●Original Article

What is “nitrox” ? Basic definition of diving with oxygen-enriched air

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酸素の割合が空気より高い混合ガス（通常は酸素32％から50％）を使う水深15～35msw（海水メートル）（60～120fsw：海水フィート）の範囲での潜水では，いくつかの明確な利点（すべて減圧にあてはまる利点）があります。高酸素濃度空気（OEA：Oxygen Enriched Air），これは高酸素濃度空気ナイトロックス（EANx：Enriched Air Nitrox）とか単に“ナイトロックス”と呼ばれていますが，このガスを使うダイビングテクニックでは，混合ガス中の窒素の割合のみに基づく減圧表が使われます（別のところでガスについて細かく触れます）。こうしたテクニックは，合衆国商務省のNOAAで開発され，これまでに科学ダイビングとレクリエーションダイビングで広く使われてきたものです。高酸素濃度空気を使う際の問題点は，その利点と同様に，酸素に基づくものです。OEAの問題の一つは，酸素中毒で，これは高PO_2で中枢神経系（CNS）に影響を与えてCNS中毒（痙攣）を引き起こすものと，長時間（複数日にわたる）の曝露によって蓄積され身体の他部に影響し“全身性毒性”につながるものです。この後者は肺で最も顕著であり，航機能検査などによって判断することができます。この両者は適切な曝露限界を設定することで避けることができます。この曝露限界とは，PO_2の範囲を1.4～1.6 atmとした時に，規定の時間限界を守ることと，高酸素状態の長い曝露に際して「酸素耐性単位」（OTU：Oxygen Tolerance Unit：累計酸素中毒単位；1単位は大体PO_2が1 atmで1分）に基づく経験から得られた表に従って合計曝露を制限することです。高圧酸素を取り扱う際に火災を起こす危険があるため，高酸素濃度混合体を混ぜたり取り扱う手順は重要です。こうした手順は規定されているものの，まだ公式の業界基準には組み込まれていません。重要な考え方の一つに，酸素と混ぜる空気の純度がありますが，これは油分が$0.1mg/m^3$未満でなければならないというものです。レクリエーションダイバーが数多く訪れる所では，OEA混合体を使うことができます。OEAのタンクを分析し，内容の記載をしなければ安全なダイビングはできません。ガスの性質上，同じ圧力では，OEA混合体の方が空気よりずっと麻酔作用を引き起こしにくくなります。

Abstract

Some distinct advantages, all related to decompression, can be achieved in diving in the range of about 15 to 35 msw (60 to 120 fsw) by using breathing gas mrixtures containing a larger fraction of oxygen than air (normally 32 to 50% oxygen). Diving techniques using Oxygen Enriched Air (OEA), also called Enriched Air Nitrox (EANx) or just “nitrox,” may use decompression tables based only on the nitrogen component of the breathing mix . These techniques have been developed by NOAA, U.S. Department of Commerce, and they are widely used in scientific and recreational diving. The problems of enriched air diving as well as the advantages depend on oxygen. One problem of OEA is oxygen toxicity, which may affect the central nervous system and cause CNS toxicity (a convulsion)at higher PO_2's, or other parts of the body aud lead to a “whole-body” toxicity in multiday exposures which is most prominent and measurable in the lung. Both can be avoided by appropriate limitations, remaining within the established time limits when in the PO_2 range of 1.4 to 1.6 atm, and limiting the total exposure according to an empirical table based on Oxygen Tolerance Units (OTUs, accumulated oxygen toxicity units; 1 unit is about 1 min at a PO_2 of 1 atm) in longer exposures to hyperoxia. Because of the danger of fire in handling high pressure oxygen, mixing and handling procedures for the oxygen-enriched mixtures are im-

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portant. These are established but not yet incorporated into formal industrial standards. One prominent concept is a specification for air to be mixed with oxygen, which should contain less than 0.1 mg/m^3 of oil. In most places where there is a lot of recreational diving it is possible to buy OEA mixes. Analysis and labeling of cylinders of OEA is critical to safe diving. Because of the properties of the gases, it is most unlikely that an OEA mixture would cause significantly less narcosis than air at the same pressure.

Background and history

A little over 20 years ago a method was introduced to the scientific diving community of diving while breathing gas mixtures of nitrogen and oxygen that are richer in oxygen than air. The incentive is improved decompression. The method is now firmly a part of both scientific and recreational diving, and appears to be a mature technology.

Some operational advantages (and some problems) can be gained by the use of mixtures of oxygen and nitrogen that have a larger fraction of oxygen than the 0.2094 normally found in atmospheric air, with a concomitant reduction in the nitrogen component. These advantages are entirely a matter of reduced decompression obligation. The price for this is special effort in mixing and handling the breathing gas and an increased probability of oxygen toxicity; this invokes a need for appropriate training.

Credit for introducing the modem practice of nitrogen-oxygen diving properly belongs to Dr. J. Morgan Wells, former Diving Officer of the National Oceanic and Atmospheric, Administration, U.S. Department of Commerce. The method using 32% oxygen was documented in the Second Edition of the NOAA Diving Manual (1979), which also included derived decompression tables and methods for preparing the gas mixtures, the Third Edition (1991) included more details on mixing. The use of oxygen-nitrogen diving gas mixtures other than air was not new with NOAA. This diving concept had been. studied intensively by the U.S. Navy in the 1950's, particularly by the late Dr. Ed. Lanphier, well known to the Japanese diving community. Although the benefits to decompression were known, the main reason for USN's imterest in O_2-N_2 mixes was for use in rebreathers. Because nitrogen's density tends to cause a buildup of CO_2 Lanphier recommended using helium instead (Lanphier and Bookspan, 1996).

Commercial application of oxygen-enriched air mixtures had been practiced from the 1950s, particularly by Ander Galerne's International Underwater Contractors and the French company Sogetram, but at the time this was kept as a proprietary technique (Galeme, et al, 1984). Galerne's secret was that he knew that a proper decompression table could be prepared by considering only the nitrogen component of the mix. Others suspected it (Logan, 1961), but Galerne had done it operationally so had a lead over competitors. It was not widely used. One reason was that it was not will understood by clients, but mainly because the cost and complexity of making, analyzing, and handling the mixtures and training for their use more than offset the benefits except under certain circumstances. When equipment for on-line mixing of oxygen and air was developed enriched air techniques were used extensively by a few operators. One project using a commercial mixer made by Dräger involved over 5000 working dives (Hartung et al, 1982).

While Morgan Wells gets credit for introducing these techniques for diving with special N_2-O_2 gas mixes (and for confusing the terminology by calling them "nitrox"), the credit for introducing this concept to recreational diving belongs clearly with Dick Rutkowski, a NOAA colleague of Wells. Rutkowski began in about 1988 to teach the NOAA techniques to ordinary scuba-trained divers. For a variety of reasons the new practice was not well received by certain leaders of the recreational diving community, and there was some controversy about "nitrox". Even though the development and spread of "nitrox" diving had all the aspects of a fad, the practice is now widespread and fully accepted within its limits. The most effective range of enriched air diving is essentially the same as the range accepted by much of the recreational diving community for air diving, to depths of about 40 msw (metres of sea water, a measure of pressure).

Let us now look at some of the terms, practices, facts, and myths that accompany this new technology.

Terminology

What is this "nitrox" and "enriched air" practice? Interestingly, the U.S. Navy called it just "nitrogen-oxygen" or "N_2-O_2" diving (or better, nowadays, O_2-N_2). Commercial diving companies for the most part called it that or "enriched air."

The term "nitrox" was used originally to mean the gas mixture in a shallow undersea habitat. In order to avoid oxygen toxicity, habitat atmospheres had less oxygen than air, and the term was appropriate for that. Unfortunately the same term was later used to describe the oxygen-enriched mixtures.

Becase of this historical precedence aud the potential for confusion and ambiguity, I heve encouraged the use of one of the original tems for oxygen-enriched mixes, "enriched air" . This is a more precise, descriptive, and less intimidating term than just "nitrox," which despite its convenience, is not specific. The term "oxygen-enriched air" (OEA) is more descriptive still and is the one I prefer. In any case, the term "NITROX" in all caps is to be discouraged.

The term "enriched air nitrox" or "EANx" was selected as a compromise, it is not so imprecise as "nitrox" alone, but retains "Nx" for the popular "nitrox" term. Sometimes divers replace the "x" with a subscript of the oxygen percentage, such that 36% oxygen enriched air would be "EAN_{36}".

Another term that may need defining is "technical diving." This is an extended range diving practice involving special equipment, gas mixes, procedures, discipline, and training. To be specific, "technical diving" involves at least one change of breathing mix during the course of the dive. Common practice is to use "trimixes" of oxygen, helium, and nitrogen, over a depth range that can extend to 100 msw or occasionally even more. Sometimes diving with rebreathers has been called "technical diving" ; this term was used especially by British Navy rebreather divers.

Diving with "nitrox" or OEA has sometimes been called "technical diving." In the sense that it is slightly outside the traditional recreational diving domain (which has nomally been limited to no-stop air diving with scuba) this usage may make sense, but in the minds of serious technical trimix divers, single-mix diving with air or enriched air does not qualify as "technical diving," especially if done without decompres-sion stops. To make it even more confusing, sometimes training organizations refer to "technical enriched air" (or "technical nitrox") diving. This usually is just extended training in enriched air diving that involves using decompression techniques, but is not really technical diving as such since it does not involve a change of gas mix during a dive.

Regardles of the terms, a most important principle is that divers need to be properly trained and equipped for the kind of diving they are doing.

Doing OEA/EANx/nitrox diving

When it comes time to go diving with OEA there are several concerns. First the gas mixes have to be acquired and managed. Next, and surely the most critical, is the substantial risk that oxygen toxicity presents to the "nitrox" diver; this must be understood. Then the diver has to know how to take advantage be the improved decompression capability in a quantitative way. Another concern is a political one, that in many jurisdictions breathing a mixture other than air may place a diver-employee such as a diving instructor in the category of a commercial diver.

Handling high pressure oxygen

The main consideration in preparing mixtures involving oxygen of oxygen-rich mixtures at high pressure is that of preventing oxygen fires and explosions. Design of systems handling high-pressure oxygen is a specialized technology and should be done only by properly trained and experienced people. Technicians, divers, and others using such systems should also be trained in their use, and this is part of training to dive with oxygen rich mixtures. "Cleaning for oxygen service" is also a specialized process, but it can be approximated by the same level of cleaning as that performed by a good household dishwasher.

First, users should understand the risks. Users should keep systems clean, "oxygen-clean" if possible. Only oxygen compatible lubricants sbould be used. Sudden pressure change should be avoided, which means that valves should be opened slowly. Eye protection should be worn when working with all high pressure gases, but especially oxygen.

Making and handling the mixes

When diving with enriched air was less common, it was often necessary for diving organizations to make their own gas mixtures. Now it is possible in most parts of the world where there is active diving to purchase pre-mixed gas. This the recommended method. However, the mixing methods may be of interest.

The simplest way to make a mixture of oxygen-enriched air would seem to be to add oxygen to air. True, but this is anything but simple. A number of problems have to be dealt with, not the least of which is handling high pressure oxygen. This has to be done with special care. Because of the pressures involved, it is not easy to add oxygen to air at cylinder pressure. Usually air is add to oxygen.

Once mixed, in most jurisdictions there are no industrial standards in place for handling or compressing O_2-N_2 mixtures. Staudards exist for air and for pure oxygen, but there is not much covering the oxygen range between air and 100% oxygen (between 23 and 100%). Here the rules default to those for pure oxygen. Nor is there a unique tank connector for this application. Another problem has been that there were no purity standards for air to be mixed with oxygen—a big issue, because to mix oily compreseed air with high-pressure oxygen is asking for trouble. Despite these problems, there are a number of successful methods of making OEA mixtures.

The simplest and most straightforward method of mixing is by partial pressure. The technician puts a measured amount of oxygen into a clean cylinder or bank of cylinders, and the cylinder is then filld to a specific pressure with ultra-pure air (air suitable for mixing with oxygen). Industrial gas suppliers use weight as the primary method for preparing gas mixtures.

Special compressors, designated "oil-less" or "oil free," can produce compressed air free of oil; these are suitable for both continuous mixing, compressing pre-mixed gas, and preparing pre-mix in tanks. The air output from standard oil-lubricated compressors can be filtered, but there is no uniform industrial standard for how pure it has to be. Prevailing gas purity standards either allow a physiologically tolerable amount of oil mist, or call for "zero" oil, or do not address that component at all. "Zero" oil cannot be attained, and it could not be measured. A typical standard far compressed air is 5 mg/m^3 of oil mist. This may be safe to breathe, but this is far too much oil for oxygen service. Industry leaders in the USA have agreed on a limit of 0.1 mg/m^3 of oil mist in air to be mixed with oxygen, and this level can be attained with ultra filtration and can be monitored.

Enriched air mixes may be made "on line" in a continuous fiow process, with the product gas either going directly to the diver or being compressed into gas storage containers. This is the process used by NOAA and described in the NOAA Diving Manual, A compressor free of oil has to be used.

The on-line method used by commercial diving companies is to add oxygen to air with a "blender" at something near normal supply pressures (10 bars; 150 psi) and pipe it directly to the diver (Hartung et al, 1982). The oxgen level should be monitored continuously, and since it is a primary risk factor should be on an alarm system. This method conceptually is quite safe, because the main gas is air and no matter what the deviation the oxygen level will not fall below that of air, the possible risk is if the oxygen level gets too high. Mixers using pure inert gases are inherently dangerous because of the possibility of getting a hypoxic mixture.

Recently gas separation units have been developed that use either membrane or pressure-swing adsorption (PSA) methods and can produce OEA mixes on site. These require only electric power and a source of clean air to be compressed. They offer great promise because they are cost effective for small operations and they eliminate the need to handle higt- pressure oxygen.

Normally the technician, preparing the mix will also analyze it, but it is considered essential that the diver also analyze the mix at the time of use.

Analysis and identification

Once a mix is prepared its history should be documented and proper labels applied, It is the responsibility of the diver to double check the analysis and ensure that the tank is properly labeled, and to ensure that the mix is used under the intended conditions. There have been several fatalities of technical divers who used a high-oxygen mix at the wrong depth. Performing oxygen analysis is an important part of training to dive with oxygen-enriched air.

Divers using oxygen enriched mixtures are reminded that there is not yet a unique connector for such mixes that is acceptable for scuba applications. Therefore it is up to the diver, primarily, to ensure that the right mixes are used. It is advisable to use regluators and fittings cleaned for enriched air service, and not to use the same regulators with air unless they are cleaned again. Scuba cylinders should be cleaned before enriched air use and dedicated to such use, should be maintained clean, and should be properly labeled. Some diving organizations that use different mixes and dive a range of depths recommend prominently marking each breathing gas cylinder with the maximum operating depth ("MOD") at which the gas can be safely breathed. This is based on oxygen toxicity.

Remaining mix problems

Setting a definition for air to be mixed with oxygen has cleared up one issue, but a couple more issues remain. One is that to follow industrial practice with gas cylinders it is preferred to have a unique tank connector for each gas category. Several have been proposed, but so far (at least in the USA) there is not a specific connector for oxygen-nitrogen mixtures in the range 23.5 to just under 100% oxygen. One is under development, how ever.

Still another controversial matter is a prevailing practice of handling mixtures with 40% oxygen or less using the same procedures and equipment as for air. This practice was suggested by the U.S. Navy and was put into use without formal testing. The "400% rule," after being used for many years without clear evidence of problems, has finally been tested in the laboratory (Forsythe et al, 1997). Divers and others relying on this "rule" are strongly encouraged to clean the equipment thoroughly, maintain cleanliness, and use an oxygen compatible lubricant such as Christo-Lube for all surfaces contacted by the high oxygen mixes. The "40% rule" is fomally discouraged by oxygen experts, but they abmit privately that there is little evidence that it is dangerous, and some evidence such as that just mentioned suggests it can apply to mixtures of up to 50% oxygen.

Oxygen the Princess

From the diver's perspective (once the gas mix is in the tank), overwhelmingly the biggest problem with enriched air diveng is the threat of oxygen toxicity. This manifests itself in two ways. By far the most serious of these is toxicity of the CNS (central nervous system), which can cause an epileptic-like convulsion. This is invoked by short exposures (minutes) to relatively high levels of oxygen, above about 1.6 atm PO_2 (oxygen partial pressure). The other, now being called "whole body" toxicity, is primarily seen in the lung after many hours of exposure to levels low enough to be tolerated for longer periods without convulsions but above a threshold of about 0.5 atm PO_2.

Avoiding CNS toxicity

For many years the only recognized limits for oxygen exposure were those in the USN Diving Manual. There were some valid aspect to thesc limits, but they were more political than physiological in origin, and they did not deal with exposures to multiple levels nor provide for recovery between exposures. Addressing the need for a better standard, NOAA sought advice from experts in producing a new set of limits for the 1991 edition of their diving manual. These limits, which provide maximum exposure times for different levels of oxygen (PO_2s), are realistic and deal with both short exposures and daily limits. No recovery provisions are included, but this is taken into account to some exten in the limits for a full day. The highest level allowed is 1.6 atm for which the allowed time is 45 min. This is appropriate for a non-working diver with no tendency for CO_2 buildup, but experience seems to be telling us that for the untethered mouthpiece diver during the working phase of a dive an upper exposure limit of 1.5 or better 1.4 atm gives a greater margin of safety and costs little in extra decompression. This safetv margin is further improved by having a full-face mask, communications, a tether, a standby diver, and a chamber at the suface (all standard for commercial divers).

Some training organizations have come up with procedures for interpolating between the different levels and durations of exposure. This proportional concept had been proposed by Kenyon and Hamilton (1989) in order to solicit reactions from the diving medical community (with no significant response, pro or con). The method considers the approach of a diver's exposure toward the limit, implemented as a fraction of the limit, the "O_2 limit fraction," or as a percentage of the limit. This concept has been independently used and described by enriched air training organizations as the "oxygen clock" or "CNS percentage". There is no evidence that this interpolation is not physiologically proper, but considering the somewhat arbitrary nature of the limits themselves the interpolation techiques. seem appropriate and appear to be verified by extensive field application. The limits themselves are more subject to variations.

A further development in this process deals with recovery, the "decay" of this fraction or percentage during periods when the exposure is less than 0.5 atm PO_2. This was developed first for the Bridge dive computer, using a halftime decay of about 90 min (Bohrer and Hamilton, 1993), That is, every 90 min the O_2, limit fraction decays (is reduced) halfway back toward 0; this may be overly conservative, but is a good starting point considering the limited data available. A linear rather than exponential decay would not be unreasonable.

Managing whole-body toxicity

A "whole-body" toxicity may follow longer exposures to levels above about 0.5 atm. It primarily affects the lungs and has been traditionally thought of as "pulmonary" or "lung" toxicity. Symptoms include chest and airway soreness, coughing, and a reduction in vital capacity, but a mumber of other non-1ung symptoms such as headache, fatigue, paresthesias, and other aches and pains have also been, noted. This toxiclty develops over time and comes on faster at higher oxygen levels. Recovery takes place when the level drops below about 0.5 atm.

Whole-body toxicity is not likely to be encountered by recreational divers, but patterns of daily diving activity utilizing the full capacity of enriched air diving could involve enough exposure to cause symptoms after a few days. A method for managing such exposures is available that uses the familiar "UPTD" or "CPTD" renamed as " 'Oxygen Tolerance Units," OTU, and an empirical bookkeeping system developed by NOAA for undersea habitats. The unit pulmonary toxicity dose is roughly equal to an exposure to one atm PO_2 for one minute. The Repex system recognizes that a person can tolerate more oxygen exposure the first day and less on successive days thereafter By considering a "dose" over all days of an exposure – a "mission" – the recovery during periods of low exposure level is effectively taken into account. The Repex set of daily limits for missions of up to 14 days is available in tabular and graphical form (Hamilton, 1989). The Repex algorithm has been installed in dive computers and computational programs.

It is worth mentioning that the threat of whole-body toxicity is of a different magnitude from that of CNS toxicity. Whole-body toxicity in the operational setting may involve symptoms, but they are mild at first and have always been found to be reversible in time, even when exposures were extreme. Toxicity can be controlled by reducing the exposure intensity or stopping it altogether. On the other hand, CNS toxicity in the form of a convulsion can strike without waming.

Individual variation in sensitivity

A troublesome characteristic of human tolerance of exposure to oxygen is that individual sensitivity varies widely. The available algorithms are estimated average levels for operational diving, but do not guarantee in any sense that a given individual at a given time is protected from toxicity. Unfortunately, we have to expect an occasional convulsion or an individual now and then to feel some chest tightness or even soreness at the end of an exposure calculated to be tolerable.

Hypoxia

Another oxygen problem deserves mention, hypoxia or too low an oxygen level. This is relatively rare in air diving, but it has proven to be one of the major hazards of mixed-gas diving. Mixes used for enriched air diving usually begin with air so there are rarely gases on hand with inadequate oxygen levels. However, any diving with rebrelathers or with mixes using inert gases can result in a diver receivixg a bypoxic mix. Proper procedures, a high level of discipline, and extreme caution are needed. Hypoxia is particularly dangerous because it induces a sense of euphoria that may prervent corrective action from being taken.

Narcosis relief and other myths

While the benefrts of oxygen-enriched air stand on their own, improved decompression, some of the promoters have advanced other benefits that are not so clear cut. One of these is that enriched air causes less narcosis than air, the assumption is that narcosis can be calculated in the same manner as decompres-sion, looking only at the inert gas. However, from a theoretical point of view oxygen is at least as narcotic as nitrogen. The evidence is scanty on this issue, and what little there is shows no difference (Linnarsson et al, 1990). The best approach–at least until more data become available–appears–to be to regard the narcotic potency of enriched air as being the same as air.

Another even more exotic phenomenon of enriched air has been pitched as "sexual prowess." Actually, a better description would be "family life," The story is that diving fishermen using air were fatigued at the end of the day and when they used enriched air they feel better, presumably because they were getting a better decompression. The cemparison here is subjective and anecdotal, but the concept that a better quality decompression leaves a diver in better shape is entirely valid.

One of the early "anti-notrox" myths was that a diver "could not be treated for DCS from nitrox diving." This was in reference to the possibility, extant but extremely improbable, that the diver's oxygen exposure would preclude treatlnent with byperbaric oxygen. True, the tresting facility would have to monitor and deal with any development of whole-body oxygen toxicity, but this is always the case. There were actually facilities that stated they would not treat divers who had been diving with nitrox until this misunderstanding was corrected. DCS following an OEA dive should be treated in exactly the same way an air dive would be, considering the other variables.

Something should be said about the use of the word "safety." Enriched air nitrox has been touted as being "safer" to dive with than air. This is not really the case. Recreational decompression procedures are "safe" in the sense that there is an extremely low probability of encountering DCS, and in particular of being injured by it. Enriched air does in fact reduce that probability still more. However, as mentioned throughout this presentation, there are other hazards that have to be dealt with or they will reduce the safety level to below that of air.

Decompression

Decompression is covered in another presentation.

Acknowledgement

Several of the concepts covered in this paper are derived from an earlier report given as Hamilton, 1996.

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