Dedication

To Rethe Pearl

Acknowledgements

Firstly to those who helped me in the large oxygen poisoning study described in Chapter 2. These are detailed at the end of that chapter.

Secondly I owe a great deal to members and officers of the Royal Naval Personnel Research Committee and its various subcommittees and working parties, many of which I had the honour of chairing. I am particularly grateful to Frank Smith and Jimmy Hamlyn of the secretarial staff.

I have appreciated the help and support of friends and colleagues in the Royal Naval Medical School and the Royal Naval Physiological Laboratory. I would particularly like to thank Dr. Reginald Withey for his encouragement and help. I am grateful for permission to use Admiralty photographs.

Finally I would like to express my gratitude to all the experimental divers I have worked with over the years. Their cheerful companionship, trust and courage have lightened the onerous task of exploring and defining the dangers of diving.

Royal Navy Frogman (oxygen breathing), 1943. Note high degree of stream-lining of suit, cylinders, weights and counterlung (upper chest and shoulder). Note division of counterlung (inspiratory and expiratory) with canister between at back.

PREFACE

OXYGEN AND THE DIVER

The purpose of this monograph is to provide a useful, accurate and critical account of previous studies of oxygen poisoning in relation to diving. It is not an historical treatise but rather an attempt to remedy the remarkable dearth of publications of the original objective data on, or related to oxygen poisoning under water. All the material presented is immediately relevant to present day oxygen or hyperbaric diving. It is hoped that those interested in diving will find this book a convenient source of reference to previously scattered and often inaccessible reports.

Oxygen poisoning is, after decompression sickness, the second great danger in diving, a danger that will increase with the increased use of oxygen-rich gas mixture in various forms of diving. Yet, astonishingly, there is no monograph devoted to the subject.

It is sometimes remarked that, as long as the diver and his supervisor stick to the rules and regulations, they do not need to know the complex details and the full 'horror' of acute oxygen poisoning. Yet no-one makes this suggestion with regard to the causation and the varying clinical pictures of decompression sickness.

The rules concerning both air and hyperbaric oxygen diving are, on occasions, inevitably stretched or broken in the almost infinitely variable world-wide scenarios of diving. There can be no excuse for not extending this open sophisticated attitude with regard to decompression sickness to all potential risks to the diver, including oxygen poisoning. The greater the knowledge of these dangers the greater the safety of the diver.

Oxygen poisoning under water did not arise as a problem until the second world war when independent divers began to breathe pure oxygen during covert operations. A large number of studies were carried out by the Royal Navy, mostly under water. It is very doubtful whether

experimental diving on oxygen of large groups to 'acute toxic end-points' will ever be undertaken again and, for this reason, the results, which cover many past and present problems are made fully available for the first time.

The author then describes a series of studies of oxygen poisoning, mainly unpublished, by the United States Navy. I am most grateful to them for providing copies of many original U.S.N. reports. The initial apparent difference of sensitivity to oxygen poisoning in the two navies is discussed. Butler & Thalmann (U.S.N.) and their colleagues also provided me with a great deal of material concerning their recent research into prolonged oxygen exposures at shallow depths, with deeper excursions.

Finally the present practises in oxygen diving are described and possible procedures or regulations to further reduce the hazards of oxygen poisoning are proposed.

In chapter 4 the risks of lung damage in divers due to oxygen toxicity are discussed. An even more cautious attitude to this problem is recommended.

The use of hyperbaric oxygen to accelerate the elimination of inert gases during decompression after air or oxy-helium diving is also reviewed. The particular dangers of underwater oxygen breathing decompression stops are emphasised.

Chapter 5 describes the development of oxygen-nitrogen mixtures in counter-lung self contained diving. These mixtures are being increasingly used by service and commercial divers. Several new types of oxygen-nitrogen mixture breathing apparatus have been introduced and the advantages and disadvantages of such apparatus are discussed, particularly in relation to oxygen poisoning. The important claim that oxygen toxicity is greatly enhanced by hyperbaric nitrogen when breathing oxygen-nitrogen mixtures and the resulting restriction of acceptable oxygen partial pressure allowed in such mixture diving, is examined. The supporting evidence of this claim, previously unpublished, is presented and reviewed.

In chapter 6 problems in relation to carbon dioxide and hyperoxic diving are discussed. The first occurrence of carbon dioxide narcosis in oxygen underwater swimmers is described. The widely accepted claim that under-ventilation and carbon dioxide retention occur in oxygen-nitrogen mixture divers with the enhanced risk of oxygen toxicity is discussed. An

abstract of Lanphier's large unpublished series of ventilation and end-tidal PCO_2 measurements in exercising divers on oxygen, air and oxygen-nitrogen mixture at various depths is presented and reviewed in some detail. The associated studies of the ventilatory response to inhaled carbon dioxide and to exercise at atmospheric pressure, breathing air, in a group of so-called 'CO_2 retaining' mixture divers is also reported.

In chapter 7, titled 'Are divers really different?', a general discussion is followed by a detailed review of many important studies purporting to show that divers have an abnormally low ventilatory reaction to exercise and to increased levels of carbon dioxide.

After examining the evidence in chapters 6 and 7 it is proposed that far more direct and convincing evidence is required to support the hypotheses that divers, in general, have abnormal ventilatory behaviour and that mixture divers, in particular, are even more vulnerable to oxygen poisoning.

Finally, those interested in the naval events related to this research may find it useful to refer to Appendix 1 before reading Chapter 2.

CHAPTER 1

ADVERSE EFFECTS OF OXYGEN AT INCREASED PRESSURES

Man, in order to remain under water, is forced to employ artificial aids and breathe gases at tensions which are never encountered in the natural environment. There is no collapse of the lungs which continue to ventilate with the gases supplied to them at that pressure. The pulmonary and general circulation are scarcely altered. In these conditions it is inevitable that the blood will equilibrate with the high tension of gases in the alveoli and that the tissues throughout the body will absorb and contain gases at these tensions. It is difficult to suggest on theoretical grounds what the reactions of living matter to high oxygen tensions will be. The protoplasm of any living organism has behind it and within its substance a long heritage of successful evolution and adaptation. Heat, cold, hypoxia, starvation and disease have been encountered and successfully resisted again and again. If an organism is exposed to such hazards it is logical to expect processes and patterns of physiological behaviour to meet these emergencies, even if some are atavistic and no longer fully effective. Living matter is wise and old and experienced but it is doubtful if it has ever encountered such tensions of oxygen.

It has long been a matter of debate why deep diving mammals such as the whale do not appear to suffer from oxygen poisoning or decompression sickness. Whales normally sound to about 300 fsw but have been known to dive to depths as great as 3000 fsw in 'escape' dives after harpooning. However, when diving, the lungs and thorax, which are capable of a far greater degree of volume reduction than in the land mammal, transfer much of the compressed air to the large dead space. In any case, even if the lung gases were fully absorbed, one single lungful is quite incapable of raising the gas content and tensions in the whale's body tissues to any

important or harmful degree. The whale's respiratory adaptations include the extreme mobility of the chest wall, allowing dives far below the limited range of breath-holding man, and marked tolerance of intermittent hypoxia and hypercarbia. It is the use of elaborate artifacts by man, which allow the continuation of normal respiration and the continued absorption of gases at increased pressures, that cause these unnatural diseases.

Thus it appears that the tissues of man breathing pure oxygen or air at pressure are exposed to an internal environment which has been previously unknown to living matter. A number of savants remarked on the possible toxic action of oxygen at increased concentrations shortly after its discovery in the atmosphere and the promulgation of the combustion theory of respiration. They claimed that the respiratory exchange would be increased, the circulation accelerated and the lungs congested and that even inflammation and death would occur. Lavoisier and Seguin (1789) denied such an increase in the oxidative processes of the body. Regnault and Reiset (1849), in a series of experiments, demonstrated that animals, exposed to an atmosphere rich in oxygen, showed no convincing evidence of any increase in their oxidative processes.

Paul Bert (1878) made enormous strides in our knowledge of the effect of varying tensions of gases. His brilliant work has withstood the test of time in the most impressive manner. He showed that oxygen at increased pressure was highly poisonous and that no living matter was exempt. Larks exposed to 15 to 20 atmospheres of air convulsed and finally died. A similar effect was obtained in these birds in approximately one fifth of this pressure of oxygen. In a large series of experiments, with many species, Bert showed that the oxygen tension was the decisive factor in the immediate effect of air or any mixture of nitrogen and oxygen at pressure. Nitrogen was apparently inactive except in its role in bubble formation with decreasing pressure. He suspected that the convulsions were caused by the action of a secondarily produced poison on the central nervous system. He therefore transfused normal animals with large quantities of blood from those that had been severely convulsed with oxygen. His results were entirely negative and he concluded that the toxic action of oxygen was a direct one. Bert demonstrated that, although oxygen was a general poison, the central nervous system was the first to be so grossly affected that it caused violent convulsions and death before marked

changes in other organs could be demonstrated. In this context he showed that the mesodermal tissues of animals, killed in this way, could be grafted and survive in healthy animals. Bert did not consider his experiments sufficiently controlled, especially with regard to the carbon dioxide present, to arrive at definite conclusions concerning the variation of tolerance in different species. He made the important observation that, contrary to all previous proposals, high partial pressure of oxygen caused an actual diminution in oxidation and a fall in body temperature. He also demonstrated that high oxygen tensions had an adverse effect on insects, arachnids, myriapods, molluscs, earthworms, fungi and germinating seeds. It inhibited the putrefaction of meat and delayed the souring of milk. He demonstrated, in other words, that oxygen at increased tensions acted as a general protoplasmic poison. He attempted to determine the most 'favourable' tensions of oxygen for metabolic activity and concluded 'that increase of oxygen tension above its normal value in ordinary air seemed to bring no advantage, far from it. When any difference is noticeable it is in favour of normal air.' It should be noted that in a number of his experiments, particularly with larger animals, the tensions of carbon dioxide allowed to develop were very high and the decompression was far too rapid. It is possible that they suffered from carbon dioxide poisoning as well as oxygen poisoning and even decompression sickness and gas embolism after decompression. Many subsequent investigators have demonstrated the convulsions of oxygen poisoning in various species (Lorrain Smith (1899), Hill and Macleod (1903), Argyll-Campbell (1929), Shilling and Adams (1933), Libbrecht and Massart (1937), Bean and Rottschafer (1939), Behnke et al (1934), but only brief mention will be made of references which may have some relevance to the present diving study.

Shilling and Adams (1933) studied acute oxygen poisoning at high pressure in large groups of rats. Although they mentioned the extreme individual variation of oxygen tolerance and the frequent occurrence of violent convulsions without any warning signs, they wrote, with regard to oxygen poisoning in man, "From our observations on animals we are of the opinion that man exposed to dangerous tensions of oxygen will have early and ample warning of convulsive seizures." Brown, Dickens and Feldberg (personal communication, 1943) carried out experiments to determine whether increased oxygen pressure would affect the mechanism of

synthesis or release of acetylcholine in sliced or ground brain tissue. No difference could be detected in the extent of acetylcholine synthesis when the brain tissue was incubated in air, or in oxygen, at pressures of 4 to 5 atmospheres. Gersh (1944) carried out extensive investigations of oxygen poisoning in cats. He convulsed these animals daily, but relieved the pressure immediately convulsions commenced and allowed the animals to recover. Complete recovery occurred in a short time and there were no neurological findings after one convulsion. These animals showed increased tolerance to oxygen at high pressure as the series progressed. After a week of daily exposures the animals began to show definite signs of neurological damage. Hopping, placing and dropping reactions were lost, especially in the forelegs. These reflexes are mediated by the cortico-spinal tracts. Increased extensor tone was also noted. A series of longer exposures at lower pressures caused more damage than brief exposures at higher pressures. After a rest of several weeks the animals showed complete recovery and their tolerance returned to the original levels. Thus it appears that the increase in 'tolerance' after repeated exposure is probably caused by cumulative damage of the more sensitive 'trigger zones.' The recovery reported is reassuring but behavioural tests were not done.

There is another important aspect of oxygen intoxication of the central nervous system. This is the apparent impairment of respiratory control (Bean and Rottschaffer, 1939). These respiratory changes may herald the onset of acute oxygen poisoning. There is usually a preliminary stage of hyperpnoea with jerky, irregular respiration which may change into slow, deep and laboured breathing. Expiratory effort becomes progressively pronounced and prolonged. Apnoeic periods may appear in the inspiratory phase and last for well over a minute. In describing these changes, the authors remarked upon the great variation in the degrees and type of respiratory disturbance.

Pulmonary Toxicity. Reverting to the end of the nineteenth century, Lorrain Smith (1899) demonstrated, for the first time, that animals breathing oxygen at moderately high tensions over prolonged periods suffered pulmonary damage. He showed that mice, exposed to 70 to 80% of an atmosphere for four days, developed congestion and consolidation of the lungs that was usually fatal. Higher tensions caused the onset of these events in the lungs in a much shorter time. As regards pathological

changes, Smith stated "Tissues of the lungs showed intense congestion in the large and small blood vessels. The alveoli were, to a large extent, filled with exudate, which was granular and fibrillated in appearance, but did not give the fibrin stain by Weigert's method, nor with eosin." No increased leucocytes or bacteria were found. Mice exposed to 3.5 atmospheres of oxygen died from pulmonary damage in five hours. They showed no convulsive symptoms although larks convulsed at this pressure in a few minutes. Many species of animals gave very similar tolerance times as regards pulmonary pathology. Smith pointed out that the lung epithelium was directly exposed to the high tension of oxygen and that the internal biochemical defences could afford it no protection. At 4.5 atmospheres some animals convulsed and others died of pulmonary damage. Smith noted the striking reversibility of this lung damage. He stated "It was found that mice have remarkable powers of recovery from the effects of high oxygen tensions. The same is probably true of man, so that in alternation between ordinary atmosphere and the atmosphere where oxygen is at an increased tension, there would be much less danger than in an exposure which is continuous."

Stadie, Riggs and Haugaard (1944), in their review, quite unaccountably belittled Lorrain Smith's outstanding contribution. French scientists, however, pay due compliment to these two great pioneers by describing the convulsive action of hyperbaric oxygen as 'L'effet Paul Bert' and the damaging effect upon the lung as 'L'effet Lorrain Smith.' Smith's findings were amply confirmed by many other workers. Some studies are of particular interest in the present context. Hill and Macleod, (1903) noted the considerable variation of individual resistance to pulmonary damage. They also produced similar lung pathology by exposure to 7 to 10 atmospheres of air (1.47 to 2.00 atmospheres of oxygen) in dogs, cats and mice. Barach (1926 showed that 80 to 85% I ATS of oxygen caused fatal pneumonia and that in one rabbit, inhalation of 70% oxygen for twelve days was followed by pulmonary oedema. He attempted to acclimatise these animals by gradually increasing the oxygen from safe concentrations up to 80 to 85% of 1 ATS. In all instances there was no acclimatisation and death resulted. He concluded that the highest concentration compatible with safety was 60% of 1 ATS.

Faulkner and Binger (1927) showed that oxygen (95% 1 ATS) had no effect on frogs nor on turtles unless they are warmed to 37.5°C when

pulmonary changes similar to those found in mammals occurred.

Temperature. Bert (1878) and Hill & Macleod (1903) reported a marked fall in body temperature in various species with acute oxygen poisoning. There were no controls in either study. Bert also demonstrated the remarkable resistance of cold blooded animals to the convulsant effect of hyperbaric oxygen. Gersh (1944) found in animal experiments that a very wide variation of ambient temperature (4 to 41°C) made no significant difference to the rate of onset of oxygen poisoning at 8 ATA. He did not confirm the previously reported fall of temperature with toxic exposures to hyperbaric oxygen.

Tissue Enzymes. Only brief reference will be made to this subject. Paul Bert (1878), with his usual prescience, proposed that inactivation of the tissue enzymes occurred in oxygen poisoning. He demonstrated that a strip of living beef muscle showed diminished oxygen uptake and carbon dioxide production at high tensions of oxygen as compared with control experiments in compressed air. He wrote "Now it is a fact of the highest interest that in the presence of this free oxygen which is simply dissolved, inner oxidations slow up, then stop . . . I know nothing in physiological chemistry more curious than this effect of dissolved oxygen." Massart (1936), Libbrecht & Massart (1937), Bohr & Bean (1940), Quastel (1939) and Dickens (1945) and many others have all confirmed Bert's findings and have demonstrated tissue enzyme deactivation.

Oxygen Poisoning in Man. The first recorded exposure to hyperbaric oxygen, apart from that occurring in air diving, was by Bornstein (1910). Two engineers breathed 90 to 95% oxygen for 30 minutes at 3 ATA in the Elbe Tunnel. Bornstein breathed oxygen under the same conditions for 48 minutes. None had untoward symptoms. In 1912 he breathed oxygen at the same pressure while exercising on a bicycle ergometer. He ceased oxygen breathing after 51 minutes after suffering cramps in the hands and legs from which he soon recovered (Bornstein & Stroink, 1912).

In 1930 during investigations carried out by the Admiralty Committee on Deep Diving, twelve subjects were subjected to two atmospheres absolute of pure oxygen for one hour and four subjects to three atmospheres absolute for 30 minutes, without untoward effects (dry pressure chamber). These air diving trials were up to 325 fsw, where partial pressures of oxygen of 1.7 to 2.27 ATA were encountered. The divers showed confusion and amnesia as well as 'unreliable' and unpredictable behaviour (Damant, 1930).

J.S. Haldane (père) thought that these dangerous symptoms were due to the raised tensions of oxygen despite the lack of supporting evidence in the oxygen exposures mentioned above (Haldane & Priestley, 1935). Hill & Phillips (1932) attempted to explain the findings on psychological grounds. There is more than a hint of unreality in their explanation and discussion of the psychological peccadilloes of a group of specially selected deep sea divers of the Royal Navy. Behnke, Thomson and Motley U.S. Navy (1935) first advanced the theory, later confirmed, that the increased tension of nitrogen was the cause of these mental disturbances.

In 1933 two British naval officers, Damant and Phillips, breathed oxygen in a compressed air chamber at four atmospheres absolute. Leonard Hill was in attendance. Convulsive symptoms occurred in 16 and 13 minutes respectively. In the first case, (Damant), violent twitching of the face was experienced which was immediately relieved by reverting to air breathing at pressure. In the second case, the subject also reverted to air breathing at the same pressure after twitching of the lips had occurred. Despite this he convulsed. These findings were not published until two years later (Thomson, 1935). Stadie, Riggs and Haugaard in their review (1944) appeared to be under the impression that this officer convulsed while returning to normal pressure and suggested that air embolism could not be excluded. This is incorrect as the subject convulsed at four atmospheres of air after removing his mouthpiece. He was under the direct observation of Sir Leonard Hill throughout (personal communications, 1943, Hill and Thomson).

Behnke, Johnson, Poppen and Motley (1935) carried out a series of observations on human subjects breathing oxygen at one to four atmospheres absolute. The subjects were seated. Blood pressure and spirometric recordings were made and blood changes studied.

One Atmosphere: 10 subjects breathed oxygen for four hours. Nine were completely unaffected. One showed slight rise in blood pressure and pulse rate in fourth hour.

Two Atmospheres (abs): 3 subjects breathed oxygen for three hours. There was no subjective change, blood pressure change or increase in leucocyte counts.

Three Atmospheres (abs): 4 subjects breathed oxygen for three hours. The only change was a slight increase in leucocyte count.

Four Atmospheres (abs): 2 subjects breathed oxygen. The first subject suffered acute syncope after 43 minutes, which was relieved by reverting to air. The second subject had twitching of left eyebrow, after 44 minutes, and then gave a sudden cry and convulsed.

In 1936 Behnke, Forbes and Motley carried out further hyperbaric oxygen exposures. Four men breathed oxygen at 3 atmospheres absolute for 3 to 4 hours. All tolerated oxygen well for three hours but showed marked facial pallor, dilatation of the pupils, rise of the diastolic blood pressure of about 10 mm Hg and impairment of visual acuity, up to 25%, towards the end of the period. There were no abnormal subjective symptoms. In the fourth hour three subjects suffered abrupt onset of vertigo, nausea and a sensation of impending collapse. When turned onto air they showed a partial stupefaction for several minutes. Impending collapse was heralded by an increase in pulse rate, a rise in the systolic and diastolic blood pressures, concentric contraction of the visual fields and failure in visual acuity of form and colour. Intense pallor of the face and marked dilatation of the pupils, which still reacted to light and accommodation, were noted. They reported a sense of alertness and stimulation after the experiment, which, associated with the rise of blood pressure, dilatation of the pupils and intense facial pallor during the exposure, suggested adrenal stimulation. The present author has experienced this syndrome with a marked euphoria after a similar exposure.

In a study by Case and Haldane (fils) (1941) (i) a subject breathed oxygen at 7 ATA (200 fsw) in the dry. After 4 minutes he suffered vertigo and malaise and reverted to air breathing. After a second exposure at 200 fsw (7 ATA) he developed twitching in the forearm and 'breathing difficulty' after 4 minutes. He returned to air breathing and decompression was commenced. Despite this he convulsed 5 minutes later. A second subject breathed oxygen for 5 minutes at 6.15 ATA (170 fsw) and developed marked restriction of vision. A third subject survived 4 minutes on oxygen at this pressure without symptoms. Four other subjects breathed

oxygen for 5 minutes at 6.15 ATA (170 fsw). One had no symptoms; one vertigo and faintness at the end, and two had 'unpleasant' respiratory symptoms at the end.

Case & Haldane (1941, (ii)) reported that about half of the subjects in these experiments stated that they could taste oxygen at 5 to 7 ATA. The taste was both acid and sweet "like dilute ginger beer." Professor Haldane, Chief Petty Officer Derrick, and the present author (unpublished data 1942), breathed oxygen for 25 to 30 seconds at 300 fsw (10 ATA). The two latter subjects could only taste what they considered to be the "rubber in the circuit." It was, in our view, the same 'taste' experienced when breathing oxygen from the circuit at 70 fsw (3.1 ATA) or at atmospheric pressure. Professor Haldane thought he could taste the oxygen at 300 fsw but was less certain than in his previous exposures. The main reason for reporting this experiment is that this is the highest pressure, known to the author, at which oxygen has been breathed by human subjects.

Behnke (1942, (i and ii)) reported that "men had repeatedly inhaled oxygen for 27 minutes at 4 ATA with no other symptoms than a sensation of "cerebral fullness" and some degree of "mental torpidity." He also reported that oxygen tolerance was greatly reduced by very moderate exercise on a bicycle ergometer (VO_2 4 x resting uptake approx.). Thus at 3 ATA average oxygen tolerance was reduced from 3 hours or more to "about twenty minutes" when subjects developed "extreme fatigue, numbness of the lower extremities and in one instance an abortive seizure." No individual exposures were described.

It will be noted that all the observations on human subjects described so far, were while breathing oxygen in compressed air.

Lorrain Smith effect: The main interest in possible pulmonary irritation and damage due to increased oxygen tensions had been in the clinical field. It was generally agreed, mainly from animal work, that tensions above 60% 1 ATA were dangerous for prolonged exposures. Fortunately, the clinical methods of administration of oxygen did not achieve consistent levels above this figure. When special efforts were made to achieve higher concentrations (near 100% 1 ATA) it was found that the intermissions on air, as recommended by Lorrain Smith, allowed such levels for several days (Boothby, Mayo and Lovelace, 1939). Becker-Freyseng and Clamann (1939) reported that one of the authors (B-F)

developed bronchopneumonia after breathing 0.9 to 1.0 atmospheres of oxygen for 60 hours. To return to our main theme, there had been no instance of pulmonary irritation in man due to hyperbaric oxygen in any form of diving (1942). Pure oxygen had not been generally used in self-contained diving and it had only been administered for short periods at relatively shallow stops (60 to 10 fsw) during decompression after air dives (Damant, 1933) or oxyhelium mixture dives (Behnke, 1942, (iii)).

Cardiovascular System: Slowing of the heart rate in the human subject at increased pressures has long been known (Bert, 1878). Benedict and Higgins (1911) reported bradycardia in young adults breathing increased percentages of oxygen. The degree of bradycardia appeared 'roughly proportional' to the percentage of oxygen breathed. Behnke et al (1935) reported that subjects breathing oxygen at 2, 3 and 4 ATA showed but little change of blood pressure except when heralding the commencement of acute oxygen poisoning when increased heart rate, rise in blood pressure and intense skin vaso-constriction occurred.

Position in Diving in 1942: The United States Navy gave times of safety when breathing oxygen as two hours at 50 fsw and thirty minutes at 90 fsw (1941). Oxygen breathing decompression stops from 60 to 10 fsw, both under water and in chambers, were being introduced at this time (Behnke, 1942 (iii)). There were no independent oxygen breathing divers. With regard to symptoms, it was stated "The first signs of oxygen toxicity are flushing of the face, nausea, dizziness and muscle twitching. A feeling of being irritable and a sense of excitement may follow." "As pressure is increased nausea, vertigo and finally unconsciousness and convulsions ensue."

The Royal Navy had used oxygen decompression from 60 fsw (submerged decompression chamber) after deep diving and from 60 fsw (deck chamber) in surface decompression for some years. There were, until 1942, no independent oxygen divers and as these were being developed, the Royal Navy followed the recommendations made by the United States Navy (see above). The fact that two Royal Naval officers had suffered acute oxygen poisoning at 90 fsw (dry) in 16 and 13 minutes appeared to have been unnoticed or forgotten. Experienced air divers were inclined to consider oxygen to be dangerous under water at depths greater than 33 fsw. This was due to the entirely mistaken view, taken in the 1930-33 Admiralty Deep Diving Trials, that the oxygen in the air (2.1 ATA at 300

fsw) caused the severe psychological disturbances encountered (see above). The instructions in the Royal Navy Submarine Escape Handbook (1942) concerning the safe times for breathing oxygen (60 min. at 100 fsw, 6 min. at 200 fsw and 3 min. at 300 fsw) appeared unrelated to any known previous investigations. With regard to the symptoms of oxygen poisoning, the Handbook stated "tingling of the fingers and toes and twitching of muscles, especially round the mouth (warning symptoms). Convulsions followed by unconsciousness and death if a remedy is not taken."

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CHAPTER 2

OXYGEN POISONING STUDIES 1942-5

In 1942 independent oxygen diving for various covert operations was introduced in the Royal Navy on a large scale and a number of incidents had occurred (see Appendix 1). The generally accepted times of safety when breathing oxygen were based on remarkably few experiments in which oxygen was breathed, usually at rest, in compressed air. No controlled experimental dives where men had breathed pure oxygen at different depths under water had ever been carried out.

The objects of the experiments described here was to gain a more comprehensive and accurate picture of the reaction of the human subject to toxic tensions of oxygen particularly under water. Large groups of subjects were therefore employed and over two thousand experiments carried out. In many experiments the subjects were wearing diving suits and were under water to determine whether the present accepted times and rules of safety gave an accurate assessment of the dangers of high tensions of oxygen when diving in open water.

The Marked Variation of Oxygen Tolerance in Man

The first series of experiments to be carried out was to determine the oxygen tolerance of a group of healthy subjects at a fixed oxygen tension (90 fsw, 3.71 ATA).

Method: This series was carried out in a dry pressure chamber of 100 cubic feet capacity. The subject was seated with his knees slightly flexed and his back rested against the side of the tank. He was well illuminated and had two trained observers seated opposite to him. The attendants were in constant telephonic communication with those outside. The subject continued to breathe oxygen until marked symptoms occurred.

Experiments in compressed air have a number of advantages. The subject's condition can be observed carefully. This is impossible if the individual is in a diving suit underwater. He gains confidence from the immediate proximity of the observers and can refer any doubts as to his condition by means of pointing or by notes to the attendants. Subjective end-points are less likely. If a sudden or violent end-point occurs, then oxygen breathing can be immediately discontinued either by the subject or the attendant removing the mouthpiece. Convulsions are a lesser risk in a well cushioned dry compartment with two attendants.

Oxygen was breathed from a 'Salvus' apparatus. This has a simple counterlung, a one pound canister, and employs pendulum breathing. Oxygen is supplied automatically by a reducing valve. The rate of flow in these experiments was 0.75 litres per minute. This was in excess of the amount required (0.3 l/min. approx.), and the washing out of the apparatus was thus assured. Excess pressure in the counterlung could be relieved by a manually operated release valve. A mouthpiece and nose clip were used in preference to a mask as there is less risk of air leaking into the circuit and the subject's face is less obscured. The apparatus was carefully checked and the absorbent canister filled with fresh soda-lime immediately before each experiment. The oxygen employed throughout these experiments was supplied by the British Oxygen Company, and is guaranteed 99.8 to 99.9% pure, the residue being inert gases. The oxygen inhaled never had a percentage of carbon dioxide exceeding 0.1%. The subject did not breathe oxygen until the chosen depth (90 ft. of sea water, 3.72 atmospheres absolute) was reached, by allowing air to run from a bank of high pressure air cylinders into the chamber.

The rinsing out of nitrogen from the lungs was carried out by inhaling oxygen deeply from the apparatus and exhaling through the nose. This was carried out six times, note being made that the counterlung was sucked empty. Washing out was repeated every five minutes for the first half hour, and every ten minutes after that time. This was in order to eliminate any nitrogen rinsed out from solution in the tissues in the body or diffusing or leaking into the apparatus. In most exposures the pulse and respiration were noted every five minutes.

A series of analyses showed that, even with frequent washing out, the percentage of oxygen breathed in the dry varied between 92 and 97%.

Subjects varied from recently trained divers to experienced divers,

submarine ratings, medical officers, special service operational personnel and mine disposal officers and ratings. All these officers and ratings were grade A1 in fitness. Ages varied from 18 to 40 years.

The attendants breathed air and were decompressed according to Boycott, Damant and Haldane's air tables. In an emergency the whole party was immediately surfaced and the subject was removed for medical attention. As he had been breathing oxygen, it was considered that there was no risk of bubble illness. The attendants were rapidly recompressed before bubble formation could occur.

Experiments carried out in this manner are referred to hereafter as 'in the dry' in contrast to those carried out under water and referred to as 'in the wet.'

Results: These are given in Table 1 (Appendix 2) and illustrated in Figure 1. Times on oxygen at 90 fsw (3.72 ATA) are shown before the subjects developed symptoms necessitating the cessation of the exposure. Five subjects convulsed the rest recovered on being turned on to air. The nature and time of occurrence of earlier symptoms are also given in Table 1.

The most striking finding was the enormous variation in oxygen tolerance in a group of human beings. Exposures, causing marked symptoms at this tension, varied from 6 to 96 minutes in a group of 37 individuals. The tolerance of each subject was unpredictable. It will be noted that the age, weight and height of all subjects is given (Table 1). Many attempts to correlate these various data with oxygen tolerance in a group of 26 have not been successful. Physical fitness, athleticism, smoking, ingestion of alcohol, and psychological health, did not appear to influence this tolerance.

At this depth the interval between early and 'terminal' symptoms varied from 0 to 55 minutes. It is possible that some of the earlier fibrillary tremors of the lips were due to nervousness or to the strain of holding the mouthpiece. Symptoms will be discussed in detail in a later section. There is strong evidence that there is an individual variation, not only in the time of exposure tolerated, but in the particular portion of the central nervous system first to be so affected that it shows overt signs of dysfunction.

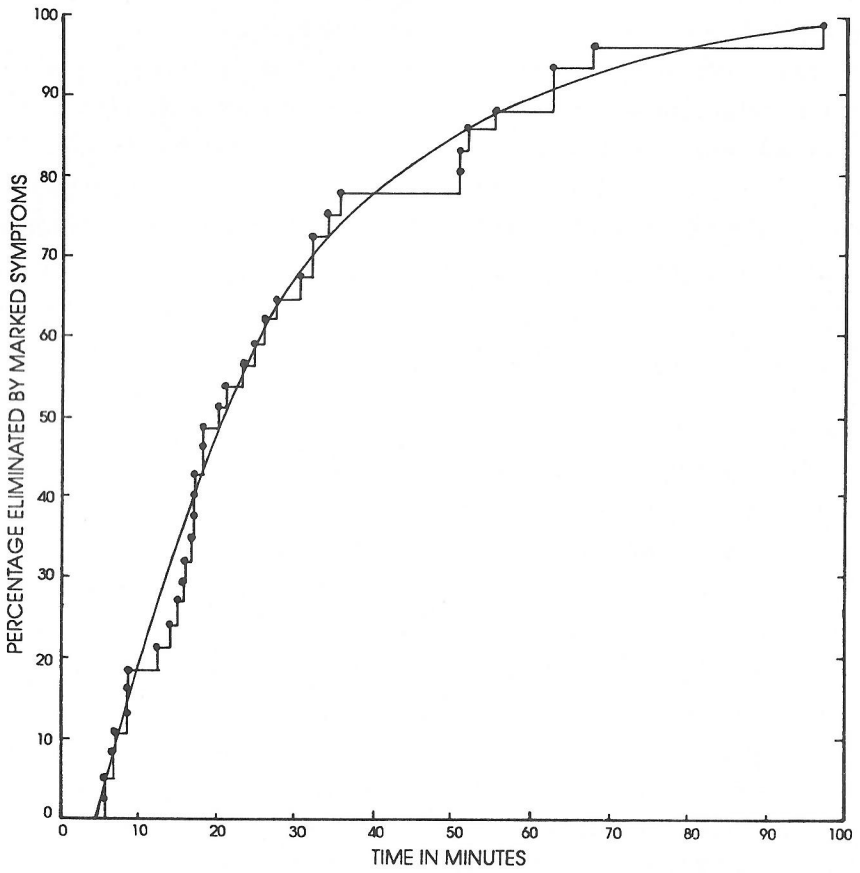


FIG. 1: Percentage of subjects in a group of 37 eliminated by toxic symptoms, as a function of the time of exposure to pure oxygen at 90 feet in compressed air. No work performed. Actual end points plotted.

In Fig. 1, the percentage of subjects eliminated by symptoms is plotted against time of exposure. This type of skew distribution was first described by Galton and Macalister. Notable examples are the response of animals to drugs and hormones, and the susceptibilities of insects to poisons (Bliss). In such distributions the logarithms of the dosages, needed to produce a given effect (e.g. to cause oestrus or death), are normally distributed. Small experimental animals i.e. rats when studied in groups, appear to have a greater resistance to oxygen poisoning than man, but it must be remembered that in animal experiments convulsions are avoided if possible. Many animals show signs of poisoning, such as twitching and

abnormal respiration, for some time at similar pressures before actually passing into convulsions. The greater resistance of experimental animals may be illusory.

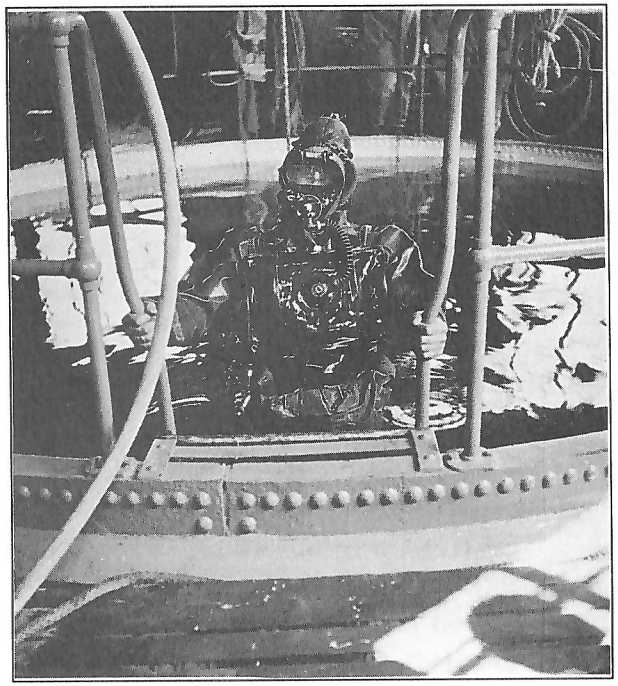
It is clear that the previously reported times of safety at this depth are dangerously incorrect. No allowance whatsoever, had been made for individual variation which is found to be over an enormous range.

Oxygen Tolerance in Man Under Water at 50 fsw (2.5 ATA)

It has already been emphasised that, up to the commencement of these investigations, all experiments regarding tolerance to oxygen under pressure had been carried out by subjects in dry chambers. This series of dives was initiated to discover whether man's tolerance was similar, under water, to that so far determined in compressed air.

Method: The diver in these experiments wore a light rubberised canvas suit with a soft helmet, (see Fig.2). The respiratory apparatus was a considerable modification of the well known Davis Submarine Escape Apparatus. It was adapted for very much longer performances by the insertion of a 4 lb. radial canister, containing carbon dioxide absorbent and by the attachment of two 2-litre bottles of oxygen, charged to 120 atmospheres (over four hours endurance). Oxygen was supplied by means of a reducing valve at the rate of 1.2 litres per minute. The excess of oxygen being supplied over the actual consumption of the resting diver (0.25 to 0.35 1/min. approx) assured the constant rinsing out of his lungs and respiratory apparatus. As the counterlung had an automatic non-return exhaust valve, no discomfort was caused to the diver.

The diver carried out the usual washing out process (see previous section) to ensure that his lungs and apparatus were filled with oxygen. He was then submerged in an open tank and tested for leaks. When his suit and apparatus were considered satisfactory he walked to the high pressure tank and was lowered into the water. The upper hatch was closed and bolted and pressure rapidly applied. On the average, subjects were breathing oxygen for ten minutes before they arrived at the appropriate experimental depth, about eight minutes being at, or near, atmospheric pressure.



"Human Torpedo" oxygen diver. Note soft helmet and vizor. Diver has mouthpiece and nose clip. Pendulum breathing into counterlung through large radial carbon dioxide absorbent canister. Luftwafe duraluminium oxygen cylinders carried on back.

The pressure tank employed in these experiments was 12 ft. in height and 6 ft. in diameter (see Fig. 2). It was filled with water to a depth of 8 ft. The diver was lowered through the upper hatch into the water. Depth was simulated by increasing the air pressure above the water. An attendant sat on a ledge inside the chamber breathing air and was in telephonic communication with the outside attendant. He wore waders and sat above a ladder running down into the water in which his legs were immersed. He held a lifeline running to the diver. The temperature of the water was maintained at 65°F. The depth reading in these experiments was actually of the air pressure above the water. Thus the pressure at which the gas was being breathed was approximately 2 to 3 ft. of water greater than the gauge reading. In open water, on the other hand, depth is estimated by lead or echo sounding, and, under these conditions, the operational depth (booted diver) would be 8 ft. greater than that measured in the pressure tank. (see Fig. 2)

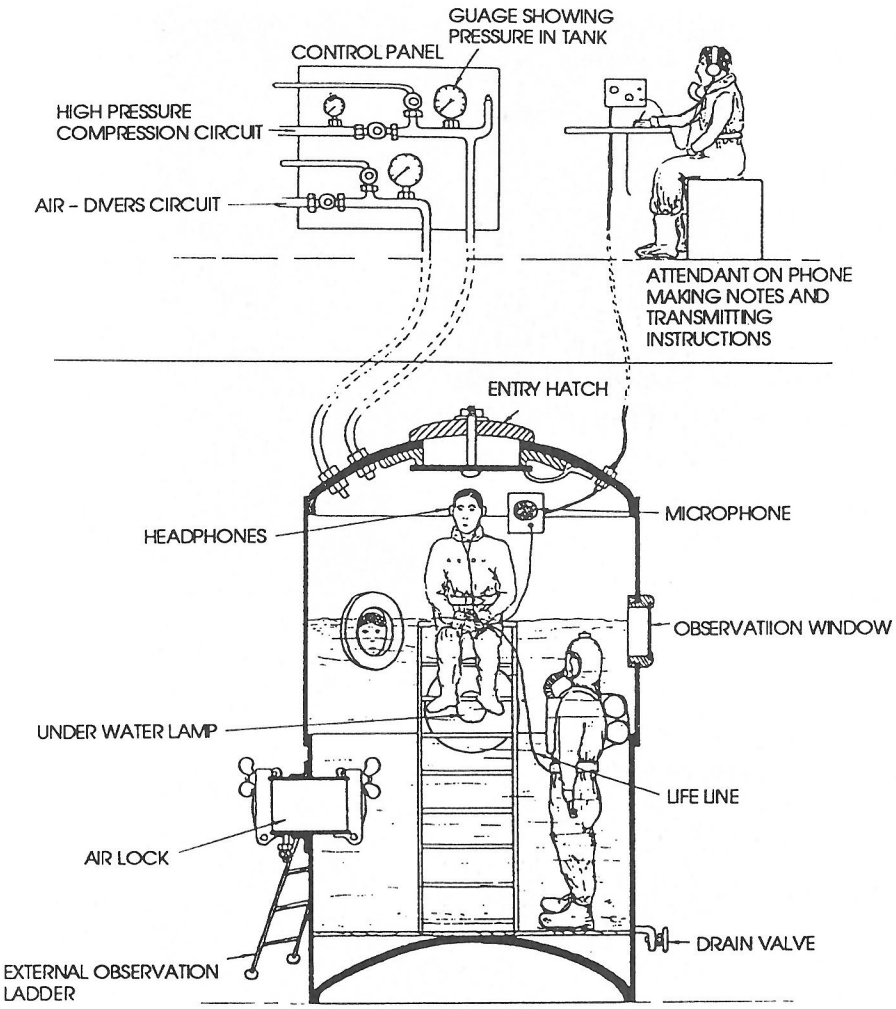
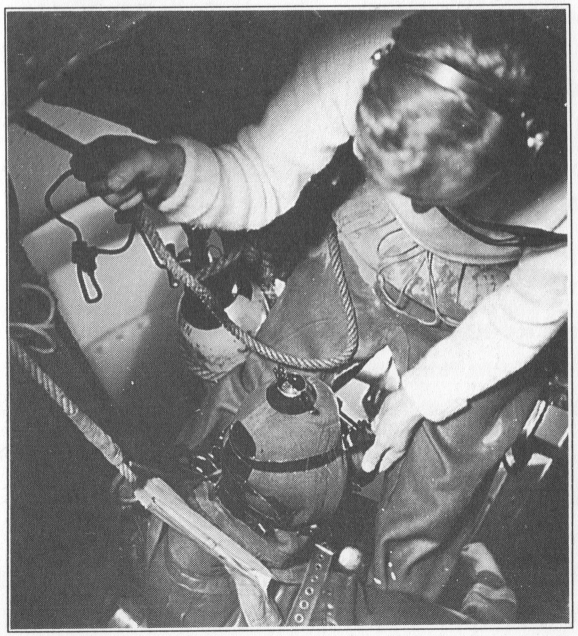


FIG. 2 **Showing wet pressure chamber with diver under water breathing oxygen in self-contained set. Internal and external attendants.**

The first series of dives was to 50 ft. of sea water (2.5 atmospheres absolute) and the time limit was 30 minutes. 100 dives were carried out. The large majority of the divers were special service operational personnel and with a few exceptions, the divers completed their half hour or had convulsive symptoms. If the diver convulsed or had severe symptoms he was hauled up by the attendant and turned on to air. The pressure was immediately released.

Welcome to the wet pot. Attendant above water breathing oxygen-nitrogen mixture to allow immediate decompression if necessary.



Attendant in wet pot instructing human torpedo oxygen diver just before going underwater.

Wet Chamber sealed. Outside attendant gets "OK" signal. Pressurization starting.

Oxygen diver being hauled out of wet pot. Vizor open and turned onto air. Airway being checked.

The mouthpiece acted as an excellent gag during convulsions and attendants were taught to hold the head correctly to maintain a good airway. The morale of these men was obviously of a very high order (see Appendix 1). Results are shown in Table 2 (see Appendix 2). Out of 100 divers, 26 convulsed, another 24 had symptoms and 50 had no symptoms.

It will be noted that the degree of exercise was not carefully controlled and mention is made in each dive as to whether any exercise was undertaken during the exposure. The degree of exercise was variable and, in some cases, for a short period or intermittently.

If we divide the dives into those exercising and those not exercising, we obtain the following:

Divers Exercising (n = 37)

8 (22%) convulsed in 10 to 30 minutes
8 (22%) lip twitching in 9 to 30 minutes
2 (5%) malaise, nausea, respiratory distress, in 11 to 31 minutes
19 (51%) no symptoms during 30 minute exposure.

Divers Not Exercising (n = 63)

18 (28%) convulsed in 7 to 29 minutes
13 (21%) lip twitching in 10 to 30 minutes
32 (51%) no symptoms during 30 minute exposure

These findings did not suggest that exercise increases oxygen toxicity but this aspect is studied more specifically later in this study.

These divers were operational personnel and not experimental divers. They considered, commendably, although quite incorrectly, that oxygen at toxic pressure was another trial to be undergone before selection was completed. Symptoms are therefore minimal.

According to previously accepted figures, men were safe breathing oxygen at this depth for two hours. It is obvious that the variation of tolerance, demonstrated in the previous section, made these figures unreliable, as they were inferred from a few experiments in the dry. The same variability is shown in this series although an exposure of 30 minutes only gave symptoms in 50% of the group. However, the total result, even allowing for variation, strongly suggests a marked decrease of tolerance

under water to that obtaining in the dry, whether the diver is resting or exercising.

The Oxygen Tolerance of Man at Rest in Compressed Air and Under Water

A series of resting dives was carried out to compare the tolerance of subjects to oxygen at increased tensions in compressed air and under water. The experiments were performed under conditions similar to those already described at both 60 and 90 fsw, (2.82 & 3.73 ATA respectively). Dives were to end-point but exposures in the dry were limited to two hours unless the subject volunteered to continue.

The following results were obtained. The time of exposure in minutes and symptoms are given (see also Fig. 3).

COMPARISON OF OXYGEN TOLERANCE IN THE WET AND IN THE DRY, AT 60 FEET AND 90 FEET, SEA WATER

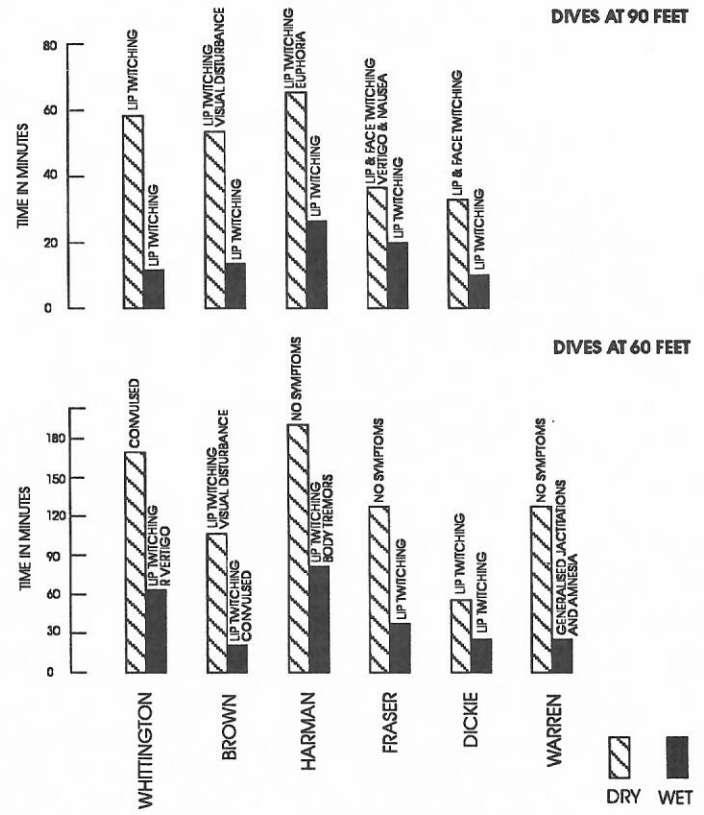


FIG. 3: Showing the marked impairment of oxygen tolerance in individuals in the wet as compareed with in the dry. Dives at 60 feet and 90 feet with end points are shown.

TABLE 3

60 FEET OF SEA WATER (2.82 ATA)

	DRY	WET
Warren	120, felt heavy and dull during last hour	25, lip twitching at end, looked 'out of touch'. Generalised jactitations for 20 seconds after being turned on to air. Retrograde amnesia.
Whittington	158 convulsed. No warning.	61, vertigo at 36 minutes, slight lip twitching at 55 minutes. Severe lip twitching at end.
Brown	101, extreme sleepiness at 20 minutes. Severe lip and nose twitching and marked 'diaphragmatic spasm' at end.	19, lip twitching at end. Convulsed 30 seconds after being turned on to air.
Harman	180, no symptoms	76, violent 'shivering' last 5 minutes. Lip twitching at end.
Fraser	120, twitching of upper lip at 100 minutes. No other symptoms except transient vertigo on reverting to air	37, lip twitching at end.
Dickie	51, slight lip twitching at 33 and 50 minutes. Sudden severe lip twitching at end	12, severe lip twitching last two minutes of exposure

90 FEET OF SEA WATER (3.73 ATA)

	DRY	WET
Whittington	54, sustained lip twitching last 4 minutes. Very severe at end	11, severe lip twitching at end
Brown	51, slight lip twitching at 43 minutes. Increasingly severe lip twitching last 8 minutes. Visual symptoms lateral movement of images and bright dazzling flashes	12, sudden severe lip twitching at end
Harman	62, pouting of upper lip 2 minutes before end. 'Pleasant sensation of intoxication' with marked euphoria	11, severe lip twitching at end
Fraser	34 fine lip twitching after 27 minutes. Convulsive movements of whole face at end. Slight nausea and vertigo during last 6 minutes	18, lip twitching at end
Dickie	32, lip twitching after 29 minutes which spread to whole of lower face and increased in severity	9, severe lip twitching last 20 seconds

Dry/Wet Ratio

It is of interest to examine the ratios of times of tolerance in the wet and in the dry.

	Series at 90 fsw	Series at 60 fsw
Brown	4.25	5.3
Whittington	5	2.6
Harman	2.4	2.4 plus
Dickie	3.4	4.1
Fraser	1.9	3.2
Warren	–	4.8 plus

It thus appears that, when oxygen is breathed under water, the period of time before toxic symptoms occur is markedly less than that which would obtain breathing oxygen in compressed air at the same pressure. This is further demonstrated with large groups later in this presentation.

The enormous importance of this finding in relation to free oxygen diving need hardly be pointed out. The degree of impairment of tolerance in the wet as compared with that in the dry is certainly far from being fully explained by the slight dilution by nitrogen of the oxygen breathed in the dry experiments (DO_2 of the order of 56 fsw in 60 fsw exposures and

of 84 fsw in the 90 fsw exposures). In the Royal Navy oxygen has only been breathed in compressed air during decompression from deep air dives (1932) when the diver enters a submerged decompression chamber and breathes oxygen to accelerate nitrogen elimination from his body. The greatest depth at which oxygen is thus breathed is at 60 fsw in the dry and then only for short periods. Thus the new use of oxygen for free covert operational diving in the Royal Navy (1942) requires urgent definition of the unexpected dangers of breathing oxygen under water.

The causes of the decreased tolerance under water remain unknown. Carbon dioxide accumulation was suspected but numerous analyses of the gas in the counterlung, of the inspired and alveolar gases negated this possibility. The highest carbon dioxide content of the inspired gas found was 0.2% (one atmosphere) and in the large majority of cases was far less. The lack of a rigid helmet, respiratory resistance, the bandaging effect of the suit, the diver's posture and hydrostatic effects in general have all been investigated to a greater or lesser extent with negative results. These experiments are not described here as they are incomplete.

Time/Pressure Relationship for Men Breathing Oxygen Underwater, Resting

The next series of experiments was an attempt to obtain a series of curves for various individuals, giving the relation of the depth of the diver in water to the time of survival when breathing pure oxygen. In view of the variation between individuals, it was realised that each of the five divers would have a different curve of safety at various depths.

Method: This series was carried out in the wet pressure chamber as described above. Each subject was dived to 50 ft., 60 ft., 70 ft., 80 ft., 90 ft. and 100 ft. In the case of the more oxygen sensitive subjects, a few more shallow dives were included. Divers were instructed to surface and to report to the attendant immediately they felt severe lip twitching or any symptoms that justified the termination of the exposure. The attendant turned the diver on to air if he considered that he was in danger of convulsing. Divers were always rested the next day and rarely carried out more than two dives per week. If a diver convulsed he was given a "stand off" for several days.

Results: Table 4 shows the results obtained (see Appendix 2). These are plotted in Figs. 4 to 8. The dives were over a period of 50 days and the

number of the day in this period is shown against each dive. The asymptote of the curve for each diver obviously depends on the maximum non-toxic depth of that particular diver. This is difficult to demonstrate as conditions in the wet pressure tank are not altogether pleasant and two or three hours endurance is about as much as one can reasonably expect.

At this stage of the investigation a new factor was becoming increasingly manifest. It was apparent that the tolerance of an individual diver varied from day to day. Thus, if an attempt is made to plot the time of tolerance against the depth, a third factor enters, that is the variation of tolerance of the diver over the period of experiments. The small inset graph in Figs. 4 to 8 is a very rough hypothetical representation of the behaviour of each subject's tolerance over this period.

Brown: (Fig.4). This diver gives an 'excellent' curve, extremely reminiscent of that obtained by Hederer and André (1940) with rabbits. The most 'aberrant' point is the dive to 80 ft. This was repeated (square symbols for repeats).

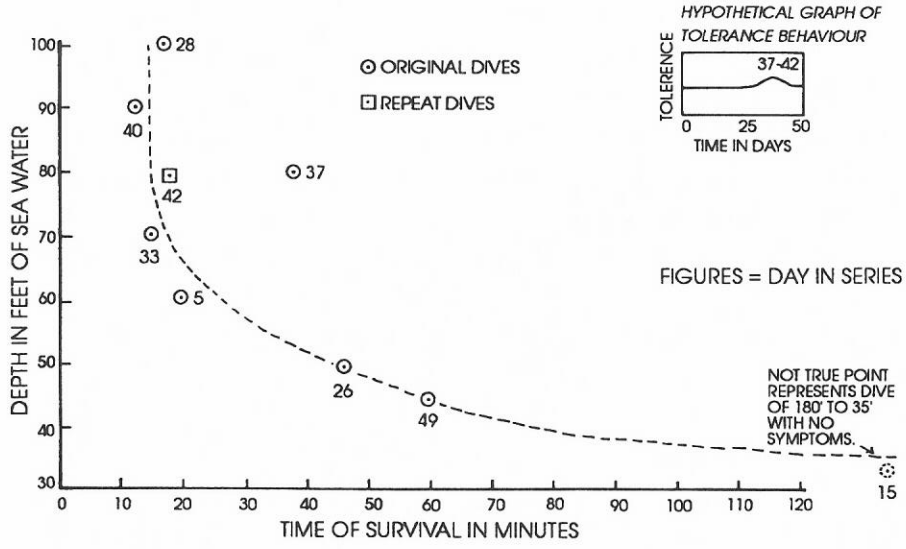


FIG.4: BROWN

Harman: (Fig. 5). This diver showed a constant high level of tolerance. There is a suggestion that his tolerance was steadily improving throughout the period.

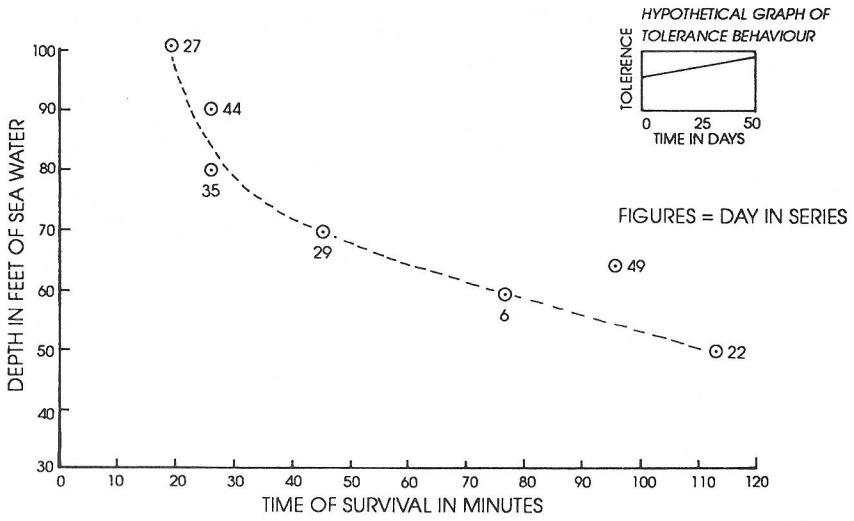


FIG. 5: HARMAN

Dickie: (Fig. 6). This series of dives, when plotted, shows marked 'scatter' although his general tolerance was high.

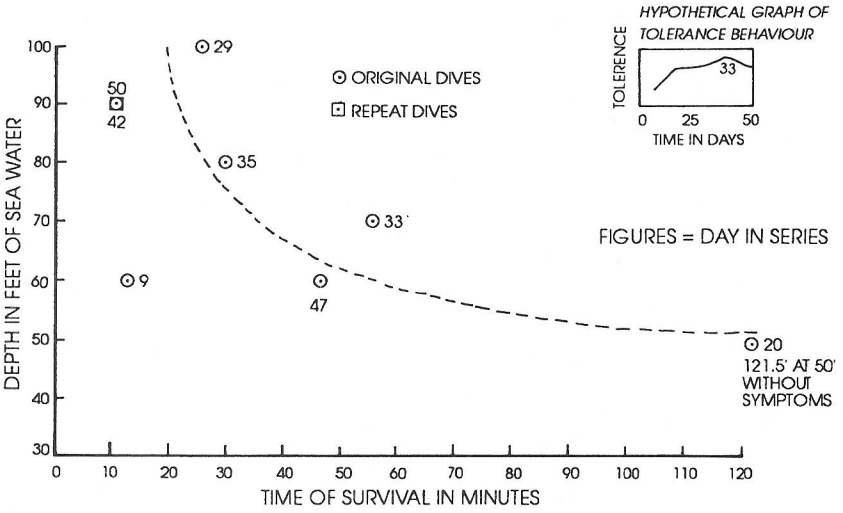


FIG. 6: DICKIE

Fraser: (Fig. 7). This diver gave a 'good' curve, with fairly sustained resistance to the toxic effect of oxygen. However, the time of survival at 60 ft. on the seventh day was markedly below the rest of his performances. A

repeat dive to this depth and another dive to 70 ft. showed that his tolerance had fallen away again.

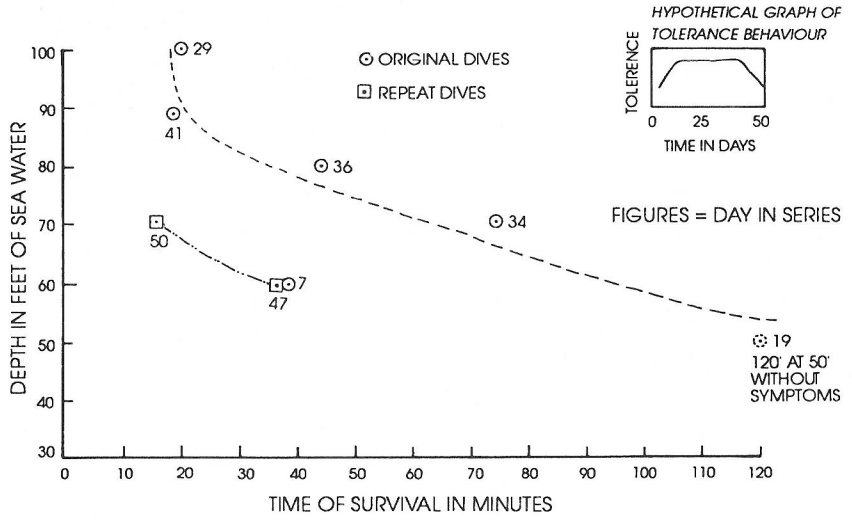


FIG. 7: FRASER

Whittington: (Fig.8). This diver showed a reasonably 'good' curve up till about the 37th day, when his tolerance appeared to fall markedly. Repeated dives at 60 ft. and 50 ft. showed that this subject had gone into a new and very inferior curve.

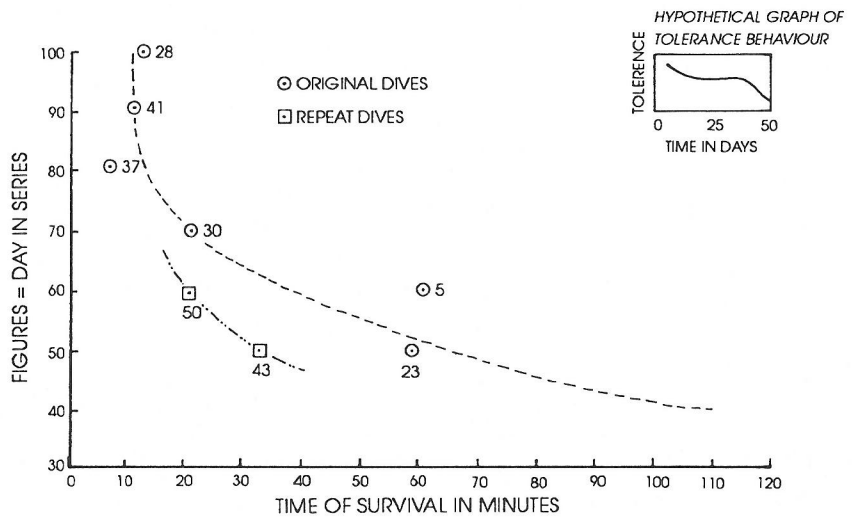


FIG. 8: WHITTINGTON

It is apparent that an attempt to plot a curve giving times of safety when breathing oxygen at various depths, for even a single diver, is quite impossible owing to his variation of tolerance from day to day. It appears that certain divers show this individual variation to a greater degree than others. As with the variation between individuals, no cause could be found of this varying susceptibility to oxygen at toxic tensions. The divers, in the series described above, were in excellent health throughout. Careful enquiries into their habits, amount of sleep, smoking, ingestion of alcohol, diet, times of meals, etc., elicited no significant factor.

Figure 9 shows a mathematical curve (time/depth) that fits approximately the medium values for each depth. It is a rectangular hyperbole representing the relation:

$$T = \frac{1{,}086}{d - 39.7}$$

where T = time of survival in minutes

d = depth of water in feet

MATHEMATICAL CURVE – APPROXIMATING ROUGHLY TO THE MEDIAN VALUES OF SUBJECTS IN FIGS 4 TO 8

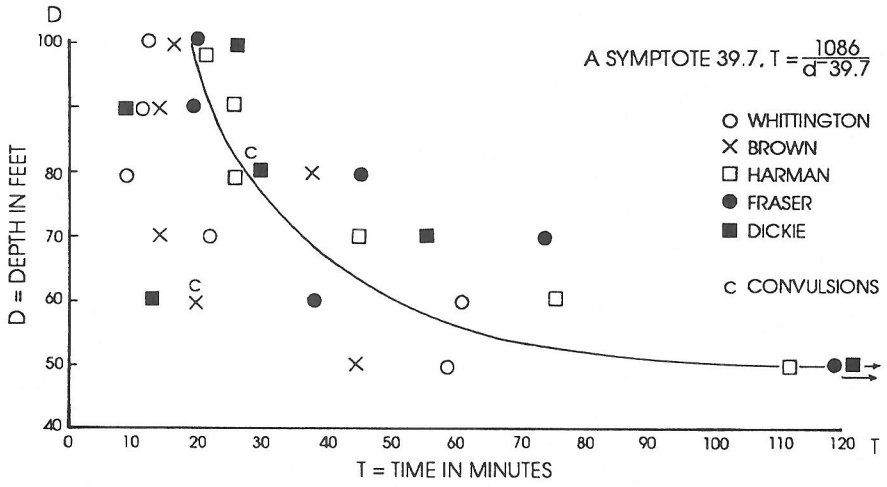


FIG. 9

The Variation of Oxygen Tolerance of the Individual

In view of the findings of the previous section, a series of under water dives were carried out to determine the degree of variation of tolerance of an individual diver breathing oxygen at a constant depth on different occasions.

Method: A diver of apparently good resistance to oxygen poisoning was selected. He dived twice a week, over a period of three months, to a constant depth of 70 ft. in the wet (65°F). On all occasions he wore the same light diving suit and self-contained oxygen breathing apparatus. No exercise was carried out by the diver who stood on bottom in very slight negative buoyancy. All dives were carried out about 11 am. after an early breakfast. His end-points were usually very definite and his health excellent throughout.

Results: These are shown in Table 5 and Figs. 10 and 11. They show that his tolerance over the period varied within a very large range.

TABLE 5

TOLERANCE OF A SINGLE DIVER AT 70 FT. IN THE WET OVER A PERIOD OF 90 DAYS

DAY IN SERIES	TIME (MINS)	SYMPTOMS
1	7	Slight lip twitching, becoming more severe
7	12	Nausea
9	86	Auditory hallucination of loud banging and lip twitching
15	27	Increasingly severe lip twitching
17	23	Slight lip twitching, severe at end
30	28	Severe lip twitching
34	61	Intermittent lip twitching, increasing in severity
37	148	Feeling "crosseyed", lip twitching
42	37	Lip twitching, coughing
44	96	Lip twitching, stertorous breathing
48	31	Severe lip twitching
56	67	Lip twitching

DAY IN SERIES	TIME (MINS)	SYMPTOMS
70	62	Slight lip twitching for 20 minutes. Tinnitus, palatal and pharyngeal spasm, spasmodic respiration, confusion
72	43	Severe lip twitching
76	41	Lip twitching, vertigo, dazzle
78	82	Lip twitching, dazzle, dyspnoea
80	29	Lip twitching, nausea
83	125	Dazzle, amnesia
90	78	Nausea, severe lip twitching

VARIABILITY OF OXYGEN TOLERANCE OF A SINGLE DIVER

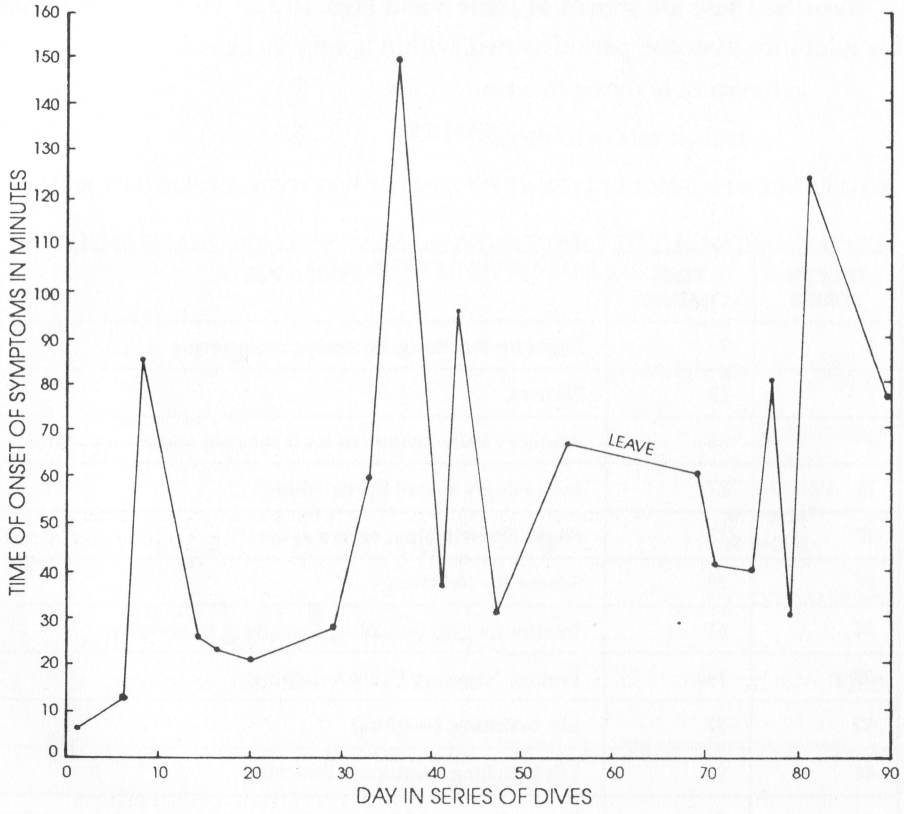


FIG. 10: Time of exposure causing toxic symptoms in the same diver under water at 70 feet of sea water over a period of 90 days. Temperature of water 65°F. No work performed.

VARIATION OF OXYGEN TOLERANCE OF SINGLE DIVER

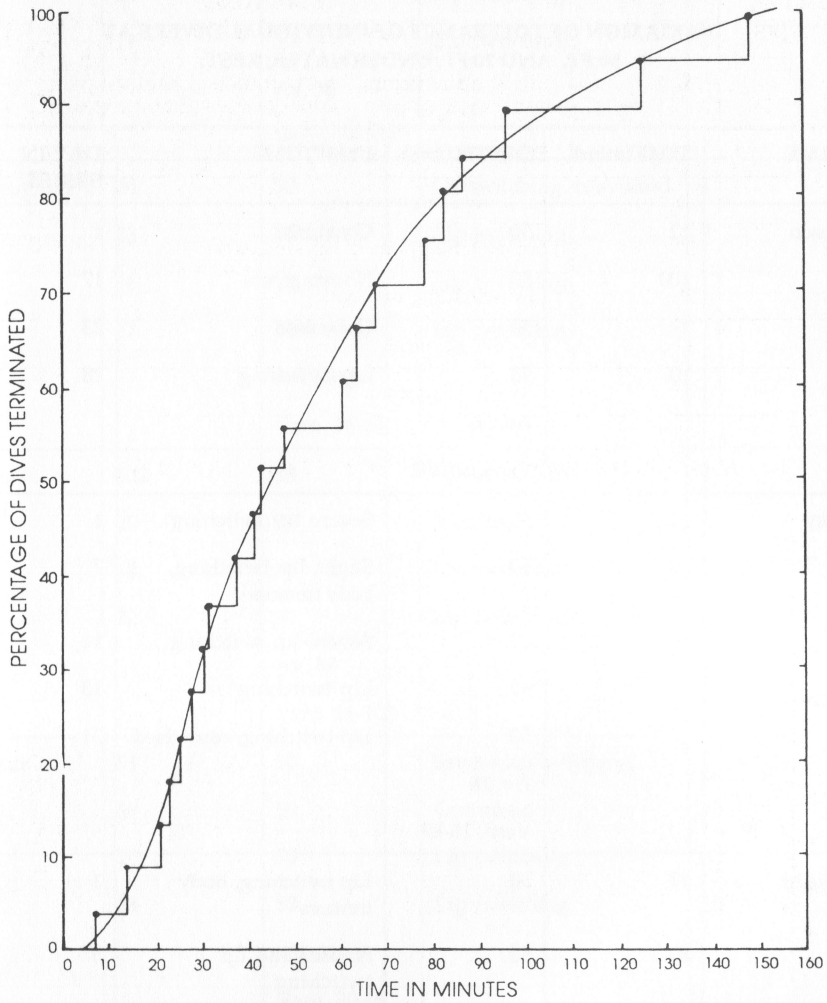


FIG. 11: Percentage of dives terminated owing to toxic symptoms as a function of duration of exposure. Temperature of water 65°F. No work performed. Depth throughout 70 feet of sea water. Dives over a period of 90 days.

Fig. 11 shows his dives plotted in order of performance as if they were carried out by twenty different divers. A curve was obtained very similar to that showing variation in the tolerance of a group of individuals. It appears from statistical analysis, however, that the diver selected for this series showed a greater variation of tolerance than the average.

A further series of repeated dives were carried out to 50 ft. by eight subjects and to 70 ft. by two subjects. Their performances are tabulated below:

TABLE 6

VARIATION OF TOLERANCE OF INDIVIDUAL DIVERS AT 50 FT. AND 70 FT. UNDERWATER, REST.

NAME	TIME (mins)	DEPTH (fsw)	SYMPTOMS	DAY IN SERIES
Gibson	12	50	Convulsed	1
	100	50	No symptoms	17
	23	50	Convulsed	23
	10	50	Lip twitching	28
		Av. 36		
		Varn. 10-100		
Gray	10	50	Severe lip twitching	1
	29	50	Slight lip twitching, body tremors	7
	25	50	Severe lip twitching	14
	21	50	Lip twitching	18
	28	50	Lip twitching, convulsed	21
		Av. 26		
		Varn. 10-29		
Knight	17	50	Lip twitching, body tremors	1
	32	50	Nausea and lip twitching	5
	24	50	Lip twitching	15
	21	50	Nausea, lip twitching	20
	39	50	Severe lip twitching	22
		Av. 27		
		Varn. 17-39		
McInnes	19	50	Lip twitching	1
	100	50	No symptoms	6
	29	50	Lip twitching	7

	20	50	Lip twitching	13
	19	50	Lip twitching	14
		Av. 38		
		Varn. 19-100		
McLaughlin	24	50	Lip twitching, convulsed	1
	53	50	Lip twitching	9
	16	50	Lip twitching	17
	27	50	Lip twitching	21
		Av. 30		
		Varn. 16-53		
Murton	102	50	Severe nausea	1
	20	50	Headache	5
	14	50	Lip twitching	10
	22	50	Lip twitching	12
		Av. 37		
		Varn. 14-102		
Shields	51	50	Severe lip twitching	1
	69	50	Convulsed	3
	20	50	Lip twitching	8
	24	50	Lip twitching	10
		Av. 41		
		Varn. 20-69		
Witham	15	50	Convulsed	1
	26	50	Lip twitching	21
	16	50	Lip twitching	24
	14	50	Lip twitching	29
	23	50	Lip twitching	
		Av. 19		
		Varn. 14-26		
		70		

NAME	TIME (mins)	DEPTH (fsw)	SYMPTOMS	DAY IN SERIES
Miller	36	70	Lip twitching	1
	68	70	Lip twitching	4
	51	70	Lip twitching	7
	44	70	Nausea	13
	43	70	Retrosternal pain and malaise	15
	32	70	Convulsed	28
		Av. 49		
		Varn. 32-68		
Herrett	36	70	Lip twitching	1
	52	70	Lip twitching	6
	26	70	Lip twitching	8
	20	70	Convulsed	12
	18	70	Lip twitching	14
	7	70	Lip twitching	19
	36	70	Nausea	27
	16	70	Paraesthesia	33
		Av. 26		
		Varn. 7-52		

It becomes clear that to judge even a single man's tolerance by one or even several dives is dangerous and unjustifiable. If we examine the performances of the three divers who survived for 100 minutes at 50 ft., we find that the averages of all their other performances at this depth are 22, 19, and 15 minutes respectively. One of the most striking cases is that of Gibson who convulsed after 12 minutes at 50 ft. 16 days later he completed 100 minutes without symptoms. 6 days after this he again convulsed at 50 ft. after 32 minutes. Such findings as this make it clear that to dive on oxygen to any toxic pressure involves a risk that is impossible to assess.

The Oxygen Tolerance of Groups of Men at Various Depths Under Water at Rest

It is clear from the above experiments that it is extremely dangerous to give any fixed times of safety for an oxygen diver at any particular depth. The variation between individuals and the variation of tolerance of each individual, make any generalisation impossible.

In this series of experiments, dives on oxygen were carried out in the wet to a definite end-point, by groups of subjects at: 50, 60, 70, 80, 90 and 100 feet in an attempt to obtain a clearer overall picture. No work or exercise was carried out during these dives.

SURVIVAL OF DIVERS ON PURE OXYGEN AT VARIOUS DEPTHS UNDER WATER

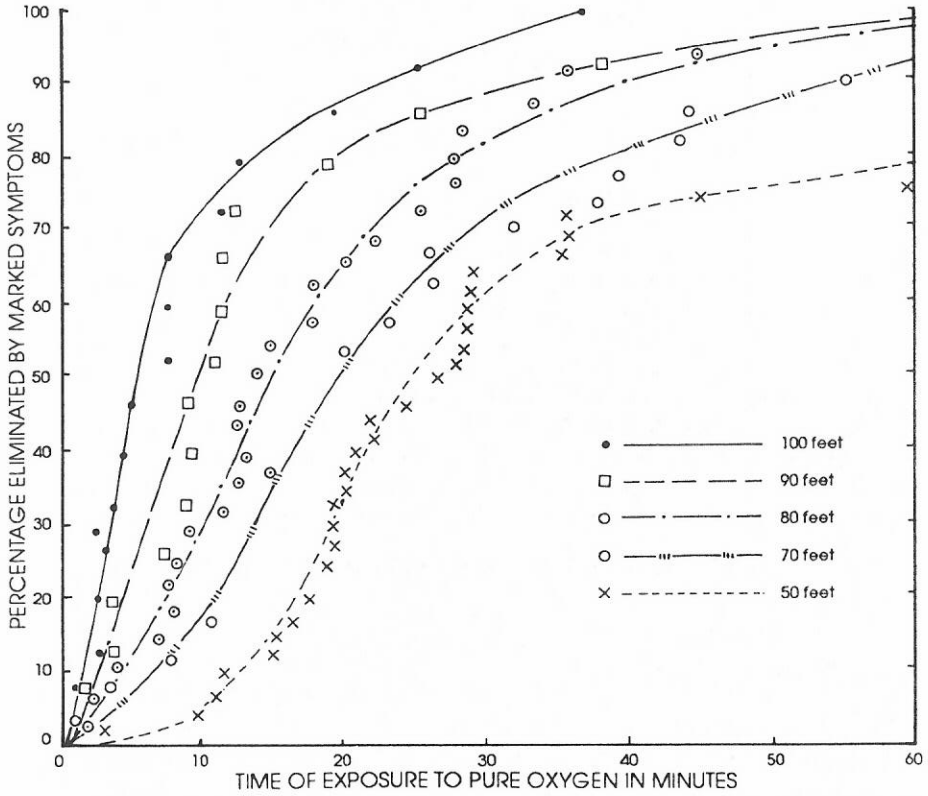


FIG. 12: Showing the percentage of divers on oxygen under water surviving at various times up to 1 hour at 50 feet, 70 feet, 80 feet, 90 feet and 100 feet of sea water. Temperature throughout 65°F. No work performed actual end points plotted.

Results: Results obtained are given in tables 7-12 (Appendix 2). In Fig. 12 the percentage of the group eliminated by severe symptoms, or convulsions, is plotted against the time of exposure at each depth. The increased toxicity of oxygen, as the depth becomes greater, is clearly shown. The highly skew distributions conform satisfactorily to the Galton – Macalister law, and it can be demonstrated that all the curves in Fig. 12 are the same curve except for a change of scale depth. In other words, variability of the group is independent of the depth. The upper parts of the curves are somewhat 'erratic' as they depend upon single performances of one or two highly resistant individuals.

Coefficient of Variation: The following table (13) shows the average and coefficient of variation of the tolerance times, in minutes, at different depths before marked symptoms arose. The series of dives to 90 ft. in the dry are included. The enormous coefficient of variation (75 to 108%) will be noted.

TABLE 13

NUMBER OF SUBJECTS	DEPTH IN FEET	AVERAGE	COEFFICIENT OF VARIATION %
40	50	43.2	104.4
18	60	29.5	81.2
24	70	26.8	75.8
27	80	19.1	80.1
15	90	16.3	108.5
15	100	10.1	95.9
37 dry	90	27.8	75.3

Relation of Tolerance to Pressure: In table 14 the time of exposure in minutes before the end-point of the same 14 subjects is shown from 50 ft. to 100 ft. in the wet. The geometric mean for each depth and its logarithm are given.

TABLE 14

DEPTH IN WATER	50 FEET	60 FEET	70 FEET	80 FEET	90 FEET	100 FEET
DIVER						
Kirk	3	2	1.5	3	2	2.5
Mulberry	11	15	4	4.5	4	3
Wallis	99	24.5	10.5	8.5	4	3
Robertson	35.5	19.5	11	9.5	11.5	4
Ward	35	8	38	13	7.5	3.25
Sims	26.5	13	12	13	9.5	7.5
McAtamney	35.5	16	39	18	9	5
Brown	44.5	19	14	35.5	12	11.5
Rogers	90	37	26	27.5	11.5	7.5
Whittington	59.5	73.5	19.5	8	11	12.25
Dickie	121	12.5	55	28	9.5	24.75
Smith	85	80	43.35	13	71	7.5
Fraser	120	37.5	74	44.5	18.5	19
Derrick	90	40	77.5	20	38	36.5
Geometric Mean	54.00	20.17	19.56	13.72	10.39	7.41
Logarithm of Mean	1.7324	1.3047	1.2913	1.1373	1.0165	0.8698

If these means are plotted against the depth in atmospheres absolute on double logarithmic co-ordinates then a linear relationship is demonstrated which is expressed by the equation (see Fig.13).

$$y = 3.18 \times^{-3.82}$$

where y = time in minutes

x = depth in atmospheres absolute

If the time is expressed in hours the equation is

$$y = 1.4 \times^{-3.82}$$

SHOWING LINEAR RELATIONSHIP BETWEEN LOGARITHM OF CRITICAL TIME OF EXPOSURE AND LOGARITHM OF OXYGEN TENSION

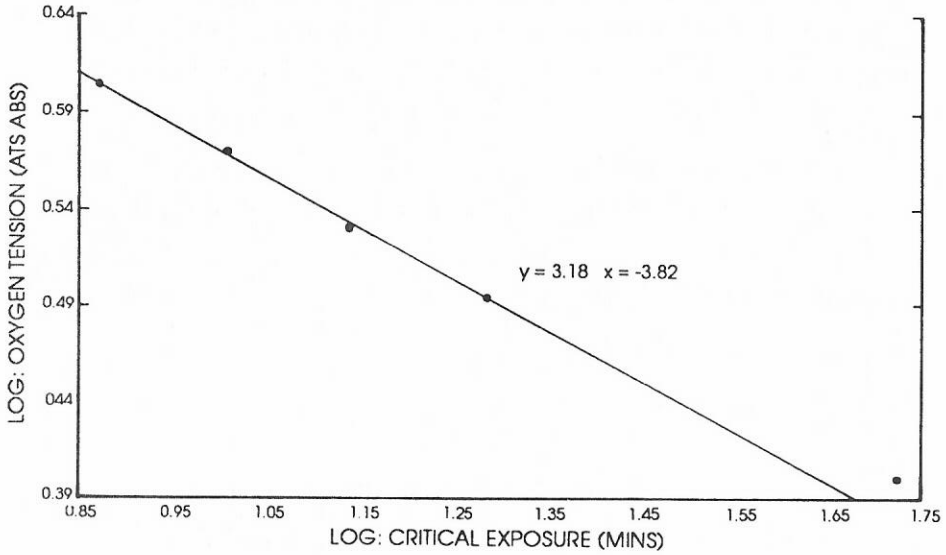


FIG. 13: The times plotted are the logarithms of geometric mean of the performances of the same 14 divers employed at all depths (see fig. 12)

Variability: Table 15 (see Appendix 2) represents an attempt to estimate the degrees of variability of the individual divers. The logarithm of the mean value for each depth is subtracted from the logarithm of the diver's time. A figure is thus obtained showing the diver's inferiority, or superiority, to the average of each depth. The variability of each diver can thus be calculated assuming that his deviation from the mean is independent of the depth. On this assumption only 40% of the total variance of oxygen divers is accounted for by the day to day variation of each individual diver. The other 60% is due to variation between the averages of different divers.

Toxicity of Oxygen in the Wet

A measure employed in the assessment of the toxicity of drugs is the concentration of the drug multiplied by the time of exposure to that concentration. In most cases a constant is subtracted from the dosage to allow for the maximal non-toxic concentration. The maximal non-toxic concentration of oxygen has not yet been determined. Here it has been assumed to be 0.209 of an atmosphere, that is the concentration in which normal physiological existence occurs. If the concentration of oxygen is

expressed as its partial pressure, in atmospheres absolute, and this is multiplied by the time of exposure, measured in hours, then the following dosages in atmosphere-hours are required to eliminate 25%, 50% and 75% at various depths.

TABLE 16

DOSAGES OF OXYGEN IN ATMOSPHERE – HOURS TO ELIMINATE 25%, 50% AND 75%

	50 feet	60 feet	70 feet	80 feet	90 feet	100 feet
25%	0.650	0.587	0.558	0.481	0.435	0.207
50%	0.939	0.870	0.921	0.789	0.588	0.363
75%	1.70	1.43	1.67	1.25	0.88	0.668

This table shows that a far smaller dosage is needed to eliminate, say, 50% at 100 ft. than at 50 ft. These results are plotted in Fig. 14.

DOSAGE OF OXYGEN TO ELIMINATE FIXED PERCENTAGES OF A GROUP

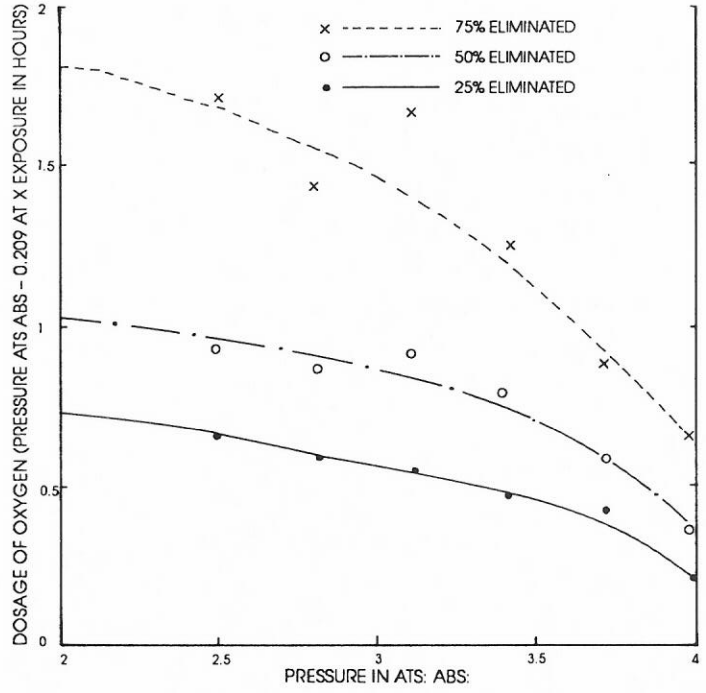


FIG. 14: Showing the decreasing dosage of oxygen (tension x time) necessary to eliminate fixed percentage of a group as depth increases.

There is obviously not only an increase in the partial pressure of oxygen as the depth increases, but a marked enhancement of the toxicity of the gas.

Oxygen Toxicity in the Wet and in the Dry

Finally, we are now able to compare the oxygen tolerance in two randomly selected groups at 3.73 ATA (90 fsw) in the wet (n = 14) and in the dry (n = 36). The greater the tolerance in the dry is clearly demonstrated in Fig. 15. (see also Tables 1 and 11).

SURVIVAL OF GROUPS OF INDIVIDUALS BREATHING OXYGEN AT 90 FEET (3.73 ATS ABS) IN THE DRY AND THE WET.

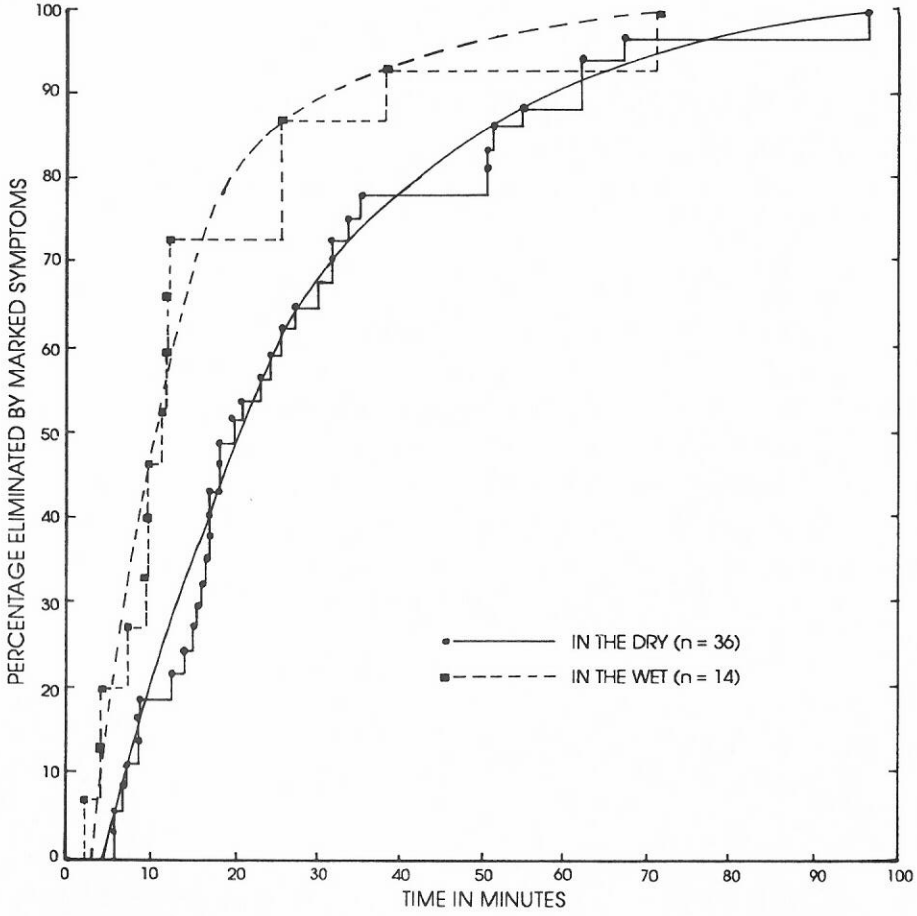


FIG. 15: Percentage of subjects eliminated by toxic symptoms at 90 feet (3.73 ATS: ABS:) breathing oxygen in compressed air and under water (65°F) in diving suit. End points plotted. No work performed during dives. (see tables 1 and 10)

Maximum Non-Toxic Depth when Breathing Oxygen Under Water at Rest

In this series of experiments an attempt was made to assess the safety of men breathing oxygen at more shallow depths and to determine at what pressure oxygen ceases to cause toxic nervous symptoms that would make free diving dangerous. As work is thought to impair oxygen tolerance, a series of dives was first carried out without exercise from 40 to 25 fsw.

Results: The individual results of these dives from 40 to 25 fsw are presented in Tables 17 to 20 in Appendix 1. For the reader's convenience a brief tabular abstract is given in the text (Table 17-20) L.T. = Lip twitching.

TABLE 17-20

Resting Dives on Oxygen to 50, 40, 35, 30 and 25 fsw

DEPTH	TIME LIMIT (mins)	NO. OF DIVERS	NO. OF DIVERS CONVG	TIME OF ONSET OF CONV. (mins)	NO. OF DIVERS WITH L.T.	TIME OF ONSET OF L.T.	NO. AND %WITHOUT SYMPTOMS.
50	120	40	16	12 to 69	21	3 to 112	3 (7%)
40	120	29	4	12 to 28	11	19 to 92	14 (48%)
35	90 (to 180)	21	1	30	5	13 to 32	15 (72%)
30	90 (to 120)	20	2	43 to 48	1	24	17 (85%)
25	120	29	0	0	1 (see text)	44	28 (96%)

It will be seen that convulsions and other toxic symptoms occur at 40, 35 and 30 fsw. 28 out of 29 divers had no symptoms during a 120 minute dive at 25 fsw. The exception was a diver who suffered nausea and vomiting after 44 minutes. This subject had similar symptoms although not so severely after approximately the same time when breathing oxygen at atmospheric pressure. Nevertheless it is possible that this diver had oxygen poisoning at 25 fsw. More prolonged exposures might have caused symptoms or even convulsions at this depth but this period of time (120 minutes) is longer

than any practical dive on oxygen to this depth. There is no statistical analysis or plotting of these results as a number of these divers were specially selected for this series because it was known that their average oxygen tolerance was poor.

It is a most surprising finding to obtain oxygen convulsions at as low a pressure as two atmospheres absolute (1.9 to 2.1 ATA). At such a tension the oxygen dissolved in the blood plasma is inadequate for even basal metabolic requirements and haemoglobin is still being actively employed for oxygen transport. Thus it appears that acute oxygen poisoning can occur before the haemoglobin oxygen cycle is de-activated and a further critical rise of brain tissue oxygen tension takes place.

The Effect of Work on Oxygen Tolerance Under Water

It has generally been considered that exercise diminishes human tolerance to hyperbaric oxygen (1943). Reference is often made to Bornstein's experiment in 1912 when he suffered clonic spasms of the arms and legs after 51 minutes exercise on a bicycle ergometer while breathing oxygen at 3 ATA in the Elbe tunnel. He had previously breathed oxygen while resting at 3 ATA for 48 minutes without ill effect. It is possible that his symptoms after exercise were due to carbon dioxide accumulation in his respiratory circuit.

Recently Behnke (1942) described how subjects breathing oxygen at 3 ATA in the dry and exercising on a bicycle ergometer suffered extreme fatigue, numbness of the lower extremities and 'abortive' convulsive seizure after 15 to 20 minutes. Usually 3 or more hours of oxygen breathing can be tolerated at this pressure.

However there are no controlled studies of the effect of work on oxygen tolerance. A large series of dives were therefore carried out in the wet with hard arm work. Control exposures with the same diver resting were also done. The subjects worked vigorously by lifting a large bag of weights by pulley without mechanical advantage. The number of lifts was measured and the height of lift controlled. Correction was made for water displacement by the weight. Dives were carried out to 50 fsw (n = 65), 40 fsw (n = 46), 30 fsw (n = 14) and 25 fsw (n = 18).

Results: These experiments show conclusively that oxygen tolerance is markedly decreased by hard work. Further, symptoms of oxygen toxicity

now definitely occured at 25 fsw. Detailed results are given in Tables 21 to 24 in Appendix 2. The amount of work performed and details of the control resting dives are also given. The impairment of oxygen tolerance by exercise can be clearly seen in figures 16 and 17 where the percentage of each group eliminated by toxic symptoms at 50 and 40 fsw, with and without work, is plotted against time in minutes to end-point.

EFFECT OF WORK ON OXYGEN POISONING IN THE WET AT 50 FEET OF SEA WATER (2.52 ATS: ABS:)

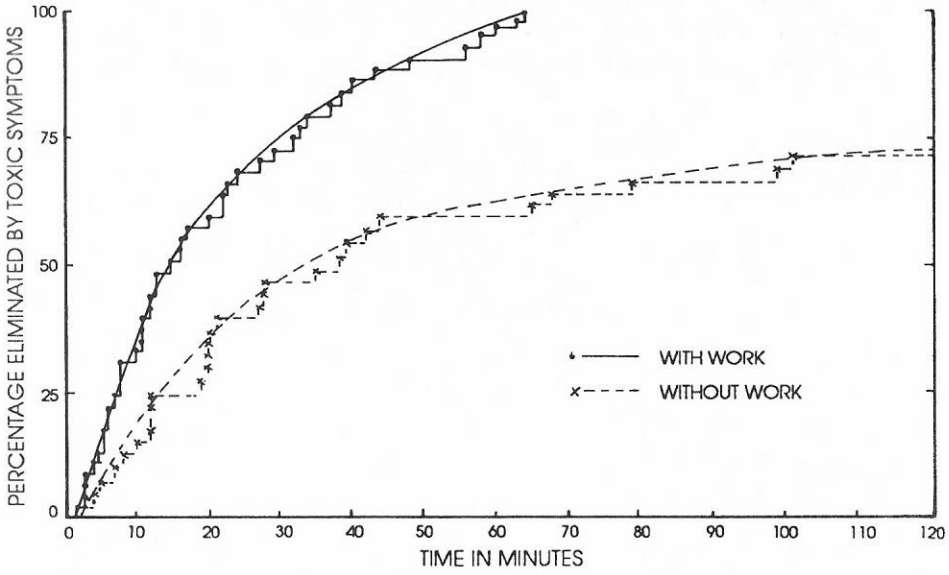


FIG. 16: Showing percentage eliminated by toxic symptoms at 50 feet in the wet (2.52 ATA) during a period of 2 hours, with and without work. Individual end points plotted. Group of 46 divers working and 41 not working. Temperature throughout 65°F.

It will also be noted in Table 24 that toxic symptoms necessitated cessation of the exposure in 5 out of 18 dives to 25 fsw in marked contrast to the resting control studies at this depth. There were no convulsions.

The physiological reasons why work reduces oxygen tolerance are not known at present. A rise of alveolar carbon dioxide, which is probably considerable when exercising on oxygen, would certainly cause cerebral vasodilatation, an increase of cerebral blood flow and of brain tissue oxygen tension, particularly as the oxygen consumption of the brain is unaltered during physical exertion.

EFFECT OF WORK ON OXYGEN POISONING IN THE WET AT 40 FEET SEA WATER (2.21 ATA)

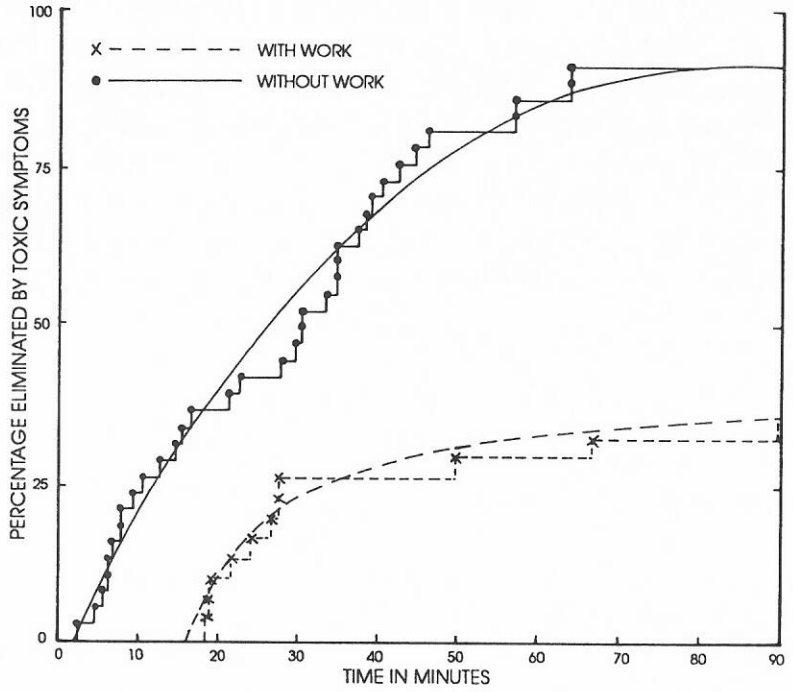


FIG. 17: Showing percantage eliminated by toxic symptoms at 40 feet in the wet (2.21 ATA) during a period of 90 minutes with and without work. Individual end points plotted. Group of 39 divers working and 31 not, working temperature throughout 65°F.

The Effect of Water Temperature on Oxygen Poisoning

Previous work has indicated that lowering of the environmental temperature increases the oxygen tolerance of small experimental animals (de Almeida, 1934 and A. Campbell, 1937).

A series of dives were carried out, in the wet, wearing the suit and apparatus used in previous experiments, to determine whether oxygen tolerance was affected by the temperature of the water in which the diver was submerged. Dives were carried out by the same group of subjects at 87.5°F (steam heated) and at 45° (ice cooled). Control dives were also performed at 65°F, the standard temperature employed in experimental oxygen dives. The group of subjects employed were on the whole of poor average oxygen tolerance. All dives were carried out at 50 ft. (2.5 ATA), this moderately shallow depth being the best at which the effect of

various factors can be assessed. Divers were allowed to vary their underwear with the temperatures, wearing light overalls in the hot series, and woollens in the cold series. It was realised that this would assist the diver in maintaining normal body temperatures but the application of this data to practical diving was the first consideration. In any case, it is very much doubted whether these experiments could have been tolerated without this variation of clothing. The gas cylinder was carried by the diver and therefore the oxygen supplied was at the temperature of the water. No exercise was carried out as this factor is known to impair oxygen tolerance. This was advantageous at the higher temperature, but disadvantageous to the diver in cold water. The majority of divers complained of the cold bitterly and found the heated dive very uncomfortable. Although body temperatures were not obtained, symptoms reported would suggest that these were affected to a certain degree towards the end of the dive.

Results: These are shown in the following table (25) and Fig. 18.

THE EFFECT OF TEMPERATURE OF WATER ON OXYGEN TOLERANCE IN MAN

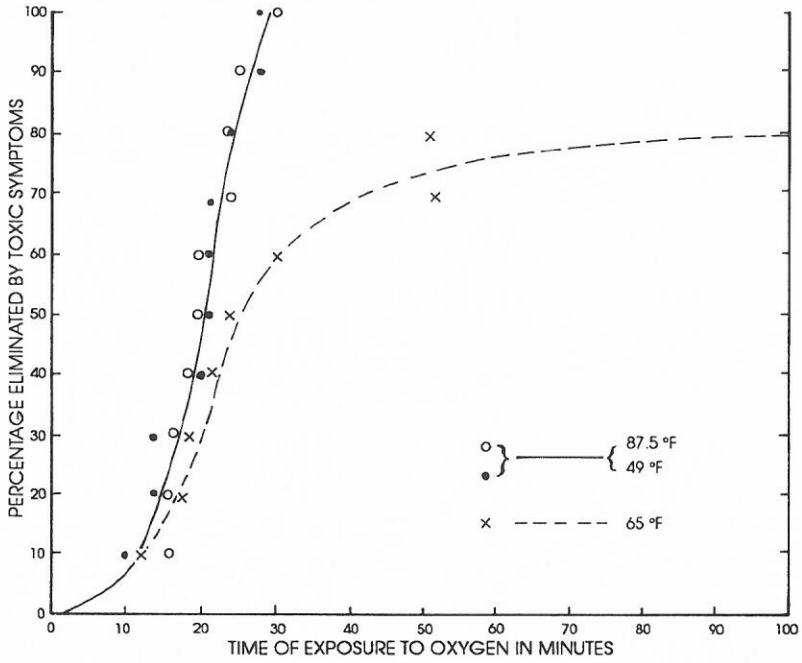


FIG. 18: Showing percentage eliminated by toxic symptoms at a pressure of 50 feet of sea water (2.51 ATA) in the wet at 65°F, 87.5°F and 49°F, plotted against time of exposure. Subjects resting.

TABLE 25

VARIATION OF TEMPERATURE. ALL DIVES AT 50 FT. TIME IN MINS.

Temperature	65° F		87.5° F		49° F	
Name	Time	Symptoms	Time	Symptoms	Time	Symptoms
Knight	17	Severe lip twitching	24	Lip twitching	21	Severe lip twitching
Witham	22	Severe lip twitching	16	Lip twitching	14	Lip twitching
McInnes	100	None	29	Lip twitching	20	Lip twitching
McCann	30	None	17	Lip twitching	20	Lip twitching
Gibson	12	Convulsed	23	Convulsed	10	Lip twitching
Gray	51	Lip twitching	25	Lip twitching	21	Lip twitching
McLaughland	24	Convulsed	16	Severe lip twitching	27	Lip twitching
Green	18	Lip twitching	20	Lip twitching	27	Lip twitching
Murton	102	Nausea	20	Headache	14	Lip twitching
Shields	51	Lip twitching	20	Lip twitching	24	Lip twitching

It is apparent from these results that the oxygen tolerance is somewhat impaired by both cold and heat.

It will be noted that, although the averages of performance in the hot and in the cold, are about half of that at 65°, the medians of time of tolerance are approximately similar at all temperatures. A possible explanation of this is that body temperatures were not greatly disturbed until after submersion of about 20 minutes duration.

Signs and Symptoms of Oxygen Poisoning

Convulsive Attacks: These convulsive attacks were, on average, of two minutes duration, the diver being unconscious. Incontinence occurred in only 5% of cases. If the subject was turned on to air immediately convulsive symptoms commenced, only one attack resulted. The subject remained

unconscious and flaccid for five to ten minutes after the convulsion. Breathing was stertorous and the cough reflex absent. The pulse was accelerated and bounding. The corneal reflex usually returned within about three to four minutes. The eyes which were averted, then returned to the central position when a rapid horizontal nystagmoid movement was usually to be seen. The pupils were dilated and insensitive to light but, shortly before consciousness was regained, they assumed their normal size and reacted to light. About this time the cough reflex returned. Subjects, on regaining consciousness, were markedly confused and dissociated and in some instances, extreme emotional instability was exhibited. Laughter, tears, singing and extreme violence were all encountered. The majority were subdued, dissociated, and ataxic for about 15 minutes afterwards. The degree of ataxy varied. In a marked case the stance was wide and the stepping act faulty, the foot either being lifted excessively or hardly at all. Gersh, (1944) in work carried out since these experiments, describes an obviously associated phenomenon in cats which lost their stepping and hopping reflexes after a number of oxygen exposures to convulsion. These animals recovered after several weeks. It would appear that the same nerve cells are affected, even after one convulsion, in man although recovery is very rapid.

Most subjects complained of headache and some had nausea and vomiting with associated anorexia. Photophobia was reported by some of the subjects. Fatigue was usually marked and the natural tendency was to "sleep it off" for about half an hour. In a few cases there was post-convulsive automatism, the subject being quite rational in conversation and behaviour, but waking up the next morning with complete amnesia of the period since the convulsion. For this reason subjects were not allowed to be alone after a convulsion for a period of twenty-four hours when normality was always regained.

These convulsive attacks, in fact, were clinically indistinguishable from an idiopathic epileptic convulsion; the tonic phase, however, did not last for more than one or two seconds. No permanent residue of any description have been found in this series which have lasted over a period of three years. There were some stiff backs and subcutaneous extravasation due to muscular violence. One subject, who had convulsed twice, developed petit-mal about six months later. A strong family history, which had been previously concealed, was elicited.

Warning Signs and Symptoms: Practically every symptom described in the aura of idiopathic epilepsy has been encountered during the period before the onset of the convulsion. Auditory hallucinations such as music, bell ringing and knocking, flashes in front of the eyes, impaired vision, unpleasant tastes and odours and paraesthesia have all been reported. Muscular twitching, sweating, vertigo, nausea, apprehension, euphoria and dreamy states have all occurred. These warning symptoms are of great importance as an accurate knowledge of such symptoms may enable persons who are exposed to dangerous tensions of oxygen to discontinue before convulsions occur. Over two thousand dives have been carried out breathing toxic tensions of oxygen, about 400 of these have been in the dry and the rest in diving suits under water. Consequently a much larger and complete picture of the signs and symptoms of oxygen poisoning in the human subject has been obtained.

First let us consider the symptom of oxygen poisoning when breathing oxygen in a dry pressure chamber. Such experiments allow the diver and observer more opportunity for introspection and observation, respectively. It is not easy to give a clear and concise description of human symptoms under toxic tensions of oxygen. There is enormous variation of the syndrome in different subjects. First, three specific cases are described to give some idea of the different events encountered.

SUBJECT A: 101 minutes of oxygen at 60 fsw (2.8 ATA). Facial pallor, almost at once, which continued throughout the dive. Fine fibrillary tremors of lips noted after a few minutes. These came and went throughout the dive and were occasionally seen in the upper face. Subject complained of drowsiness during the last twenty minutes. A few seconds before the end he had severe twitching of the lips; the nose was also involved. Severe diaphragmatic spasm just before coming on to air.

SUBJECT B: 25 minutes at 90 fsw (3.7 ATA). Facial pallor marked during whole exposure. Passed into tonic phase of convulsions without any warning signs or symptoms.

SUBJECT C: 54 minutes at 90 fsw (3.7 ATA). Facial pallor not marked till after about twenty minutes. Choking sensation after thirty

minutes, which passed off. Slight but definite fibrillation of upper lip after eighteen minutes which continued for the next twenty-five minutes. Some definite and sustained lip twitching four minutes from the end and severe generalised lip twitching at the end.

These are only three random examples of a very varied picture. An attempt will be made to survey the general findings.

Facial pallor usually occurs a few minutes after the commencement of the exposure. It varies from person to person in degree and time of onset and may be generalised or circumoral. The general appearance of the face after this presumable skin vaso-constriction naturally varies. A number of subjects appeared like patients with mitral stenosis. One subject had a large recently vascularised scar on the face. The whole of his face appeared dead white, apart from the scar, which stood out a most conspicuous red, presumably because the newly vascularised tissue had not the same degree of vasomotor control. The degree of facial pallor is no indication of the subjects sensitivity nor of an impending end-point. In a large number of cases very fine fibrillations of the lips or face may be seen early in the experiments and intermittently throughout the exposure. These were attributed to two factors, the fatigue of the lips holding the mouthpiece and a very natural nervous tension. Some subjects showed such fibrillations when wearing a mouthpiece at atmospheric pressure but they are undoubted increased by breathing oxygen at increased tensions. Fibrillation frequently appears in muscles which later show severe and sustained twitches. A number of subjects showed facial perspiration varying in degree from fine beads on the upper lip and forehead to literal pouring. Generalised perspiration is not usual but is occasionally seen. Slight nausea and vertigo and choking sensations that wax and wane may be encountered some time before the end-point. The course of these minor crises is absolutely unpredictable and the observer has to be constantly on the alert for a sudden exacerbation of symptoms with the danger of convulsing.

The next group of symptoms to be discussed may be called warning symptoms which, although not demanding immediate cessation of the exposure, signify that intoxication is becoming more intense and that the end-point will not be greatly delayed. Sensations of sleepiness, depression

or euphoria are encountered in a number of cases about 10 minutes (at 3.7 ATA) before the end-point. Apprehension may be marked and increase as the end-point approaches. Changes in behaviour may be noted by the observer during this period; the subject showing clumsiness with his apparatus, loss of balanced judgement, fidgeting or an unnatural disinterest in the experiment. Sensations of oppression in the praecordium are described during this period. Palpitations, which may involve not only an awareness of the heart's action but of the arterial pulsation throughout the body, are occasionally reported. Visual symptoms include loss of visual acuity, dazzle in the visual field, lateral movement of visual images and apparent changes in the intensity of illumination. Subjects have described the constriction of the peripheral visual field without knowledge of this phenomenon. This is encountered more frequently after prolonged exposures at toxic pressures and it is therefore only experienced by the more resistant subjects. Acoustic hallucinations are not common. Music, bell ringing and knocking have all been reported. No voices have been heard. On other occasions hearing may become impaired. Nausea and vertigo, together or separately, may become so severe that the subject will revert to air breathing before convulsive symptoms occur.

Definite twitching movements of the lips usually mean that the end-point is not far off. This is the most common end-point. The twitches are powerful and sustained. They are usually seen one side of the upper lip but if the exposure continues they increase in power and frequency and spread to the whole mouth and face. On occasions a marked twitch may be followed by a long period of quiescence before recurrence. This is exceptional and in most cases, if the exposure is continued, convulsive movements of the lips pass into generalised jactitations or far more commonly, convulsions. Twitching of the cheek and nose are often seen with or without lip twitching. Occasionally isolated twitching of the arm or leg will occur.

In a few minutes or seconds before the end-point, respiration, which in most cases has been normal and serene throughout, shows a number of abnormalities. The commonest occurrence is rapid panting. In other cases there appears to be a marked inspiratory predominance probably associated with tonic contraction of the diaphragm. This may give rise to a grunting respiration, to a sensation of abnormality in the epigastrium or, in the more severe case, to an acute state of apnoea in the inspiratory

position. Hiccough is another symptom of diaphragmatic disturbance. On being turned onto air many subjects recover but, with less fortunate subjects, it may be too late and they pass into convulsions.

Three unusual end-points can be mentioned. In one case, after about ten minutes of vertigo and dazzle, the subject commenced agonising, uncontrollable, spasmodic vomiting which continued for several minutes. In another case the subject passed into a heavy, stuporous sleep from which he was roused with difficulty. In the third case acute syncope occurred with pallor, cold sweat and thready pulse. The clinical picture was indistinguishable from that of acute traumatic shock.

As can be seen from the above, an acute description of such a varying picture is not easy. The impression gained is of two distinct processes occurring in may different patterns. One is an insidious intoxication which may affect the function of practically any part of the central nervous system and, added to this, is an increasing convulsant tendency which is usually, but not always, first manifested in the facial muscles and finally becomes generalised. There are great variations in the resistance of the individual to the general background of intoxication and in the resistance of the individual to the convulsant factor. Again, certain individuals may show powerful convulsive movements, either localised or generalised, but retain consciousness. Others pass into what is indistinguishable from an epileptic fit immediately after such convulsive movements and, occasionally, in their complete absence.

Off Effect: The "off effect" on returning to air breathing after exposure to toxic tensions of carbon dioxide is well known. There is a sudden exacerbation of symptoms often associated with headache, nausea and vomiting. An "off effect" is sometimes encountered after the cessation of breathing oxygen at toxic tensions. It does not occur so frequently as that after breathing carbon dioxide. Severe nausea, increased pallor, sweating and vertigo may all occur in a subject who was previously symptomless. Other subjects show a sudden marked dissociation and panting. In one or two cases it appeared that convulsions were precipitated by reverting to air breathing. This may be due to the fact that such a degree of toxaemia had been reached that convulsions were inevitable, although reversion to air breathing had taken place. A possible explanation of the oxygen "off effect" may be as follows. It is known that the respiration of the brain tissue is impaired by high tensions of oxygen. As a result of Dicken's work,

it appears not unlikely that the nerve cells are "eliminated" individually and show a distribution of tolerance very similar to that demonstrated in a group of men. It is possible that certain cells, whose elimination will cause symptoms or convulsions, are on the brink of this event. The sudden reduction of oxygen tension to a far lower non-toxic level may, by the law of mass action, further reduce metabolism in these damaged cells and the resultant cessation of function cause symptoms or even convulsions. This theory is favoured by the fact that a number of subjects with a severe end-point have convulsed during decompression in air, when the oxygen tension is lowered even further. It has therefore become a rule in this work that, if a subject has severe symptoms and has reverted to air breathing, he is not decompressed until his symptoms have remitted and relative normality has been attained. In experimental work with animals in high tensions of oxygen a number of observers have noted that several animals, which were previously symptomless, began to convulse during decompression. If the pressure is very great and the decompression very rapid this may be due to bubble formation but these convulsions usually occur long before sufficient fall of pressure has taken place for such an explanation to be valid.

After Effects with Non-Convulsant End-Point

The recovery from a non-convulsant end-point is remarkably rapid and comparative normality is attained in five, or less, minutes. Twitching usually ceases in about a minute or less. The subject often appears dazed for a few minutes longer and his respiration are irregular with intermittent deep excursions. Euphoria is frequent but this may well be due to a natural relief at having survived a toxic exposure without convulsing. Pallor persists in some cases for as long as an hour and in a few cases, the subject behaves as if he is slightly intoxicated for the same period. This latter syndrome is known in experimental diving circles as "oxygen jag".

> *The most important finding in this large series of exposures was that the symptoms of oxygen poisoning vary enormously in different people and in the same person during different exposures. No list of warning signs or symptoms can be given that would ensure a safe and timely cessation of the exposure.*

The traditional symptom of paraesthesie of the extremities is very rare there being only one case in five hundred toxic end-point exposures.

Oxygen Poisoning Under Water

In a series of 388 non-working dives to end-point, under-water symptoms were recorded and classified. Results were as follows:

TABLE 26

Symptoms	Number of Cases	Percentage
Convulsions	46	9.2
Twitching of lips	303	60.6
Vertigo	44	8.8
Nausea	43	8.3
Respiratory Disturbances	19	
Dyspnoea	8	
Coughing	6	
Spasmodic respiration	2	
Diaphragmatic spasm	2	
Choking sensation	1	
Twitching of parts other than lips	16	3.8
Generalised jactitations	7	
Upper face alone	2	
Arms	2	
Legs	2	
Hands	1	
Palate and fauces	1	
Trunk muscles (erector spinae)	1	

Symptoms	Number of Cases	Percentage
Sensations of Abnormality	16	3.2
Drowsiness	7	
Numbness	3	
Exhaustion	3	
Malaise	2	
Confusion	1	
Visual Disturbances	5	1
Dazzle	3	
Loss of vision	2	
Acoustic Hallucinations	3	0.6
Paraesthesiae	2	0.4
Generalised	1	
Facial	1	

The most striking observation was the remarkable predominance of lip twitching as the only symptom. It is probable that many of the other more subtle symptoms occur, but that they are difficult to appreciate in a diving suit under water.

Symptoms in the Wet with Work

It must be emphasised that throughout the series in which symptoms have been described the subjects were not carrying out exercise. Since Bornstein's single experiment in the dry on an ergometer (1912), it has been stated in the literature that exercise at toxic depths causes twitching of the muscles being employed.

During the series at toxic depths with hard arm work, analysis of symptoms in 120 end-points gave the following figures:

TABLE 27

Symptoms	Number of Cases	Percentage
Convulsions	7	6.8
Lip Twitching	60	50
Vertigo	25	20.8
Nausea (vomiting in two cases	21	17.5
Choking sensation (pharyngeal spasm)	3	2.5
Dyspnoea	3	2.5
Body tremors	2	1.7

It appears that nausea and vertigo increase in frequency, if the subject is exercising. The most interesting finding, however, was that twitching of the muscles being exercised was not encountered in the whole series. These divers were carrying a very large and efficient absorbent canister and as already suggested, the symptoms described by Bornstein may have been due to added carbon dioxide poisoning. A series of experiments carried out to investigate the effect of work on oxygen tolerance in the dry were marred by inadequate carbon dioxide absorption and are not reported here.

Behaviour of Subject Before Toxic Symptoms Appear

Divers breathing oxygen at increased tensions, before signs or symptoms of toxaemia occur, feel remarkably normal. The mental torpidity, described by some observers, has not been noted even at considerable depths except after long exposures in the dry. Men have been able to carry out complicated tasks necessitating high skill and judgement while breathing oxygen under water at markedly toxic pressures. The capacity for hard physical work appears to be in no way impaired. Underwater divers are more free of symptoms than those in the dry, right up to the moment of lip twitching or convulsing. No doubt the abnormal environment and accoutrement obscure minor premonitory symptoms.

Divers who have gone on to oxygen at such depths as 100 ft., have

volunteered the information that they felt an immediate clarification of thought. This is due to the sudden cessation of exposure to increased tensions of nitrogen. The normality of the subject breathing oxygen at these tensions and the frequent suddenness of convulsive symptoms makes oxygen breathing at toxic depths highly dangerous, particularly as the subject often gains a very false sense of security.

The "Lorrain Smith" Effect in Divers

Information on this subject is very scanty. In the experiments described by Behnke, Johnson, Poppen and Motley (1934/35) four subjects breathing oxygen in the dry at three atmospheres absolute for three hours, four subjects breathing oxygen in the dry at three atmospheres absolute for three hours, and two subjects breathing oxygen at four atmospheres for 40 minutes, showed no signs or symptoms of pulmonary damage.

In view of the fact that oxygen appears more toxic when breathed under water, as judged by the onset of nervous signs and symptoms, it was considered possible that the pulmonary effects might also be accelerated. No data is available concerning lung damage in divers breathing raised tensions of oxygen under water. The series in the dry, mentioned above, is far too small for general conclusions to be made.

In well over a thousand experiments, where subjects were breathing oxygen at toxic pressures (4.68 to 1.91 atmospheres absolute) the exposure was terminated owing to signs or symptoms involving the central nervous system. No signs or symptoms of pulmonary irritation or damage were encountered during the whole series. Frequent chest examinations were completely negative. A few examples of long dives breathing oxygen, in the wet and dry, are here given:

IN THE DRY (Time mins/Press. ATA)		IN THE WET (Time mins/Depth fsw)	
Whittington,	159/2.8	Warren, Dickie, Fraser	120/50 (2.5 ATA)
Harman,	180/2.8	Fraser,	45/79 (3.4 ATA)
Whittington,	55/3.7	Miller,	75/79 (3.4 ATA)
Harman,	62/3.7	Derrick,	37/99 (4 ATA)
Derrick,	96/3.7		
Smith,	61/4.7		

It was concluded from this very large study of oxygen dives, that at toxic tensions, nervous symptoms or convulsions will terminate the exposure before any demonstrable harm is suffered by the pulmonary epithelium. At more shallow depths, however, nervous symptoms are only encountered after very long exposures or not at all. It was thought possible that there may be a greater risk of lung damage at such depths. Dives for three hours at 2.1 atmospheres absolute (36 fsw) in the wet caused no pulmonary irritation. A series of prolonged dives to 12 ft. (1.36 atmospheres absolute), with periods at 50 ft. (2.5 atmospheres absolute), gave equally negative results. Incidentally none of these divers had any nervous symptoms.

Prolonged Dives: These divers cruised or exercised in a leisurely fashion at 12 feet. There was no significant exercise in the deeper excursions. (Time in mins./Depth fsw).

Derrick (i)	–	180/12, 30/50, 90/12 5 hours continuously on oxygen at 12 and 50 fsw.
Derrick (ii)	–	120/12, 30/50, 120,12, 30/50 5 hours continuously on oxygen at 12 and 50 fsw.
Rickwood	–	240/12, 30/12 5 hours continuously on oxygen at 12 and 50 fsw
Goss	–	249/12, 30/50, 90/12 6 hours 9 minutes on oxygen at 12 and 50 fsw

It can be stated, with reasonable certainty, that no real underwater dive will ever be made where lung damage will result from high tensions of oxygen.

With regard to comparison with animals, L. Smith (1899) reported rats dying of pulmonary damage as early as 20 minutes on oxygen at 4.5 ATA. Yet the subject Smith completed 61 minutes at 4.7 ATA in the dry with no symptoms or demonstrable pulmonary damage. Total evidence available at present suggests that man has more resistance than small experimental animals to lung damage by high tensions of oxygen.

Cumulative Effects

A number of these subjects have breathed oxygen at increased tensions several times a week for two years. It was considered possible that, although the pulmonary damage suffered in a single exposure was inappreciable, there may be a cumulative effect. Frequent routine examinations of the subjects' chests were therefore carried out, x-rays were taken regularly and the vital capacity noted. In not a single case has there been any positive finding. Their general health and considerable athletic activities have also been carefully watched and again, with negative results. One subject who dived to toxic depths to end point two or three times a week for three months won the Portsmouth Middle Weight Boxing Championship during this period. The weight records of all subjects have been satisfactory. It would appear that there is no cumulative effect on the lungs in oxygen diving.

Cardiovascular Findings in Oxygen Poisoning

It was amply confirmed that breathing oxygen at increased tensions (2 to 4 ATA) caused bradycardia in the majority of cases.

The degree of this occurrence varies enormously. Subjects were resting for 15 minutes before the exposure and the prolonged rest and quiet environment may have caused further slowing. The initial pulse rate may also have been raised owing to "keying up" before the exposure. A number of subjects had symptoms which could well have caused increase of the pulse rate, as a result of apprehension, but the slowing of the pulse continued. The degree of bradycardia had no fixed relation to tolerance nor did the pulse changes give any warning of acute symptoms. Summarising, it can be stated, although the pulse changes in a number of cases were little more than can be accounted for by prolonged basal conditions, in other cases a marked and definite bradycardia was encountered.

Only a limited number of blood pressure recordings were made at 90 ft. There was a gradual slight rise of systolic and diastolic pressure for 20 to 25 minutes. Diastolic pressures then remained steady at 10 to 15 mm. higher than normal, except for a few minutes before the end-point when a further brisk rise occurred. These findings are similar to those of Behnke, Forbes and Motley (1935/36). In the shorter exposures the 'terminal' rise was obtained before the blood pressure had stabilised at its new level.

A number of subjects' nail bed capillaries were observed microscopically while they were breathing toxic tensions of oxygen. Controls were carried out breathing air at atmospheric and increased pressures and oxygen at atmospheric pressure. No significant changes were found. One subject's capillaries were under observation while suffering from lip twitching and no changes were seen.

Facial pallor has already been described in the section on symptoms.

X-ray and clinical examination have shown no enlargement of the heart in subjects who have been frequently exposed to high tensions of oxygen over a long period. It is a common belief among divers (1942), particularly in the Italian Navy, that oxygen breathing causes increase in the size of the heart. This has not been confirmed.

Neurological Findings in Increased Tensions of Oxygen

Routine neurological examination of subjects breathing oxygen at 90 and 60 ft. (3.73 and 2.74 atmospheres absolute) showed no significant change in reflex activity. Restriction of the peripheral visual field was described by a number of subjects but specific tests were not carried out. The only other finding was the development of a positive Chvostek sign (twitching of face on tapping the facial nerve in front of the external auditory meatus) in a number of subjects during exposures to hyperbaric oxygen in the dry. This sign usually developed in the latter half of the exposure; it was not a reliable sign of the approach of acute symptoms although it became more marked as the exposure proceeded. Some subjects had an acute end-point without the occurrence of a positive Chvostek sign at any time. Controls carried out in air at atmospheric pressure, revealed that a number of otherwise normal subjects have a positive Chvostek sign which may be present one day and absent on another. In one experiment a subject developed a unilateral positive Chvostek sign while breathing oxygen at atmospheric pressure. It disappeared a few minutes after the cessation of the exposure. A positive Chvostek sign in air, or developing during the exposure, did not necessarily signify poor oxygen tolerance.

Jacksonian Attack: One very interesting subject can be mentioned here. This man had a number of severe end-points including two convulsions. Acute toxic nervous symptoms always commenced with twitching of the muscles of the left hand which then spread to the arm. Lip twitching was

usually present at this stage. The subject then convulsed or recovered on being turned on to air. The series of events, in fact, were similar to those in a Jacksonian epileptic attack and would suggest that this subject had a slightly lower threshold in one small cortical or sub-cortical area that precipitated the convulsive process. There was no known history of head injury or relevant disease.

Neurological Residua of Oxygen Poisoning and Convulsions

This question is of great importance in human physiology. The convulsant action of oxygen has been suggested by several authorities for the therapeutic treatment of psychoses (1945). In this series of experiments every attempt was made to avoid convulsions. It can be stated that in three years of continued experiments, no evidence of any kind has been obtained to show that acute oxygen poisoning, or even several convulsions, has any adverse after effect on the person's neurological integrity, intellectual ability or personality. Such a finding is in accord with those in animal experiments. Finley could find no histological abnormality in the brains of rats convulsed till death. Gersh (1944) could demonstrate no functional or histological abnormality in cats after a single convulsion and found that many successive exposures to the point of convulsion gave such a slight histological findings that are artefact could not be excluded. The neurological findings in animals with maximal damage cleared up in a few weeks.

Electroencephalographic Findings: Note: These investigations were carried out at the National Institute for Medical Research by Brown, Downman and MacIntosh. Expert opinion on the recordings was given by Wing Commander D. Williams. Only those experiments which were carried out on the subjects in the unit are briefly described here. They are more fully reported in R.N.P.R.C. 94/1944.

Exposure to oxygen at 120 ft. had no immediate effect on the E.E.G. recording. In general, there was a slow increase in the amount of fast activity i.e. the 25-32/second band and also an increase of the voltage of the 3-5/second waves. Coupled with this was a progressive decrease of the amount and voltage of the dominant frequencies, i.e. the 8-12/second band. The tracing tends towards a sequence of 3-5/second wave with a super-imposed ripple of fast activity.

Infrequently, spikes i.e. single, high voltage, fast, sine waves appeared and increased in number shortly before the end-point. Subjects who had non-convulsive end-points showed no other changes. Those who convulsed gave a picture of electrical activity, during and after the fit, which was indistinguishable from that seen in grand-mal epilepsy. It was apparent that there is nothing specific in the convulsions of oxygen poisoning, as regards electrical activity, once they have commenced. In some cases there were signs of disturbances, i.e. short bursts of 5/second activity, with increasing voltage, just before the attack. Others showed no change of cortical electrical activity whatsoever before the major convulsive attack. In view of the similarity of the convulsion to those in grand-mal, both clinically and electrically, it was thought that a study of the E.E.G. of subjects in air, and with hyperventilation, might show inborn instabilities or convulsant tendencies that could be correlated with oxygen tolerance.

Fifteen subjects were graded in order of their oxygen tolerance. This was based on average tolerance during many dives at 60 ft., 90 ft., and 120 ft. in the dry and 50 ft. in the wet. E.E.G. records were classified as normal, abnormal or doubtful (suspicious but indefinite features present). Final assessment was the result of two independent opinions. Results are given in the following table.

TABLE 28

Subject's Endurance Rating	E.E.G.	Whether Convulsed
1	Normal	-
2	Normal	-
3	Normal	-
4	Doubtful	1
5	Abnormal	2
6	Doubtful	-
7	Abnormal	2
8	Abnormal	-
9	Doubtful	-
10	Doubtful	2
11	Normal	-
12	Doubtful	-
13	Doubtful	3
14	Normal	-
15	Doubtful	1

There is no statistically significant correlation although it will be noted that the three most resistant subjects had normal E.E.G's. However, the other two "normals" occurred in the last five in endurance rating. It is of interest to note that all those who had actually convulsed had abnormal or doubtful records. Nevertheless the third most resistant subject with a normal E.E.G. convulsed after this series was completed. Personality assessments also gave no definite correlation with oxygen tolerance.

Conclusion

In the first large series of experiments on human beings knowledge of the dangers and symptoms of oxygen poisoning has been greatly expanded. It has been clearly demonstrated that these dangers are far greater than previously realised.

> *The variation of tolerance between individuals, the variation of tolerance of each individual, the impairment of tolerance with work and under water, all make diving on pure oxygen below 25 feet of sea water a hazardous gamble.*

The impairment of tolerance under water is as mysterious as it is unfortunate. Despite the fact that the first comprehensive description of human symptoms of oxygen poisoning is given here, it is emphasised that no signs or symptoms can be given that would ensure a timely cessation of oxygen breathing in all cases. The variation of symptoms, even in the same individual and at times their complete absence before convulsions, constitute a grave menace to the independent oxygen diver.

The only possible conclusion is that such tensions of oxygen should be scrupulously avoided.

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