made in a Bethlehem Model 1836 10-HP chamber, which had a volume of approximately 170 liters. The chamber atmosphere was monitored with a Beckman Model F-3 paramagnetic oxygen analyzer; the oxygen partial pressure was varied between 0.2 and 3.2 ATA, depending on the experimental condition. In the 60 s prior to pressure reduction, the oxygen partial pressure was changed to provide 0.51 ATA at the pressure level to which the chamber was being decompressed. Carbon dioxide levels were not monitored because previous exposures had demonstrated that the chamber life-support system kept the carbon dioxide level well below 0.2% surface equivalent. Chamber pressure was monitored with a recently calibrated Heise gauge (zero to 2000 fsw) and maintained within \( \pm \) 4 fsw of the specified pressure. The temperature in the chamber was kept at 28 \( \pm \) 2°C.

During each pressure exposure, five rats were exercised at a rate of 5 rpm (3.33 m/min) in a rotating cage. The 5-section cage was constructed of wire mesh over a Plexiglas frame, 63.5 cm long and 22.4 cm in diameter; each section was approximately 12 cm wide. The cage was rotated in the chamber by a sparkless, shaded pole motor (Eberback Corp., Con Torque: 115 V, 60 cycle, 1/10 HP).

Procedures during the experimental exposures were:
1. Compress to 0, 66, or 99 fsw (1, 3, or 4 ATA) with oxygen as rapidly as possible.
2. Compress to 462 fsw (15 ATA) with helium at the rate of 150 fpm (4.55 atm/min).
TABLE 2
INTERCORRELATION MATRIX OF EXPERIMENTAL VARIABLES

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<th>3</th>
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<td>3.</td>
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<tr>
<td>4.</td>
<td>0.44</td>
<td>—0.56</td>
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</table>

\( r = .40 \Rightarrow (P < .05) \quad (r = .54) \Rightarrow (P < .01) \)

\( E_{D50} = 10.4 + 0.24 (O_2) - 0.01 (T) + 0.006(Wt) \); 
\[ \text{SEE} = 0.56 \text{ atm}; r = .73. \]

\( O_2 \) = oxygen partial pressure in ATA; \( T \) = time in minutes; \( Wt \) = weight in grams; \( E_{D50} \) = effective dose (change in pressure, atm) to produce symptoms in 50% of the animals.

3. Check the oxygen level and correct as needed.
4. Remain at 15 ATA for 1, 5, 10, 20, 40, or 80 min, depending on the experimental condition.
5. Alter the oxygen level to equal 0.5 ATA at the observation pressure\(^1\) in the last 60 s of the bottom time.
6. Decompress to the observation pressure at the rate of 1 atm/s.
7. Evaluate and classify rat behavior for the presence or absence of signs of decompression sickness\(^2\) at the end of a 20-min observation period.

RESULTS

The \( E_{D50} \)’s obtained in each experimental condition are shown in Table 1. The intercorrelations among the experimental variables are given in Table 2. Statistical analysis of these results indicates that both the oxygen partial pressure \((P < 0.01)\) and the exposure time \((P < 0.001)\) affect pressure reduction tolerance. These are the expected results; if they had not been statistically significant, the study would have been in question. The main objective of this study was to determine if the differences in pressure reduction tolerance between the various oxygen levels were directly related to the size of the oxygen partial pressure differences. This evaluation used the 0.2-ATA oxygen condition as the base line against which the 2.2- and 3.2-ATA conditions were compared. The assumption that oxygen does not contribute to the total gas tension suggests that the average pressure reduction tolerance across the various exposure times should be 2 atm greater for the 2.2-ATA oxygen conditions and 3 atm greater for the 3.2-ATA conditions. A chi-square test of the results shown in Fig. 2 indicates that there is very little chance that the oxygen contribution assumption is correct. The incremental change in pressure reduction tolerance does not correspond to a change in oxygen partial pressure.

\(^1\) The observation pressure levels were selected to produce a decompression incidence between zero and 100%. A least-squares best-fit line was applied to the data to establish an \( E_{D50} \) estimate. The st of the \( E_{D50} \) estimate after exposure at 15 ATA is ± 0.05 atm.

\(^2\) A 20-min observation period was sufficient to observe 99% of the decompression sickness signs that occurred; signs included paralysis, convulsions, and tumbling in the cage.
Fig. 2. Changes in pressure reduction tolerance associated with time and various oxygen partial pressures.

DISCUSSION

It would appear that the theoretical assumptions that underlie the EAD concept are valid only for a relatively narrow range of oxygen partial pressures. With the total pressure held constant, the trade-off between oxygen and the inert gas does not appear to produce a corresponding linear change in pressure reduction tolerance over the full range of tolerable oxygen exposures. Admittedly, these results are based upon research using rats as subjects, and we do not fully understand the decompression relationship between rats and man (Berghage, David, and Dyson 1979). Also the oxygen partial pressures in this study are higher than those normally used. The operational evidence mentioned in the introduction of this paper indicates that the cardiovascular or pharmacological effects of oxygen are probably exerted at relatively low Po2 values, and the area of interest is between perhaps 0.2 and 1 atm of oxygen or within the range that will saturate hemoglobin even in the venous supply. Small increases in the oxygen partial pressure breathed by large animals may initially result in an increase in pressure reduction tolerance, but, based on the results of this and another unpublished study done in this laboratory, the relationship does not appear to be linear over the entire range of oxygen effects, from anoxia to toxicity.

The decompression rate of 1 atm/s used in this experiment is much greater than the rate used in human studies, and undoubtedly influenced our results. At this decompression rate any gas, inert, oxygen, or carbon dioxide, probably would not have time to equilibrate and would therefore contribute to bubble formation. Thus, the conditions of this experiment are heavily weighted toward the occurrence of decompression sickness caused by gas retention in the tissue. With more reasonable rates of decompression, results might change drastically. It is important to note, however, that the initial increases in Po2 from 0.2 to 2.2 had a significantly beneficial effect.
Some decompression advantages are obviously gained by breathing elevated oxygen partial pressures. It does not appear, however, that subtracting the oxygen partial pressure from the total gas present is an accurate way of describing oxygen’s contribution. Oxygen is physically and biologically active, and its effects in the decompression process are probably much more complex than present theories would have us believe.

Naval Medical Research and Development Command, Work Unit No. M0099-PN.001.1190. The opinions and assertions contained herein are the private ones of the writers and are not to be construed as official or reflecting the views of the Navy Department or the naval service at large.

The experiments reported herein were conducted according to the principles set forth in the “Guide for the Care and Use of Laboratory Animals,” Institute of Laboratory Resources, National Research Council, DHEW, Pub. No. (NIH) 78-23.

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T. E. Berghage and T. M. McCracken. La profondeur équivalente d’air: réalité ou fiction. Undersea Biomed. Res. 6: 379–384, 1979. Dans la plongée au gaz mélangés le concept d’une profondeur équivalente d’air (PEA) suggère que l’oxygène ne contribue pas à la tension gazeuse totale de tissu et peut être mettre de côté dans le procédé de décompression. La validité de cette hypothèse avait été contrôlée d’une manière expérimentale en exposant 365 rats aux pressions partielles d’oxygène variées pendant des durées variées. Si l’hypothèse de PEA est correcte, dans la pression d’exposition constante chaque changement unitaire de la pression partielle d’oxygène correspondrait à un changement unitaire de la tolérance réduction-pression. Les résultats de cette étude suggèrent que le concept de PEA ne décrit pas d’une manière suffisante le bénéfice décompressif qui vient de la respiration des pressions partielles d’oxygène élevée. Les auteurs suggèrent que les effets dérivés de la respiration d’oxygène fluctuent de façon non linéaire à travers une plage de l’anoxie à la toxicité d’oxygène, et qu’un concept simple du remplacement du gaz inertes ne reste plus tenable.

théorie de la décompression
profondeur équivalente d’air
tables de décompression

REFERENCES


