



ACCLIMATIZATION YOU DON'T WANT - CARBON DIOXIDE

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In a US Navy experimental facility, testing for new decompression schedules was underway using nitrox mixtures with a higher concentration of oxygen than the 21 percent in air.

The Navy investigators first used 100% O₂ at various pressures to work out tolerance limits for oxygen itself. They established a tentative "limit curve" based upon presumably reliable data. The actual tests were carried to 25% longer times than on the limit curve. No serious toxicity was observed inside the limit curve, so this was accepted as safe.

It seemed rational to assume that PO₂ was the only crucial variable to derive limits for mixtures. Simply translating the limits for 100% O₂ into curves for different nitrox mixtures on the basis of oxygen partial pressures, meant the mixtures should have been all right. But in the first experiment that they tested nitrox mixtures, the diver convulsed. After that there were problems suggesting early oxygen poisoning and other strange effects where no difficulties were expected.

WHAT'S GOING ON WITH MIXED GAS?

The year was 1952. The U.S. Navy Experimental Diving Unit (EDU), then located in Washington, D.C., was ordered to work out a system utilizing "mixed gas" to reduce decompression requirements for practical applications like clearing mines from a harbor. Project Officer Lieutenant Commander J.V.

Dwyer and Assistant Medical Officer Lieutenant E.H. Lanphier (MC) took major responsibility for this work.

Dives with nitrox mixtures appeared to produce an unusual number of problems compared to previously worked-out oxygen limits. Furthermore, these problems did not occur when using helium-oxygen mixtures with the same oxygen pressure.

The only plausible explanation involved carbon dioxide. There was no CO₂ in the mixes, and dead space in the breathing apparatus was minimal; but data from an earlier study (1) indicated that, at depth, some divers breathed less than others during similar exertion. Divers who breathed much less probably did not eliminate CO₂ adequately. This was of particular concern from the standpoint of susceptibility to oxygen convulsions. CO₂ excess increases brain blood flow, and that increases the "dose" of oxygen to the brain. Lanphier and Dwyer experimentally verified that some EDU divers breathed less than others during equivalent work. They sampled end-tidal gas (the last gas breathed out in a normal expiration, ideally consisting only of alveolar gas) for an estimate of levels of CO₂ in arterial blood. At depth, end-tidal CO₂ was definitely high in certain individuals, particularly when N₂-O₂ mixtures were used (2). (Note: it is sometimes possible for end-tidal CO₂ samples to overestimate arterial levels with certain breathing patterns, most notably slow, deep breathing. For this reason, studies using end-tidal gas readings should cross-verify against arterial samples, as was done in this study).

An independent study in 1995 repeated the EDU conditions and confirmed the results. Investigators looked at CO₂ retention during hyperbaric exercise while breathing 40/60 nitrox. They determined that CO₂ retention "is not expected to be globally aggravated by breathing nitrox down to 30 meters, but that some individuals could be so affected." (3)

STARTLING RESULTS WITH HELIUM-OXYGEN MIXTURES

From continued work it became clear that while breathing nitrogen-oxygen mixtures at depth, carbon dioxide retention occurred, whereas with helium-oxygen, ventilation was essentially unimpaired and CO₂ levels stayed close to normal. Conclusions reached following the 1956 and 1957 studies (4) included the following:

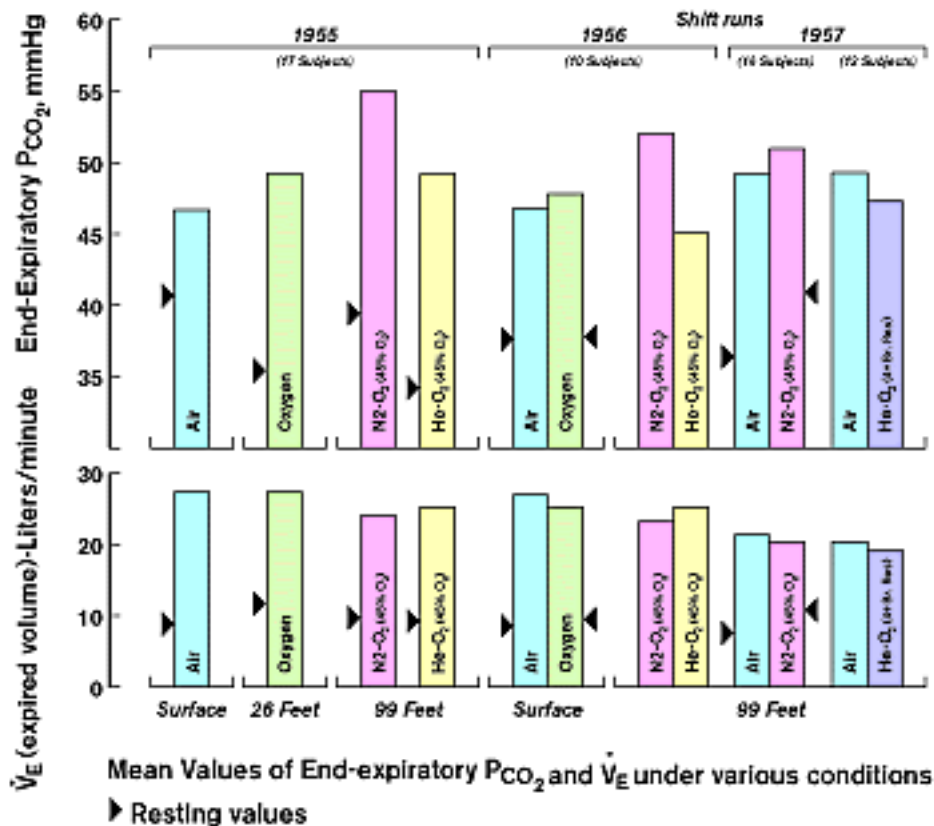
- (1) Retention of carbon dioxide during working dives at moderate depth is a definite reality.
- (2) Only when the breathing medium is a helium-oxygen mixture is an increase in body carbon dioxide tension absent or small.
- (3) Although increased breathing resistance and dead space both favor carbon dioxide retention, keeping these factors to a practical minimum does not eliminate the problem.
- (4) Some individuals are much more likely to develop high carbon dioxide tensions than others, but all individuals show a tendency in this direction especially when breathing a nitrogen-oxygen mixture. There is no sharp dividing line between "retainers" and "normals."
- (5) The most effective method of minimizing the complications caused by carbon dioxide retention is to use helium-oxygen mixtures for "mixed gas" dives.

The recommendations of Research Report 7-58 can be reproduced verbatim:

"It is recommended that:

- (1) Attempts to use high-oxygen nitrogen-oxygen mixtures be abandoned as a means of reducing the requirements of decompression.
- (2) Studies leading to the use of helium-oxygen mixtures for "mixed gas" diving be carried forward as rapidly as possible."

Figure 1: USN Experimental Diving Unit • Nitrogen-Oxygen Mixture Physiology 1955-57



USN Experimental Diving Unit - Nitrogen-Oxygen Mixture Physiology 1955-7.

WHY IS CO2 RETENTION A PROBLEM?

As early as 1878, physiologist Paul Bert demonstrated 'auto-intoxication' of animals by their own carbon dioxide in a super-oxygenated environment. He was also aware of the possible connection between carbon dioxide and oxygen toxicity (5). CO2 retention at depth was once suggested as the sole cause of nitrogen narcosis (6, 7). Another, less prominent idea, was that only CO2 retainers might suffer oxygen toxicity during exertion more readily than others (8). Carbon dioxide retention is now viewed as a contributor to oxygen toxicity and nitrogen narcosis, suspected as a contributor to decompression sickness, and implicated in incidents of underwater confusion and loss of consciousness.

During World War II, British Royal Navy torpedo divers using oxygen rebreathers were passing out

without warning. The term "shallow water blackout" was used in 1944 by Barlow and MacIntosh (9) for blackout suspected, and later confirmed, from too high CO₂ levels (hypercapnia). It was termed "shallow water" because oxygen rebreathers could not be used in deep water because of the high oxygen content. Most of the cases weren't deep enough to have been O₂ toxicity, which had previously been the prime suspect. The problem subsided after improving carbon dioxide absorption canisters. Although the term "shallow water blackout" had the established meaning of CO₂ retention-induced blackout, it was later applied to unconsciousness from too low oxygen (hypoxia) in breath-hold diving, especially following excessive hyperventilation. The mix-up has continued into common use.

NORMAL CO₂ PRODUCTION AND REMOVAL

Normally, arterial CO₂ is held, almost without exception, within 3 mmHg during both rest and exercise, a very tight range. How does your body do this?

How much, and how deeply you breathe, is regulated by your arterial oxygen pressure, carbon dioxide tension, pH, by reflexes in your lung and chest wall, and through control by your brain.

Not enough oxygen in your breathing mixture enhances the ventilatory drive; there is a hypoxic drive to breathe. CO₂ is an even more profound respiratory stimulant. Of all the various inputs, your arterial CO₂ is the most influential. That means that rising production of CO₂ with exercise increases how much and how fast you breathe, regulating your CO₂, so that CO₂ does not normally rise at all, even during heavy exercise.

In the normal population, CO₂ is also constant at rest, only rising a bit during sleep. (An important exception involves the condition of sleep-apnea. Sleep apnea is a sleep disorder involving snoring, where the snorer stops breathing during sleep because of upper airway obstruction, resulting in repeated shortage of oxygen to the brain. Carbon dioxide levels rise, due to absence of ventilation for varying periods, sometimes hundreds of times per night. Sleep apnea sufferers are often overweight, heavy necked males. For long-term treatment, losing weight is often very effective.)

MECHANISMS OF CO₂ RETENTION

Normally, no great rise in your CO₂ levels occurs during rest or exercise. Sometimes it does rise, however. Why is this?

Several variables seem to impair the CO₂ response during underwater work. From Lanphier three main contributors emerged: Breathing high partial pressures of oxygen (elevated P_iO₂), inadequate ventilatory response during exertion, and increased work of breathing (10).

High PO₂ decreases ventilation in some situations. Lanphier found that increased inspiratory oxygen pressure accounts for about 25% of the elevation in end tidal CO₂. Lambertsen et al. (11) demonstrated

that exercise while breathing hyperbaric oxygen decreases ventilation significantly. Other authors find that at a given work rate below the anaerobic threshold, (steady-state exercise) ventilation is not appreciably different between 100% O₂ breathing, and air breathing (12, 13, 14). Your respiratory centers respond to CO₂ to the extent that it keeps things level whether working or at rest, with some modifications. Working hard enough to produce lactic acid will change that to compensate for the metabolic acidosis, but high inspired oxygen levels knock out the chemoreceptor response to lactic acid, which helps explain CO₂ retention in working divers who at least are verging on anaerobic threshold.

Most of the elevation of PaCO₂ were accounted for by the increased work of breathing at depth. Work of breathing is made more difficult by the higher gas density at depth. Your body compensates by reducing ventilation - easily demonstrated by trying to breathe through a narrow tube. In a 1977 study of tolerance to various gases at extreme densities, Lambertsen et al., found a "prominent reduction of total and alveolar ventilation (15). Response was unrelated to any narcotic properties of the gases in questions, demonstrating that ventilatory suppression was not a function of narcotic depression. It was the gas density and work of breathing limited pulmonary function. The early work at EDU seemed to show that the critical factor in the CO₂ problems was the higher gas density of the nitrogen mixtures compared to helium mixtures.

WHY CO₂ ACCLIMATIZATION?

Ordinarily, rising levels of CO₂ produce an increasingly uncomfortable desire to breathe more. However, there is a great range of response. Some people have a normal response, others are remarkable in retaining CO₂ to a large extent - they just don't have much response to CO₂. The question behind carbon dioxide retention is, why do some subjects not increase ventilation to regulate their rising CO₂ levels?

Some evidence suggests that the tendency to retain CO₂ increases with chronic exposure to high CO₂ environments, such as those encountered during specific diving situations. The body gets used to higher levels, allowing them to occur without the usual autoregulation that would correct the situation.

In the first EDU studies, almost all of the subjects had been experienced "hard hat" divers. The volumes of air needed for adequate ventilation of a helmet are very great, particularly at significant depth. Adequate ventilation of a helmet is unlikely, so acclimatization to CO₂ may have been an occupational necessity.

Divers often had other reasons for repeated elevation of their arterial PCO₂ such as repeated deep breath-hold diving in submarine escape training. Schaefer (16) found that submarine escape tank instructors retained more CO₂ than the average untrained man. He suggested a possible adaptation effect. Kerem, et al. (17) found that both diver and non-diver subjects exhibited similar resting CO₂ arterial levels, but when exercising, arterial CO₂ was higher in divers. They confirmed this in a later study of CO₂ retention during nitrox breathing (3). MacDonald and Pilmanis (18) found a moderate, consistent elevated CO₂ level and characteristic hypoventilation in 10 of 10 male divers they tested on open circuit scuba during open water dives.

There may be some sort of selection, where those who tolerated high CO2 levels via a blunted chemoreceptor or other adaptive response, self-select to continue with their diving career. That situation must be less prevalent today, so the number of CO2-tolerant divers from that source may be considerably smaller. Perhaps, a number of the carbon-dioxide retaining divers are sleep-apneics, who routinely experience high carbon dioxide levels during sleep. The large, heavy, body types of many divers suggests this.

In some cases, CO2 retention occurs in subjects with no experience with high-CO2 environments, but who may be exposed in other ways, most notably a learned adaptation from breathing patterns that regularly produce elevated internal CO2 levels. When scuba diving first became prevalent, "skip breathing" was often taught or popularized by word of mouth as a means of conserving the air supply in open circuit scuba. Educational efforts to discourage skip breathing have had some effect, so fewer individuals have probably become CO2-tolerant in this way.

Some CO2 retainers lack any history of probable acclimatization. There are a few individuals (we don't know just how few) who retain CO2 with no suggestion that this is an adaptive response. A 1995 study by Clark, et al., (19) found increased levels of arterial CO2 with increasing exertion in normal subjects exposed to 2 atm of oxygen on dry land.

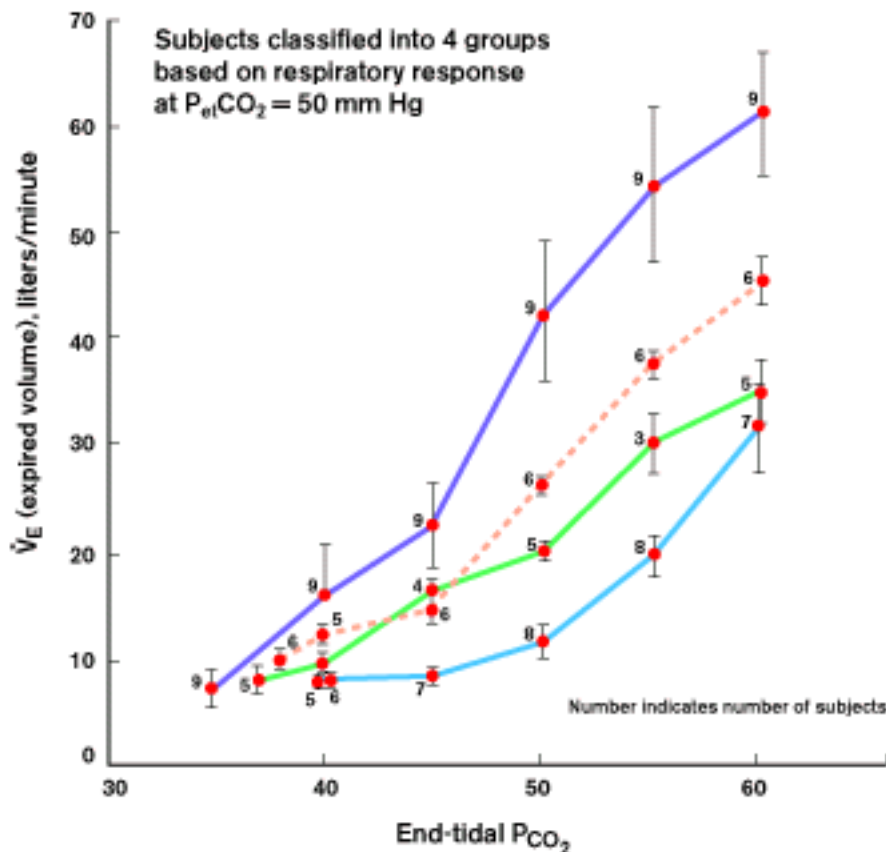
Still, CO2 acclimatization is not as cut-and-dried as it may sound. A recent book on the control of respiration (20) makes this statement: ". . . significant, sustained CO2 retention is extremely rare in health, even under the most extreme conditions of exercise intensity and flow limitation." One of the editors, Jerome Dempsey, acknowledges that this statement does not necessarily apply to individuals who have had some reason for adaptation to CO2. Dempsey (21) says that in a career of exercise-related research, he has encountered only one or two individuals who would be classified as "CO2 retainers" in terms of our definition.

IDENTIFICATION OF RETAINERS

Many attempts have been made to identify carbon dioxide retainers. Such people could be at unexpected risk of CO2 blackout, unusual degrees of nitrogen narcosis, or susceptibility to oxygen toxicity. Identification, for that reason, would be a helpful screening.

The main hope at EDU originally was that outstanding CO2 retainers could be identified and kept from hazardous exposures. If so, others could take advantage of the benefits of nitrox diving. A dry-land test of ventilatory response to various levels of inspired CO2 was set up (3). There was a great spread of results (Figure 2), and these were compared with the CO2 levels that the divers developed spontaneously at depth. In about 60% of cases, high CO2 at depth corresponded to low response to inspired CO2; but in the other 40%, such a relationship was not seen. The correlation was not good enough for a fair, reliable selection test.

Figure 2: USN Experimental Diving Unit Carbon Dioxide Response Study 1957



VENTILATORY RESPONSE TO CO2

USN Experimental Diving Unit Carbon Dioxide Response Study 1957

In other work involving tethered swimming at submaximal work rate, 11 of 19 subjects developed elevated CO2 levels. A CO2 rebreathing test did not clearly pre-identify these people, leading to the conclusion that identification of CO2 retainers may require a test with exercise (22). A tethered fin-swimming test is an example.

David Elliott recommends screening tests be developed for compressed air divers for working divers doing heavy work deeper than 120 feet who might be at risk of unconsciousness (23). However, it seems there is no easy, reliable method of identifying retainers in advance. However, unusually low air-use rates would arouse our suspicions. The need for better and more accurate tests is evident

AVOIDING CO2 RETENTION

If the solution of the CO2 retention problem does not lie in personnel selection, what other avenues are open? Avoidance of "skip breathing" and any other attempt to conserve air seems obvious, but it may be easier to recommend than to accomplish. Providing ventilatory assistance to divers may deserve

investigation.

Another solution would be to use He-O₂ mixtures instead of N₂-O₂. There is work supporting that CO₂ retention is minimal or non-existent when the breathing medium is a helium-oxygen mixture (2, 4) (eg 7-55 & 7-58). In the probable range of depths and times, helium should not be much less desirable than N₂-O₂ from the standpoint of decompression. Some advantages of nitrox would be lost if heliox were to be adopted, but safety may be considered a deciding factor.

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LITERATURE CITED

1. Report of the Cooperative Underwater Swimmer Project (CUSP). (Jan 1953) National Research Council Committee on Amphibious Operations Report NRC:CAO:0033,
2. Lanphier EH. (1955). Nitrogen-Oxygen Mixture Physiology, Phases I and 2. Formal Report 7-55, Washington: Navy Experimental Diving Unit.
3. Kerem D, Daskalovic YI, Arieli R, Shupak A. (1995). CO₂ retention during hyperbaric exercise while breathing 40/60 nitrox. *Undersea & Hyperbaric Medicine* 22(4): 339-346.
4. Lanphier EH. (June 1958). Nitrogen-Oxygen Mixture Physiology, Phases 4 and 6. Research Report 7-58. Navy Experimental Diving Unit. Panama City Florida 32407.
5. Bert P. (1878) *La Pression Manometrique*. G. Masson, Paris.
6. Bean JW. (1950). Tensional changes of alveolar gas in reactions to rapid compression and decompression and question of nitrogen narcosis. *Am J Physiol* 16, 417-425.
7. Seusing J and Drube HC. (1960). The significance of hypercapnia for the occurrence of depth intoxication. *Klin Wschr* 38, 1088-1090.
8. Lambertsen CJ, Owen SG, Wendel H, Stroud MW, Lurie AA, Lochner W, and Clark GF. (1959). Respiratory cerebral circulatory control during exercise at 0.21 and 2.0 atmospheres inspired PO₂. *J*

Applied Physiol 14, 966-982.

9. Barlow HB, and MacIntosh FC. (1944). Shallow water black-out. Royal Navy Physiological Laboratory Report R.N.P. 44/125 UPS 48a.
10. Lanphier, EH, Lambertsen CJ, Funderbunk LR. (1956). Nitrogen-oxygen mixture physiology Phase 3. End tidal gas sampling system carbon dioxide regulation in divers carbon dioxide sensitivity tests. Research report 2-56. Dept of the Navy. Navy Experimental Diving Unit. Panama City Florida 32407.
11. Lambertsen CJ. (1955). Respiratory and circulatory action of high oxygen pressure. Proc. Underwater Physiol. Symposium. Pubn. 377, Nat. Ac Sc & Nat Res C. Washington, DC.
12. Asmussen E and Nielsen M. (1946). Studies on the regulation of respiration in heavy work Acta Physiol Scand. 12, 171-178;
13. Wasserman K. (1976). Testing regulation of ventilation with exercise. Chest, 70, 173S-178S
14. Welch, Mullin, Wilson, and Lewis. (1974). Effects of breathing O₂- enriched mixtures on metabolic rate during exercise. Med Sci Sports, 6, 26-32
15. Lambertsen CJ, Gelfand R, Peterson R, Strauss R, Wright WB, Dickson JG, Puglia C, and Hamilton RW. Human tolerance to He, Ne, and N₂ at respiratory gas densities equivalent to He-O₂ breathing at depths to 1200, 2000, 3000, 4000, and 5000 feet of sea water (predictive studies III). Aviat, Space and Env Med. 48 (9): 843-855.
16. Schaefer KE (1965). Adaptation to breath-hold diving. In Physiology of breath-hold diving and the Ama of Japan. Pub 1342, p 237-251, NRC-NAS, Washington, DC.
17. Kerem D, Melamed Y, and Moran A. (1980). Alveolar PCO₂ during rest and exercise in divers and non-divers breathing O₂ at 1 ATA. Undersea Biomed Res 7, 17-26.
18. MacDonald JW and Pilmanis AA. (1980). Carbon Dioxide retention with underwater work in the open ocean. In The Unconscious Diver. 25th Undersea Medical Society Workshop Madison Wisconsin 18-20 September 1980. E.H. Lanphier (ed). UMS Bethesda, MD.
19. Clark JM, Gelfand R, Lambertsen CJ, Stevens WC, Beck, G. Jr., and Fisher DG. (1995). Human tolerance and physiological responses to exercise while breathing oxygen at 2.0 ATA. Aviat. Space, Environ. Med. 66: 336-345.
20. Dempsey J, and A Pack, Editors. (1995). Regulation of Breathing. Second Edition. Marcel Dekker, Inc. NY, Basel, Hong Kong.

21. Dempsey, Jerome. Personal communication, August 1995.
 22. Hashimoto A, Daskalovic L, Reddan WG, and Lanphier EH. (1981). Detection and modification of CO2 retention in divers. Undersea Biomed Res (Suppl.) 8, 47 (abstract 68).
 - 23 Elliott D. (1990) Loss of consciousness underwater. In Diving Accident Management: Proc. Forty-first Undersea and Hyperbaric Medical Society Workshop, pp 301-310, Durham, NC.
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