The Story of CO2 Build-up

by the Reverend Edward Lanphier

How did I ever get myself into this? That question crossed my mind; but I knew the answer, and it felt good. *"This"* was trying to determine oxygen tolerance limits for US Navy oxygen and mixed gas diving. The year was 1953, and I was under pressure equivalent to 50 feet of sea water in the "wet pot" of a research chamber at the old US Navy Experimental Diving Unit (EDU) in Washington, D.C. I was Assistant Medical Officer and Physiologist there. In those days, the only assurance the enlisted divers had that an experiment was reasonable was the willingness of officers like me to go through it ourselves, which we always did.

Right then, I was swimming vigorously on the "trapeze swim ergometer" that Engineering Officer Jolly Dwyer and I had dreamed up for just such purposes. I was very glad that I'd spent weeks working out in the pool with my Giant Duckfeet to get in shape for runs like this. We had to be working hard to make the tests meaningful; exertion was one of the main factors known to make oxygen toxicity come on sooner. My legs were handling the load pretty well, the full-face mask was supplying plenty of pure oxygen, and the 15 minutes of the test must have been nearly over. A week or so before, I'd made the same run, 15 minutes at 50 feet , with no problems, but the work load had been lighter then.

I wasn't expecting any trouble, but very suddenly one of the muscles in my right leg contracted sharply & endash; involuntarily and uncontrollably. It didn't last for long, but it upset my swimming completely. Could this be a warning of an impending oxygen convulsion? It probably was. If so, I was lucky. Some of the subjects, like Dwyer, had gone into grand-Malabar epileptic-type seizures with no warning at all.

I started to get off the "trapeze," and my alert in-water tender grabbed me. Good thing! Now I was having great all-over jerks and spasms and couldn't help myself at all. The tender maneuvered me to a ledge where he could keep my head out of water, and he took off the mask so I could breathe chamber air instead of oxygen.

The outside tenders kept us at the 50foot pressure to make sure they didn't cause gas embolism by decompressing me with airways in spasm. Gradually, I straightened out. Otherwise, I'd probably have gone on into a full seizure with unconsciousness and board-like rigidity followed by violent thrashing. No wonder scuba divers usually drowned when this happened to them in open water.

Anyhow, I'd been lucky. They told me later that I'd stopped at 14 minutes, 45 seconds, just 15 seconds short of my goal. That was OK. If I'd been the whole 15, we would never have known how close I'd been to real trouble. As it turned out, that was the riskiest dive in the entire series; and we set the final limits well on the safe side of that.

The divers were instructed to quit if they developed any of the recognized warning symptoms like muscular twitching, nausea, dizziness, or abnormalities of vision or hearing. But a symptom like that was often not definite enough to add to the data. Convulsions were the unquestionable thing, and they were bound to happen occasionally. Neither brain waves nor anything of that sort would provide adequate end points.

We knew from earlier studies, especially those conducted by the Royal Navy, that developing reasonable O2 limits wasn't going to be easy. For reasons largely unknown, oxygen tolerance varies greatly between individuals and even in the same person from one time to the next. The best we could do was to draw a line at times that missed, by a reasonable margin, the instances of apparent toxicity of different depths.

For simplicity, we'd started out with pure oxygen; and most people thought we could just translate the limits to mixed gas on the basis of inspired oxygen partial pressure (PO2), much as the nitrogen pressure was used to figure mixed gas decompression according to the "equivalent air depth" principle. Fortunately, we decided to test the tentative PO2 limits with dives on mixed gas at greater depths. What happened then gave us a real shock. Convulsions occurred with nitrogen-oxygen mixtures at pressures and times that should have been safe. The results were quite different from those with 100% O2, and at first there was no obvious reason.

Diving medical people had known for some time that when carbon dioxide accompanied inhaled oxygen, the onset of toxicity was speeded up. A few years before our study, Dr. C.J. Lambertsen and his research team at the University of Pennsylvania showed why. CO2 not only derails a mechanism that normally helps protect the brain from high PO2 but actually increases brain blood flow and the "dose" of oxygen reaching brain tissue.

CO2 buildup was a frequent problem in closed circuit scuba, where failure of the CO2 absorbtion system could easily occur. Excessive dead space in the breathing circuit is another cause. We could find nothing about our setup that would have added CO2; but at about this time, studies elsewhere suggested that some divers held onto excessive amounts of the CO2 produced in their own bodies. Wouldn't *"retained"* CO2 have the same effect in the brain as CO2 that is inhaled?

Body metabolism involves consumption of oxygen and production of CO2. Muscular effort greatly increases both processes. Oxygen is supplied and CO2 is removed by diffusion between blood and gas in the lungs. Normally, ventilation of the lungs and lung blood flow increase along the CO2 production in such close proportion that the partial pressure of CO2 (PCO2) in arterial blood leaving the lungs is almost steady over a wide range of exertion.

We had to go through a major research effort to be sure of what was going on, but it became clear that some of our divers did not increase their breathing sufficiently when they worked, developing a high PC02 as a result. This tendency was aggravated, apparently by higher gas density and increased work of breathing, when mixtures were tested at greater depths. It's been suggested that O2 toxicity may increase during exertion only if body PCO2 levels increase; but this idea has never been tested.

The divers who didn't breathe enough came to be called *CO2 retainers*. We were never sure how they got that way, nor were we able to find a sure-fire way of identifying them in advance. Most of our retainers were hardhat divers, and being exposed to high CO2 levels in the helmet may have blunted their breathing response to CO2. But our champion retainer hadn't done much actual diving.

Submarine escape training tank instructors at New London did a lot of deep breath-hold diving, and low response to CO2 wasn't surprising in them. In frogmen, retaining CO2 appeared related to years of habitual "skip-breathing" attempting to save air during SCUBA dives.
Most retainers showed unusually small increases in breathing when they inhaled various percentages of CO2, but this characteristic wasn't dependable enough for a good test. The retainers didn't form a distinct and easily identifiable group; they covered the range from "almost-normal" to "far-out." In more recent years, we tried to study CO2 retention at the University of Wisconsin. We focused on scuba divers who claimed to use less air than anybody, or who had CO2-type headaches during or after dives. We found that the only conclusive test was measurement of the PCO2 in blood or expired gas during exertion in water. We found only

one young man who had responses entirely like those of our retainers at EDU; and in him, there was no obvious cause.

Actually, we didn't find Sam. He found us. He was an avid scuba diver, but he'd had some very scary experiences at depth, enough so that he was willing to consult my laboratory and be studied. He'd nearly passed out at depth on several occasions and once had a massive headache with nausea and vomiting for hours after aborting such a dive.

CO2 Retention and "Narcosis"

Sam's case reminded us that speeding the onset of oxygen poisoning isn't the only serious consequence of CO2 retention. One of our EDU retainers had passed out during a simple air dive to 150 feet in the wet pot. A student at a Navy diving school had been sent to us for study when he lost consciousness on a shallow open-water training dive, and we found that he retained CO2 to a marked degree. Almost all authorities assumed that CO2 excess would be signaled by increases in breathing that couldn't be missed, but we had learned that this isn't always true.

I'm the exact opposite of a CO2 retainer; but I discovered that I wasn't immune to serious CO2 effects. A student and I were testing a new bicycle ergometer at 7.8 atm (224 ft.) in the dry chamber in my lab in Buffalo. Nitrogen narcosis is very evident on air at that pressure, but we were doing ok until we started breathing on the measuring circuit. That, it turned out, gave us only about half the air we needed at the work rate set on the bike. Herb tried the bike first. He stopped pedaling after about three minutes, out cold with his eyes rolled back.

As soon as I could get Herb out of the way, I took the bike. I knew I wasn't getting nearly enough air, but I was too narc'd to think straight and was determined to finish the 5-minute test no matter what. I pedaled myself right into oblivion, and coming around slowly afterwards with a horrible feeling of suffocation was the worst experience of my entire life. Both of us surely would have drowned if such a thing had happened when we were alone underwater.

CO2 can knock you out all by itself, but the combination with nitrogen narcosis is especially potent. It turned out what we weren't the first to discover that, and others since have described similar effects. On the day we started studies on Sam, the latest issue of *Undersea Biomedical Research* arrived. It carried a fine description of studies on two British divers who had passed out at depth, apparently because of CO2 retention.

In 1980, we invited world authorities on CO2 and related matters to Madison for a conference on loss of consciousness in divers. There was no question that CO2 could sometimes be a major problem, but not much new information surfaced. Since then, there have been scattered reports of fatalities or near-misses that sound like CO2 narcosis with or without nitrogen effects. Very recently, reports from the US Navy and from Dr. Lundgren's laboratory in Buffalo have stressed the precarious mental condition that can develop in hard-working dives with CO2 buildup.

Conclusions

It is hard to say whether excess CO2 is more hazardous with high PO2 or in situations involving narcosis. Under sufficiently stressful diving conditions, such as very heavy exertion, unusual work of breathing, or failure of CO2 absorption, CO2 build-up can threaten any diver. CO2 retainers who do not realize that they have this problem are certainly at the greatest risk of all, and we know no easy means of identifying them. My own opinion is that any diver who habitually uses less air than otherwise comparable divers, or who often has headaches associated with diving, or who has experienced unusually severe narcosis should dive with particular caution. A CO2-response test in a pulmonary function laboratory, and an exercise stress test with measurement of expired volume and alveolar or blood CO2, may be indicative especially if the results are abnormal. Normal findings do not necessarily rule out the retention tendency.

Good advice for all divers is to not "push the limits," particularly those who may be CO2 retentive. The general "rules" for oxygen or mixed gas safety may be just fine for almost everybody else. Likewise, "safe" depth limits, "moderate" levels of exertion, and usual warnings of O2 toxicity or CO2 poisoning definitely do not apply to everybody equally; individual susceptibility is always a major factor . Though the US Navy has liberalized the oxygen limits that we worked out in the 1950's; the 1987 Diving Manual, Volume 2, contains this inconspicuous but important proviso on page 16-4:

Although the limits described in this section have been thoroughly tested and are safe for the vast majority of individuals, occasional episodes of central nervous system oxygen toxicity may occur. This is the basis for the practice of requiring buddy lines on closed-circuit oxygen diving operations.

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Reccomended Reading

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Call-outs

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