Screening for oxygen intolerance in U.S. Navy divers

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Butler FK Jr, Knafelc ME. Screening for oxygen intolerance in U.S. Navy divers. Undersea Biomed Res 1986;13(1):91–98.—All U.S. Navy diving candidates are screened for their tolerance to hyperbaric oxygen by taking an oxygen tolerance test (OTT). During a recent experimental oxygen dive series at the U.S. Navy Experimental Diving Unit, three divers were noted to be reproducibly oxygen sensitive. These three divers were then given additional OTTs to see if any evidence of central nervous system oxygen toxicity would be detected by these multiple tests. The additional OTTs did not produce any signs or symptoms of oxygen toxicity in these already proven susceptible divers. A subsequent review of the records of the Naval Safety Center yielded a total of 1347 OTTs from 1 January 1972 to 31 December 1981. A review of diving accidents reported during this period revealed that 26 episodes of oxygen toxicity were noted during OTTs for a derived failure rate of 1.9%. Analysis of oxygen toxicity episodes encountered during operational Navy diving for this period found that 9 episodes of nonconvulsive oxygen toxicity were seen in mixed gas diving and 3 episodes of nonconvulsive oxygen toxicity were noted in closed circuit oxygen diving. Conclusions from this paper are: a) Screening for oxygen intolerance is complicated by intraindividual variation in oxygen tolerance; b) U.S. Navy diving using 100% oxygen during the period studied has had an acceptable safety record according to the data on record at the Naval Safety Center; c) the OTT as currently administered by the U.S. Navy does not identify all individuals who are relatively susceptible to oxygen toxicity; d) those individuals who *do* fail the OTT are unusually susceptible to oxygen toxicity; and e) because of the need to continue to identify these unusually susceptible individuals, the OTT should continue to be administered to U.S. Navy diver candidates.

oxygen
oxygen toxicity
oxygen tolerance
oxygen screening

Beginning with the closed-circuit Fleuss scuba apparatus invented in 1876, pure oxygen has been used in the conduct of diving operations. The Draeger LAR V closed-circuit breathing apparatus currently used by U.S. Navy (USN) combat swimmers utilizes oxygen (O_2) as the breathing medium. The USN He-O_2 decompression tables use 100% O_2 at 50 and 40 ft decompression stops to accelerate helium off-gassing. Additionally, USN Treatment Tables 5, 6, and 6A use 100% oxygen at

pressures up to 2.8 ATA in the management of gas embolism and decompression sickness. The use of hyperbaric oxygen entails the risk of central nervous system (CNS) oxygen toxicity. Signs and symptoms of CNS oxygen toxicity may include any of the following: convulsion; muscle twitching; nausea; tinnitus; irritability; apprehension; visual disturbances; dizziness; and incoordination (1–6). The physiological event or events responsible for CNS oxygen toxicity have not been precisely defined (7), but several investigators have noted that certain individuals seem to be much more susceptible to CNS oxygen toxicity than the rest of the divers in their studies (1,4) (Butler FK Jr, Thalmann ED unpublished data). This phenomenon was described as "inter-individual" variation by Donald (1).

Because of this inter-individual variation, all U.S. Navy diving candidates are screened for their tolerance to hyperbaric oxygen by taking an oxygen tolerance test (OTT). The test is administered in a dry recompression chamber compressed on air to a pressure equivalent to 60 ft (18.2 m) of sea water (fsw). The subject breathes 100% O_2 at rest via an oro-nasal mask for 30 min. The inside tender observes the candidate for any sign of oxygen toxicity. If any of the previously mentioned symptoms occur, the test is terminated by removing the mask and allowing the subject to breathe air. If a convulsion or muscle twitching has occurred, the candidate is permanently disqualified from diving. If symptoms other than muscle twitching or convulsion are seen, the test is terminated but may be repeated at a later date (8).

Recent experience at the U.S. Navy Experimental Diving Unit (NEDU) has revealed that three reproducibly oxygen-sensitive divers had not been identified as such by their initial screening OTT. This paper will discuss the incidence of oxygen intolerance detected by the OTT and relate these results to experience gained in the experimental dives mentioned as well as to operational Navy diving. This will allow an assessment to be made of the effectiveness of the OTT as a screening test.

METHODS

The experimental data were obtained from two experimental oxygen dive series conducted at NEDU. The experimental design and results are discussed elsewhere (4) (Butler FK Jr, Thalmann ED, unpublished data). In all, 533 exposures to hyperbaric oxygen were conducted. Dive depths ranged from 20 to 50 fsw (6.1 to 15.2 msw). Bottom times from 5 to 265 min were tested with the duration of bottom time being generally inversely related to the depth of exposure. All dives were conducted in the wet with exercising divers and moderate cold stress. Divers' breathing mixture was monitored for O_2 and CO_2 to ensure a uniform hyperoxia and absence of hypercarbia.

The Naval Safety Center in Norfolk, VA, maintains records of all U.S. Navy diving. Each diver or candidate completes a Diving Log-Accident/Injury Report (Form OPNAV 9940) after each dive. This describes the type and purpose of the dive, the dive profile, equipment used, and, if an accident has occurred, the details of the accident and its treatment. Computer records for all reported USN diving accidents and hyperbaric oxygen treatments for the period 1 January 1972 to 31 December 1981 were obtained from the Safety Center and reviewed. Incidents of oxygen toxicity occurring during closed-circuit scuba dives, decompression from heliox dives, Treatment Tables, or OTTs were identified and studied. (Treatment

Tables conducted on civilian diving accident victims were not included inasmuch as the civilian patients had not had a previous OTT.) A major caveat in this method of tabulation lies in the fact that not all dives and not all diving accidents are properly documented by submission of a Form OPNAV 9940. If an OPNAV 9940 is not prepared for a particular dive or if no mention is made of an oxygen toxicity episode on the OPNAV 9940, then there is no official record of that event.

The total number of OTTs administered during this period was also determined. All dives identified as "selection" dives were retrieved from the Naval Safety Center computer files. The information provided for each dive was studied to determine whether it was likely to represent an OTT. The criteria needed to identify a dive as an OTT were as follows: a) A depth of 60 or 112 fsw (the OTT is often administered in conjunction with the 112 fsw pressure test); b) a bottom time between 25 and 60 min; c) equipment code consistent with a dry chamber; and d) the student diver identification code.

RESULTS

The experimental oxygen dive series at NEDU resulted in 46 episodes of oxygen toxicity; 5 of the episodes were convulsions, 12 more were felt to be definitely the result of CNS oxygen toxicity, and 29 were reported as "probable" oxygen toxicity symptoms (4) (Butler FK Jr, Thalmann ED, unpublished data). Twenty-six individuals took part in the first dive series; 53 individuals participated in the second series. Some individuals dove in both series. During the course of the diving, 3 individuals were identified as being usually susceptible to oxygen toxicity. Table 1 provides physical descriptions of these 3 divers and their toxicity episodes. Diver A had 2 convulsions in 3 dives. Diver B had 1 convulsion and 1 "definite" hit on 4 dives. Diver C had 2 convulsions and 4 "probable" hits in 11 dives. All of the convulsive and "definite" episodes occurred after oxygen exposures which were tolerated without difficulty by the other divers in the study. Based on the multiple toxicity episodes suffered by these 3 divers on exposures that produced no significant oxygen toxicity in the other divers, these individuals were felt to represent the more oxygen-sensitive end of the spectrum of "inter-individual" variation.

TABLE 1
NEDU OXYGEN SENSITIVE DIVERS

Diver	Age	Height, cm	Weight, kg	Toxicity Episodes	Number of Dives	Oxygen Tolerance Tests
A (1982)	33	193.0	84.1	2 Convulsions	3	10
B (1982)	35	180.3	86.4	1 Convulsion 1 Definite	4	5
C (1983)	27	193.0	81.8	2 Convulsion 4 Probable	11	2

Once these 3 divers were identified as being relatively susceptible, additional oxygen tolerance tests were administered to each diver to see if repeated testing would produce any symptoms of oxygen toxicity. (All divers had had at least 1 OTT previously.) Diver A underwent a total of 10 OTTs, Diver B had a total of 5, and Diver C had 2. These totals include their previous screening OTT. None of these individuals who had been found to be unusually oxygen-sensitive during the experimental diving developed any symptoms during any of the oxygen tolerance tests.

The review of the computer records yielded a total of 26 oxygen toxicity episodes, including 10 convulsions, occurring during OTTs for the period studied. Table 2 provides a listing of the symptoms described. A total of 1347 OTTs were documented in the Safety Center files. The incidence of oxygen toxicity encountered during OTTs is therefore calculated to be 1.9%. It should be noted that this figure represents an average of only 135 OTTs/yr. This is a relatively small number and probably represents significant underreporting to the Safety Center. The magnitude of the underreporting and to what extent the data obtained from the computer records are representative of unreported OTTs cannot be determined from the files examined.

Tabulation of the reported cases of oxygen toxicity encountered in operational diving in the 10-yr period under consideration is shown in Table 3. Only 1 convulsion was reported to the Safety Center in this period. Decompression from He-O_2 dives resulted in 9 oxygen toxicity episodes, the largest number reported.

DISCUSSION

The primary purpose of the OTT is to prevent individuals who are unusually susceptible to oxygen toxicity, as described previously, from being exposed to hyperbaric oxygen under operational diving conditions. Convulsions that occur in the water place the diver in significant danger of death from drowning or gas embolism. This

TABLE 2
OXYGEN TOXICITY SYMPTOMS REPORTED DURING OXYGEN TOLERANCE TESTS (1972–1981)

Sign/Symptom	Number	Percent of Total Sign/Symptoms
Convulsion	10	34
Muscle twitching	7	24
Dizziness	5	17
Nausea	2	7
Visual changes	2	7
Unconsciousness	1	3
Other	2	7
Total	29	100

Note: Although only 26 oxygen toxicity episodes were noted, a total of 29 symptoms are listed because 3 of the episodes reported two symptoms. One percent discrepancy in percentage total is the result of rounding error.

TABLE 3
OXYGEN TOXICITY EPISODES REPORTED DURING OPERATIONAL NAVY DIVING AND OXYGEN TREATMENT TABLES (1972–1981)

Type of Dive	Convulsions	Other Oxygen Toxicity Symptoms
Surface-supplied He-O_2 (oxygen decompression)	0	9
Closed-circuit oxygen	0	3
USN Table 5	1*	0
USN Table 6/6A	0	6

*Although reported as a "mild convulsion," the time course reported for the toxicity episode suggests that the episode was probably a focal seizure (muscle twitching).

hazard can theoretically be avoided by identifying in the more controlled environment of a hyperbaric chamber those candidates who would be at increased risk.

This screening process is complicated by the fact that the results of a single oxygen exposure on an individual may not be reproducible on subsequent exposures. A dramatic example of this is provided by Donald (1) in his description of a diver who made 3 dives to 50 ft (15.2 m) while immersed in water (immersion significantly decreases tolerance to oxygen at a given partial pressure). On his 1st dive, this diver had a convulsion after only 12 min; several weeks later he made a 2nd dive to 50 fsw under the same conditions and completed 100 min without symptoms. On a 3rd dive, the diver experienced a convulsion after 32 min. Donald (1), in the same paper, describes an individual who was compressed to 70 ft (21.2 m) in a dry chamber (at rest) on 20 separate occasions and kept at depth until symptoms or signs of oxygen toxicity developed. The range of time elapsed was from 7 to 148 min, but Fig. 1 shows that in 15 of the 20 dives toxicity developed between 21 and 90 min into the dive. The results of these repeated exposures on the same divers and the onset of CNS oxygen

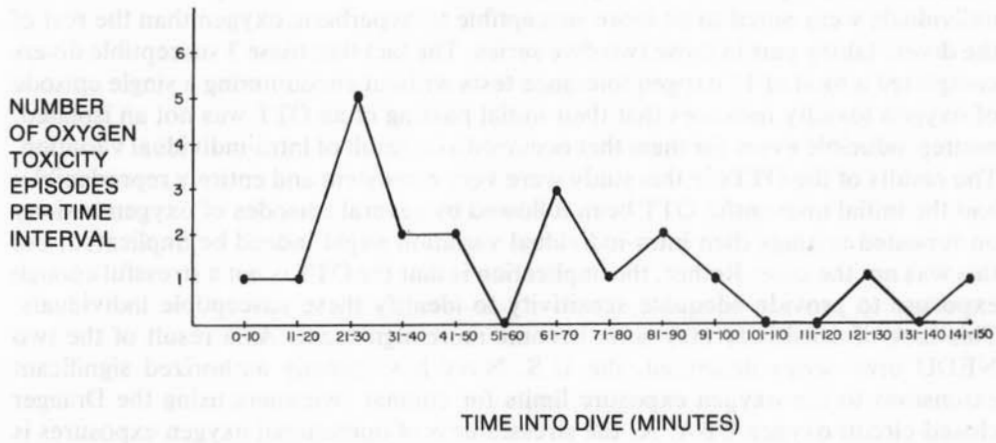

Fig. 1. Time to development of oxygen toxicity signs/symptoms in a single diver on 20 different dives [*from* Donald (1)].

toxicity at different times in the different exposures illustrates what Donald (1) describes as "intra-individual variation." With respect to the oxygen tolerance test, this concept means that a person may have a significant variation in his oxygen tolerance from day to day. Some navies have, in fact, discontinued the administration of screening oxygen tolerance tests primarily because of this intra-individual variation.

How well has the OTT succeeded in preventing oxygen toxicity episodes in U.S. Navy operational diving? As seen in Table 2, no convulsions were reported in either mixed-gas diving with 100% oxygen decompression or closed-circuit oxygen diving. There were 9 episodes of nonconvulsive oxygen toxicity reported during decompression from mixed-gas diving and 3 episodes of nonconvulsive oxygen toxicity in closed-circuit oxygen diving. No deaths or permanent injury to any divers were reported. These data indicate that Navy diving using 100% oxygen has had an acceptable safety record for the past 10 yr and that the divers who pass the OTT are able to tolerate oxygen exposures routinely encountered in operational diving situations. (A question that cannot be answered is whether or not the diving candidates who *failed* the OTT and were disqualified would have been able to tolerate these exposures as well.)

The disparity between the many episodes of oxygen toxicity seen at NEDU as compared to the relatively few operational toxicity episodes noted in Table 2 may be explained by any or all of the following: a) The dives in the NEDU series were experimental dives and the profiles conducted involved cold, working exposures for bottom times representing increases of as much as 320% compared to the limits specified in the U.S. Navy Diving Manual; b) the experimental dive subjects were thoroughly briefed regarding oxygen toxicity and were closely observed by their tenders during the dive, with both divers and tenders instructed to report any sign or symptom that might represent a toxicity episode; c) meticulous records were maintained of all reported episodes with no possibility of an incident failing to be reported through administrative shortcomings.

Since 10 convulsions were reported during OTTs compared to none during operational diving in the period studied, one might ask whether the OTT is more stressful an oxygen exposure than necessary. The experience at NEDU (4) (Butler FK Jr, Thalmann ED, unpublished data) provides evidence to the contrary. As described, 3 individuals were noted to be more susceptible to hyperbaric oxygen than the rest of the divers taking part in these two dive series. The fact that these 3 susceptible divers completed a total of 17 oxygen tolerance tests without encountering a single episode of oxygen toxicity indicates that their initial passing of an OTT was not an isolated, nonreproducible event for them that occurred as a result of intra-individual variation. The results of the OTTs in this study were very consistent and entirely reproducible; had the initial uneventful OTT been followed by several episodes of oxygen toxicity on repeated testings then intra-individual variation might indeed be implicated, but this was not the case. Rather, the implication is that the OTT is not a stressful enough exposure to provide adequate sensitivity to identify these susceptible individuals. This lack of sensitivity may soon become more significant. As a result of the two NEDU dive series described, the U.S. Navy has recently authorized significant extensions to the oxygen exposure limits for combat swimmers using the Draeger closed-circuit oxygen UBA. As the stressfulness of operational oxygen exposures is increased by the use of these new limits, there may be an increased number of toxicity episodes noted in relatively oxygen-susceptible individuals who have not been iden-

tified by the current OTT. This would necessitate either a return to the previous, more restrictive exposure limits or the development of a new OTT that will more reliably identify susceptible individuals. Essential to the development of such a test will be the identification of a biological parameter that can be used as an indicator of imminent CNS oxygen toxicity before overt symptoms occur, and thus provide sensitivity without subjecting an unacceptably high number of diving candidates to oxygen convulsions.

For the present, however, the failure of repeated OTTs to produce symptoms in these 3 proven susceptible divers does suggest that the diver candidates who fail the oxygen tolerance test are indeed unusually susceptible and would be at a significantly greater risk of developing oxygen toxicity than the general population of divers. In the opinion of the authors, this is sufficient reason to continue administering the OTT to U.S. Navy diver candidates.

CONCLUSIONS

1) Screening for oxygen intolerance is complicated by intra-individual variation in oxygen tolerance.
2) U.S. Navy diving using 100% oxygen during the period studied has had an acceptable safety record according to the data on record at the Naval Safety Center.
3) The oxygen tolerance test as currently administered by the U.S. Navy does not identify all individuals who are relatively susceptible to oxygen toxicity.
4) Those individuals who *do* fail the oxygen tolerance test are unusually susceptible to oxygen toxicity.
5) Because of the need to continue to identify these unusually susceptible individuals, the OTT should continue to be administered to U.S. Navy diver candidates.

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Butler FK Jr, Knafelc ME. Dépistage de l'intolérance à l'oxygène chez des plongeurs de la Marine américaine. Undersea Biomed Res 1986; 13(1):91–98.—Tous les candidats de plongée de la Marine américaine sont évalués pour leur tolérance à l'oxygène hyperbare à l'aide d'un Test de Tolérance à l'Oxygène (TTO). Au cours d'une série récente de plongées expérimentales à l'oxygène à l'Unité de plongée expérimentale de la Marine américaine, il fut observé que trois plongeurs étaient sensibles à l'oxygène de façon reproductible. Ces trois plongeurs furent donc soumis à des TTOs additionnels afin d'observer si des signes de la toxicité à l'oxygène du système nerveux central pouvaient être détectés par ces tests multiples. Les TTOs additionnels ne produisirent aucun signe ou symptôme de toxicité à l'oxygène chez ces plongeurs déjà reconnus comme susceptibles. Une revue subséquente des dossiers du Centre de sécurité de la Marine indiqua un total de 1347 TTOs du premier janvier 1972 au 31 décembre 1981. Une étude des accidents de plongée qui furent rapportés durant cette période révéla que 26 incidents de toxicité à l'oxygène avaient été notés au cours des TTOs pour un taux calculé d'échec de 1.9%. L'analyse des incidents de toxicité à l'oxygène subits au cours de la plongée opérationnelle de la Marine pour cette période dévoila que 9 épisodes de toxicité à l'oxygène sans convulsions avaient été observés lors de la plongée avec un mélange respiratoire mixte et que 3 épisodes similaires avaient été constatés lors de la plongée à l'oxygène en circuit fermé. Les conclusions tirées de ce papier sont: (a) le dépistage de l'intolérance à

l'oxygène est compliqué par la variation intraindividuelle dans la tolérance à l'oxygène; (b) les plongées de la Marine américaine qui utilisèrent de l'oxygène à 100% durant la période étudiée eurent un record de sécurité acceptable d'après les donnée enregistrées au Centre de Sécurité de la Marine; (c) le TOT à l'oxygène, tel qu'administré présentement par la Marine américaine, n'identifie pas tous les individus qui sont relativement susceptibles à la toxicité de l'oxygène; (d) les individus qui échouent le Test de tolérance à l'oxygène sont exceptionnellement susceptibles à la toxicité à l'oxygène; and (e) à cause du besoin de poursuivre l'identification des individus exceptionnellement susceptibles, le TTO devrait continuer à être administré aux candidats de plongée de la Marine américaine.

oxygène
toxicité à l'oxygène
tolérance à l'oxygène
sélection

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