The state of oxygen-enriched air (nitrox)

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Diving, scuba diving, enriched air - nitrox

Abstract

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The evolution of the use of oxygen-enriched air (nitrox) in diving can be traced to its origin in 1874, its use in the scientific diving community in 1979, and its introduction on a global scale to the recreational diving community in 1985. As with any emerging technology that has found a broader market appeal, controversies invariably arise. In 2000, the DAN Nitrox Workshop reviewed physiological issues as they pertain to recreational nitrox use such as carbon dioxide retention, oxygen toxicity potential, and narcosis, and nitrox decompression sickness (DCS) incidence rates compared to air. In collaboration with the recreational diving industry, nitrox equipment engineering considerations vis-à-vis the 40%-oxygen-cleaning rule, nitrox training, and operational data were also reviewed. To provide an update on the state of nitrox, the workshop information is synthesized and additional new certification and operational data reviewed for 2000–2005.

Introduction

The use of oxygen-enriched air (nitrox) has been a mainstream recreational diving mode since it was first introduced to sport divers in 1985 by former NOAA Deputy Diving Officer Dick Rutkowski. The mainstream recreational diving training associations (PADI, NAUI, and SSI) now support nitrox training programmes in addition to their traditional open-circuit compressed-air scuba programmes. The training organisations that focus on technical diving (IANTD, ANDI, and TDI) have amassed several additional years of experience in providing nitrox training to the recreational diving community.

In 2000, the DAN Nitrox Workshop[1] was prioritised as a diving safety project of interest to the diving industry by means of Divers Alert Network financial support. As with any emerging technology that has found a broader market appeal, controversies invariably arise. Ignorance, myths, and misconceptions often fuel opposite views. A critical interdisciplinary examination of the current issues surrounding nitrox was in order to disseminate credible diving safety information. This forum was provided to objectively evaluate the available operational and physiological data relating to the use of nitrox, and discuss risk management, equipment, and training parameters.

An approximation of the magnitude of nitrox consumption was essential. This seemed achievable by our ability to provide a denominator of nitrox divers and nitrox dives, as a sub-set of the overall level of recreational diving activity. Many other discussions of nitrox-related topics flowed from these numbers, i.e., comparable incidence rates of decompression sickness (DCS) in nitrox and compressed-air use, and growth of nitrox training and equipment sales.

Physiological issues such as carbon dioxide retention and oxygen toxicity were also in need of critical examination. Nitrox training and equipment issues were discussed to comprehensively address risk management and legal considerations regarding its use. The recreational diver is the ultimate beneficiary of our improved collective knowledge of the state of the art of nitrox diving in 2000. The intermediary beneficiaries of this information are the providers and manufacturers of nitrox products (instructors, equipment manufacturers, dive stores, and nitrox dispensers).

The history of nitrox

Hamilton discussed the evolutionary history of nitrox diving along the following timeline:[2]

1874 H Fleuss probably made the first nitrox dive with a rebreather.

1947 C Lambertsen published the first nitrox paper.[3]

1955 E Lanphier described the use of nitrogen-oxygen mixtures in diving and the equivalent air depth method for using a standard air table with an enriched air mix.[4]

1960s A Galerne used on-line blenders for commercial diving.

1979 M Wells developed NOAA nitrox and equivalent air depth (EAD) tables were published in the NOAA diving manual for scientific diving.

1985 D Rutkowski developed a nitrox training programme for recreational diving.

1989 The Harbor Branch Oceanographic Institution Nitrox Workshop addressed the following issues and rationale:[5]
- oxygen limits
- decompression and the EAD
- nitrox mixing

- terminology: the term 'nitrox', borrowed from habitat diving, implies that nitrogen is the advantage. The US Navy now prefers 'oxygen-nitrogen'. New NOAA designations are NN_{32} and NN_{36}. EAN_x was agreed upon, with 'x' being the percentage of oxygen (O_2). The correct term proposed was 'oxygen-enriched air'.

1991 **'**Not Invented Here' went to work. Bennett, Bove, and *SkinDiver Magazine* all took stands against nitrox use by recreational divers.[6,7]

1992 The Scuba Diving Resources Group (a committee of the Outdoor Recreation Coalition of America) organised a nitrox workshop in response to nitrox agencies and products being denied access to the Diving Equipment and Marketing Association (DEMA) trade show in Houston.[8] The workshop resulted in the following endorsements:
- the EAD principle
- the NOAA limits for oxygen exposure (but lower limits were encouraged)
- the use of normal DCS treatment procedures for air diving after nitrox dives (the O_2 exposure of recreational nitrox dives should not affect treatment)
- pending testing, mixes up to 40% O_2 could be used in equipment suitable for air provided equipment was clean and O_2-compatible lubricants were used
- dry nitrox would not corrode cylinders and other gear appreciably faster than air
- air for mixing should be 'oil free'
- cylinders used for nitrox should be compatible with O_2
- mixes should be analysed properly before use, and
- mixing in standard cylinders by adding O_2 and topping with air is considered unsafe.

1993 The aquaCorps TEK93 conference took place in San Francisco. A measurable and attainable air quality standard was set by nitrox industry leaders at 0.1 mg/m^3 oil.

1993 The Canadian Forces issued EAD tables, based on the standard air tables, with an upper O_2 limit of 1.5 ATA PO_2 and depth and time limits more stringent than the air tables.[9]

1996 PADI takes the plunge, nitrox has arrived. NAUI, SSI, and even BSAC have nitrox programmes.[10] The diving media have become supportive of nitrox.

1999 A survey by RW Hamilton for the US Navy showed 100,000s of (not well-documented) open-circuit nitrox dives. Commercial diving does not use nitrox much, but it has become fashionable among recreational divers. The DCS incidence record is good, and nitrox dive computers are readily available.

1999 The Occupational Safety and Health Administration (OSHA) was petitioned by PADI and Oceanic in 1995 on behalf of Dixie Divers, Inc. for a recreational nitrox variance for scuba instructors from commercial diving regulations that was approved for:
- PO_2 of 1.4 ATA and a maximum 40 per cent nitrox mix
- 130 feet maximum depth and dives within the no-stop limits
- a stand-by diver, and
- diving within one hour of a chamber.

2001 NOAA diving manual includes a chapter as stand-alone course guide for nitrox diving.

The physiology of nitrox

DECOMPRESSION

Nitrox improves decompression, which is based on the fraction of nitrogen (N_2) only. Therefore, more O_2 and less N_2 is better. Nitrox allows for greater bottom times for no-stop dives. Decompression dives (with required stops) using an enriched-air mix will result in a total decompression time shorter than that required with air. When nitrox is breathed and air decompression tables are used, the decompression times are not affected, but the dives are considered more conservative. This benefit can apply to repetitive dives, flying after diving, and diving at altitude.

OXYGEN TOXICITY

Convulsions from central nervous system (CNS) toxicity can occur without warning and likely lead to loss of the mouthpiece and subsequent drowning. Warning signs and symptoms, if they do occur, include: visual disturbances (including tunnel vision); tinnitus; nausea; twitching or muscle spasms (especially in the face); irritability, restlessness, euphoria or anxiety; and dizziness. Thus, the diver's exposure to high levels of oxygen must be managed by time limits at maximum PO_2 (Table 1.) Standardised recreational nitrox depth limits are 110 feet of sea water (fsw) (EAN_{36}) and 130 fsw (EAN_{32}). Pulmonary or whole-body oxygen toxicity is monitored by oxygen toxicity units (OTU) or units pulmonary toxicity dose (UPTD). Because of the length of exposure time required to elevate oxygen

Table 1
NOAA oxygen exposure limits[12]

PO_2 (ATA)	Maximum single dive (mins)	Maximum 24 hrs (mins)
1.60	45	150
1.50	120	180
1.40	150	180
1.30	180	210
1.20	210	240
1.10	240	270
1.00	300	300

Table 2
PO_2 limits adopted by the Israeli Navy

Degree of retention	End-tidal CO_2 (torr)	Mixed-expired CO_2 (torr)	Maximum PO_2 (ATA)
None	<50	<41	1.6
Moderate	50–55	41–45	1.4
Extreme	>55	>45	1.2

levels, the onset of CNS effects is unlikely to occur in recreational diving applications. Whole-body symptoms include primarily pulmonary effects (coughing, chest pain, and a reduction in vital capacity) and more diffuse symptoms (paraesthesiae, numbness of fingertips and toes, headache, dizziness, nausea, and a reduction in aerobic capacity).

NARCOSIS

Nitrogen narcosis in oxygen-enriched air diving is not a real issue. However, O_2 can be as narcotic as nitrogen[13] but nitrox diving is not efficient at depths where narcosis becomes prominent.

CO_2 RETENTION

CO_2 build-up is not an issue for recreational nitrox mixes, but may be a hazard in the deeper range of nitrox diving.[14] It causes a reduced ventilatory response, such that breathing a dense mix while exercising can lead to unconsciousness. Headaches are a symptom of hypercapnia, caused by dilation of the arterial vessels in the brain. Kerem et al discuss the Israeli Navy experience with pure O_2 rebreathers,which shows victims of CNS O_2 toxicity to be both retainers and late detectors of build-up of inspired CO_2/malfunctioning absorbers.[15] For higher-risk, extreme CO_2 retainers, more conservative PO_2 limits were adopted by the Israeli Navy (Table 2).

NITROX EFFECTS

The late Jon Hardy initiated a study of human function to test nitrox as a product in 1999.[16] Does diving with nitrox as the breathing gas cause:

- less nitrogen narcosis?
- less fatigue?
- less gas consumption?
- better thermal balance?
- less decompression stress?

Initial results showed no variation in gas consumption between air and nitrox under similar conditions. Difficulty was acknowledged in experimentally designing a study to objectively measure fatigue, decompression stress, and thermal balance. Unfortunately, testing of the reduced nitrogen narcosis of nitrox was not completed by Hardy. More recently, in a double-blinded, randomised controlled study, 11 divers carried out dives breathing either air or EAN_{36} at 18 msw in a dry chamber for 40-minute bottom times.[17] Divers were assessed before and after two exercise periods during the dive. These chamber exposures produced no measurable difference in fatigue, attention levels, or ability to concentrate.

Table 3. Manufacturers' nitrox equipment recommendations (modified from Oliver[18])

Company	Maximum fO_2 authorised (%) 23.5	<41	<51	100
Apeks		1		
Aqua-Lung		1		
Atomic		1		
Beuchat			2	
Cressi-Sub	x			
Dacor (parent company policy)		2		
Dive-Rite		2		
Genesis		4		
International Divers Inc.		1		
Kirby-Morgan			1	
Mares America		2		
Oceanic			2	
OMS				1
Sherwood Scuba		4		
Scubapro		1		2,4
Thermo valve		2		
Zeagle (policy reevaluated)		3		4

Key code - Enriched Air Nitrox (EAN) Sep 00

x Maximum limit. EAN not recommended.
1 All models are factory-prepared for EAN using O_2 compatible materials.
2 Designated models factory-prepared for EAN using O_2 compatible materials.
3 Standard air components declared acceptable. Viton o-rings available.
4 Conversion components available for installation by technician qualified to prepare for O_2 service.

Nitrox equipment

Oliver summarised the findings and conclusions of the DEMA Manufacturers Committee on oxygen-enriched air and provided manufacturers' recommendations on nitrox and equipment use.[18]

Two major manufacturers (Scubapro and Aqualung) issued technical bulletins in 2001 on the use of their equipment with nitrox:

SCUBAPRO ENGINEERING BULLETIN #271 (05 SEPTEMBER 2001)

- All Scubapro regulators sold after October 2000 are approved for use with nitrox up to 40% O_2 and for an operating pressure not to exceed 3300 psi. The regulators can be used with gases under the restrictions listed above straight out of the box. Specific models are listed by Scubapro.
- For use with gases (other than air) falling outside of the range detailed above (i.e., 40+% O_2, 3300+ psi), the only approved regulator is the MK20 (brass version only) after appropriate cleaning and installation of the nitrox kit, when the operational limit becomes 100% O_2 to 3500 psi.

AQUALUNG AND APEKS REGULATORS

- New Aqualung and Apeks regulators are now EAN compatible up to 40% O_2 right out of the box. See <www.aqualung.com>, technical library–nitrox compatibility and converting existing regulators to EAN_{40} use.
- Owner's responsibility is to maintain cleanliness of the regulator and cleaning procedures (note switches from air to nitrox). Second-stage cleaning prevents cross-contamination.
- Difference in the regulators is in the manufacturing process (i.e., a regulator 'safe' room). Hyperfiltered air (condensed hydrocarbons < 0.1 mg/m^3) is used for testing, as are some oxygen-compatible components.

Table 3 shows updated manufacturers' recommendations.

Nitrox training and operational data

Table 4 lists the nitrox training requirements for the recreational and scientific diving communities.

Table 5 presents updated (until 2005) nitrox instructor and diver certification information since the original data published in 2001. For reference, Table 6 shows total numbers of entry-level open-water scuba certifications as collected by DEMA for 2000–2005.[19] Finally, Table 7 is likewise updated for available nitrox and air exposures and cases of DCS.

Vann concluded that laboratory and open-water experience suggests that nitrox diving may be practised with low risks of DCS and O_2 toxicity.[20] From DAN data on mixed-gas diving dating from 1990 for diving fatalities, from 1995 for diving injuries and from 1997 for safe dives:

- a higher proportion of safe divers used nitrox than of divers who were injured or died
- nitrox divers were older than air divers
- over 60% of nitrox divers who dived safely had specialty training
- safe nitrox diving was most common aboard charter boats and there were no air or nitrox fatalities from liveaboards
- nitrox divers who dived safely dived fewer dives over more days than did air divers
- in general, nitrox divers dived deeper than air divers, regardless of whether they dived safely, were injured, or died
- for either air or nitrox, injured divers and diving fatalities had higher proportions of rapid ascent and running out of gas than did safe divers
- maximum PO_2 was above 1.3 ATA for half of the 74 injured nitrox divers
- while the incidence of O_2 toxicity during nitrox diving is unknown, convulsions and/or unconsciousness were reported for three divers who had a maximum PO_2 of 1.4, 1.6, and 1.9 ATA respectively
- careful depth control is important to avoid excessively high PO_2 during nitrox diving.

Table 4
Recreational and science/government training requirements

	IANTD	ANDI	TDI	PADI	NAUI	SSI	NOAA	NASA	AAUS	UNCW
Max PO_2 limit (ATA)	1.6	1.6	1.6	1.4	1.4	1.6	1.6	1.6	1.6	1.6
O_2 content range (%)	22-40	22-50	22-40	22-40	22-40	22-40	32 & 36	46	22-40	28-40
O_2 cleaning (%)	>40	>21	>40	Mfr	>40	>40	>40	>23	n/a	>40
O_2 limits (ATA)	all agencies NOAA									
OTU/UPTD	300/day	n/a	n/a	n/a	350/day	NOAA	Repex	415/day	Repex	Repex
Mix analysis accuracy	all agencies ± 1%									
EAN_x table/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T/DC	T	T/DC	T/DC
Agency tables	Y	Y	NOAA	Y	Y	Y	NOAA	USN	NOAA	USN
Table model	B-PiN_2	B-PiN_2	USN-EAD	Rogers-RDP	RGBM-USN	USN-EAD	USN99-EAD	USN-EAD	mUSN99-EAD	mUSN99-EAD
Encourage DC	Y	Y	Y	Y	Y	Y	N	n/a	n/a	n/a
Prerequisites	none	none	OW	OW	none	OW	n/a	n/a	n/a	n/a

(B – Buhlmann; DC – dive computer; EAD – equivalent air depth; m – modified; Mfr – manufacturer's recommendation; OW – open water certification; RGBM – reduced gradient bubble model; Rogers-RDP – recreational dive planner; USN – US Navy; USN99 – US Navy 1999 dive tables (unpublished))

Table 5
Available nitrox diver certification data up to November 2000 as reported by organisation representatives at the 2001 workshop[1] on oxygen-enriched air diving and then thereafter

Period:	Until November 2000			November 2000 to November 2005		
Level:	**From**	**Divers**	**Instructors**	**Instructors**	**Divers**	**Region**
NAUI*	1992–	4,472	878	10,221	92,859	Worldwide
PADI	1996–	46,788	7,274	24,817	223,932	Worldwide
SSI	1996–	1570	605	1,500	12,417	USA
IANTD	1991–	64,378	8,140	6,140	89,049	Worldwide
TDI	1994–	66,206	12,823	8,758	51,592	Worldwide
ANDI	1989–	49,118	3,196	5,350	81,200	Worldwide
UNCW	1986–	803	n/a	8	523	USA
NOAA	1981–	139	n/a	n/a	323	USA
NASA	1996–	384	8	n/a	n/a	USA
AAUS	1987–	n/a	n/a	n/a	n/a	USA
TOTAL		**233,858**	**32,924**	**56,794**	**551,895**	

(*NAUI instructor number increase (2000–2005) results from their authorisation to teach nitrox in addition to compressed-air scuba; n/a – data either not tracked organisationally, or not available; nitrox certifications for divers participating in Aggressor and Sea Hunter fleet courses are included in the totals of the training agencies)

Discussion and conclusions

The DAN nitrox workshop concluded the following in 2000 for entry-level, recreational, open-circuit nitrox diving:

- no evidence was presented that showed an increased risk of DCS with the use of oxygen-enriched air (nitrox) versus compressed air
- a maximum PO_2 of 1.6 ATA was accepted based on the history of nitrox use and scientific studies
- routine CO_2 retention screening is not necessary
- O_2 analysers should use a controlled-flow sampling device
- O_2 analysis of the breathing gas should be performed by the blender and/or dispenser and verified by the end user
- training agencies recognise the effectiveness of dive computers
- there is no need to track whole-body exposure to O_2 (OTU/UPTD)
- use of the ‘CNS oxygen clock’ concept, based on NOAA O_2 exposure limits should be taught. However, it should be noted that CNS oxygen toxicity could occur suddenly and unexpectedly
- no evidence was presented, based on history of use, to show an unreasonable risk of fire or ignition when using up to 40% nitrox with standard scuba equipment. The level of risk is related to specific equipment configurations and the user should rely on the manufacturer’s recommendations.

Additional data collected for 2000–2005, while insufficient for statistical purposes (due to some data categories not being tracked organisationally and therefore remaining unknown), serve to show several trends. The certification numbers of nitrox instructors and divers has approximately doubled, and there does not appear to be a commensurate doubling of nitrox DCS incidence rates. However, comparisons of DCS probabilities between compressed air and nitrox remain tenuous at best. Yet, over one million more nitrox dives (from fill data) were done in the last five years than in the history of its use until November 2000. Liveaboard diving operations report almost exclusive nitrox and dive-computer use aboard their vessels. Due to their operations at remote dive locations and given the nature of their captive diver audiences (i.e., adequate time for reporting of DCS symptoms prior to returning to port), one would expect any significant DCS rates from nitrox diving to be readily apparent.

The Diving Equipment and Marketing Association reported almost one million entry-level open-water scuba certifications and the nitrox training organisations reported over 500,000 nitrox certifications. The relationship or overlap between nitrox and open-water certifications cannot be defined at this point in time due to data collection criteria. The maximum PO_2 limit of 1.6 ATA continues to be used

Table 6
Numbers of entry-level, open-water scuba certifications as reported by DEMA (2005) based on records from NAUI, PADI, SDI, and SSI[19]

Year	No. certifications
2000	185,714
2001	198,241
2002	183,394
2003	173,476
2004	173,225
2005 (Jan–June)	74,758
Total	**988,808**

Table 7
Available nitrox and air dive data for occurrence of decompression sickness (DCS) as reported at the 2001 workshop[1] and then thereafter

Period:	Until November 2000				November 2000 to November 2005			
	Nitrox fills	DCS	Air fills	DCS	Nitrox fills	DCS	Air fills	DCS
NAUI	17,604	0	n/a	n/a	3,242,309	n/a	n/a	n/a
PADI	n/a	17	n/a	n/a	n/a	n/a	n/a	n/a
SSI	n/a	0	n/a	n/a	n/a	n/a	n/a	n/a
IANTD	1,411,266	0	n/a	n/a	n/a	n/a	n/a	n/a
TDI	n/a	0	n/a	n/a	n/a	n/a	n/a	n/a
ANDI	967,450	0	n/a	n/a	n/a	n/a	n/a	n/a
Ocean Divers	26,000	n/a	235,504	n/a	34,000	0	n/a	n/a
UNCW	23,407	5	21,201	n/a	13,365	0	18,911	1
NOAA	4,894	1	156,697	22	15,618	2	64,757	18
NASA	34,651	0	n/a	n/a	45,635	n/a	0	0
AAUS	18,461	1	442,679	27	52,325	3	518,695	14
Aggressors	33,778	1	n/a	11	127,759	n/a	n/a	n/a
Sea Hunter	30,400	0	n/a	n/a	130,600	0	15,000	0
TOTAL	**2,567,911**	**25**	**856,081**	**60**	**3,661,611**	**5**	**617,363**	**33**

with no documented ill effects. No further issues have arisen from manufacturers with respect to their equipment being used with nitrox without incidental exposure to oxygen content above 40%.

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