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Present Status of Underwater Medicine. Review of Some Challenging Problems*

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Extension of depth limits in deep diving

The practical needs to search for oil and of salvage operations at greater depth have been mainly responsible for an extension of scientific exploration to greater and greater depths. Between 1968 and 1972, the depth of simulated dives in chambers using helium-oxygen mixtures increased from 1170 and 1189 feet to 2001 feet. The latter was accomplished by Comex in Marseille under the direction of Dr. FRUCTUS[1]. In the Comex Dive to 1170 feet in 1968, the 'High Pressure Nervous Syndrome' (HPNS) was observed consisting of clinical symptoms such as tremors of the fingers while at rest, muscle jerks and episodes of somnolence associated with the appearance of slow waves in the EEG record and transformation of the waking tracing into a sleep EEG record. BRAUER[2] suggested that the HPNS represented a helium barrier to deep diving at around 1200 feet, assuming that the effects were produced by the high pressure of helium. It was subsequently shown that a reduction of the fast compression rates previously used (10 ft/min) helped ameliorate the symptoms of the HPNS to a certain degree. FRUCTUS et al.[1] suggested as a working hypothesis that the disorders of the HPNS were related to the development of osmotic dysbarism (KYLSTRA et al.[3]).

Working out slower compression schedules varying between 3.0 feet/min and 0.6 feet/min, the occurrence of the HPNS was postponed to higher pressures and greatly reduced in its severity in the Comex dives to 1706 and 2001 feet. A similar result was obtained in the British dive to 1500 feet by the introduction of 24 h acclimatization stops at 600, 1000 and 1300 feet during the compression schedule. However, the compression rate itself remained high, at 16 feet/min (BENNETT[4]).

The results of the deep dives indicate that the HPNS is an important hazard of deep oxygen-helium dives and that it is apparently caused by two factors a) pressure of helium per se and b) rate of compression. Slowing the rate of compression produced apparently a gain of approximately 500 feet of depth in as much as the 'helium barrier' has been pushed from 1200 feet to approximately 1700 feet.

According to FRUCTUS[1] at 1640 feet a stabilization occurred but the HPNS did not disappear until after a time lapse of 40 h. Its characteristics (static tremor, muscular jerks, lack of coordination of movements, marked EEG changes, slow waves) remained constant during the remaining 60 h of the bottom time in the dive to 2001 feet. No significant improvements were noted until 40 h after the decompression started and had brought the divers into the 1000 foot range. He concluded that selected and trained divers could work and live efficiently at a depth of 1400 feet breathing helium-oxygen; however, physiological limits are approached in the 1700 feet zone[1].

During exposure to helium with oxygen at a pressure of 1200 feet of sea water no effects limiting intellectual or psychomotor performance, neurophysiological functions, exercise capacity were observed[5].

When crude neon (heavier gas than helium) was inhaled at a depth of 1200 feet of sea water in an ambient helium-oxygen atmosphere, two problems were encountered: 1. an increasingly severe dermal itching and the development of gross dermal lesions containing gas bubbles and 2. vestibular derangement and vertigo without impairment of auditory function. These conditions have been explained as a consequence of an isobaric gas exchange discussed below in more detail.

The HPNS has been regularly observed under high pressure and has been interpreted as a stimulatory effect of helium. The lack of anesthetic effects of helium has lead MILLER and et al.[6] to advance the critical volume hypothesis suggesting that the ex-

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[1] X. FRUCTUS, C. AGARATE and F. SICARDI, Proc. Fifth Symposium on Underwater Physiology, Freeport, Bahamas 1972, p. 7.

[2] R. W. BRAUER, Seeking man's depth level. Ocean Industry *3*, 28 (1968).

[3] J. A. KYLSTRA, J. S. LONGMUIR and M. GRACE, Science 161, 289 (1968).

[4] P. B. BENNETT, Memo Physiological Studies Report No. 1–711, Royal Naval Physiology Laboratory, Alverstoke, 1971.

[5] C. J. LAMBERTSEN, Proc. Fifth Symposium on Underwater Physiology, Freeport, Bahamas 1972, p. 8–9.

[6] K. W. MILLER, W. D. M. PATTON, R. A. SMITH and E. B. SMITH, Molec. Pharmac. *9*, 131 (1973).

pansion of the membrane caused by helium when dissolving (expansion causes anesthesia) is smaller than the compression due to the effect of pressure per se (compression producing a stimulation) so that the net effect is compression and the critical volume for anesthesia is never reached. This theory also explains the pressure reversal of anesthesia demonstrated in a large series of experiments in newts by MILLER et al[6].

Evidence for a pressure reversal of a narcotic action of a gas mixture (N_2-3.5 Ata, 0_2-1.4 Ata) in human subjects has been obtained during saturation excursion dives to simulated water depth of 1000 feet[7]. The inhalation of this gas mixture did not produce narcotic effects at 500 and 600 feet but did so at depths of 200 and 300 feet as indicated in EEG changes and performance changes.

The use of multiple inert gas mixtures in decompression introduced by BÜHLMANN and KELLER[8], for the purpose of shortening the decompression time based on the different speed of uptake and elimination of helium and nitrogen in tissues may also have additional beneficial effects in reducing the occurrence of decompression sickness through the antagonistic effects of helium pressure and inert gas narcosis.

Extension of the depth of submarine escape

Escape from depths of 600 feet has been accomplished by the Royal Navy in open sea trails with a pressurization time of 20 sec, bottom time of 1.5 sec and a free ascent rate of 8.5 feet/sec to the surface (DONALD[9]).

It has been proposed that the depth for submarine escape could be considerably extended by using a hyperbaric suit which enables the submariner to attain an increasing ascent rate and to maintain an overpressure for a certain period on the surface which would be equivalent to a decompression stop at 10–20 feet[10].

GAIT and MILLER[11] have proposed to substitute carbon tetrafluoride for nitrogen as the inert gas dilutent in submarine escape procedures which would double the depth capability. Since carbon tetrafluoride is a more slowly saturating inert gas oversaturation in any critical tissue can be avoided during the short exposure periods required during submarine escape procedures.

LD_{50} studies in mice exposed for 1 min to high pressure of carbon tetrafluoride- or nitrogen with sufficient oxygen available in the breathing atmosphere showed a 35% greater depth for carbon tetrafluoride.

Extension of depth in breathold diving

Since 1968 exploits in breathhold diving have shown that man has the capacity to dive to depths in excess of 200 feet (60 m) a world record which had been held by a Greek sponge diver STOTTI GEORGHIOS since 1913. This raised questions about the validity of the generally held assumption that the depth threshold is determined by a point at which total lung volume (the amount of gas contained in the lungs at the end of maximal inspiration) is compressed to the residual volume (volume of gas in the lungs at end of maximal expiration). In the recent record breathhold dives, CROFT 240 feet (1968) and subsequent deeper dives of JAQUES MAYOL and ENZO MAIORCA 256 feet (78 m), the divers went to considerable greater depths than could be predicted on the basis of their total lung volume/residual volume ratios. Bloodshifts into the throax during diving replacing air and resulting in a decrease of residual volume were found to be the cause of greater than predicted diving depth capability (SCHAEFER et al.[12]). Thoracic blood volume displacements were measured at depths of 25, 50 and 90 feet in the Escape Training Tank and at 130 feet in open sea dive using an impedance plethysmograph. The blood forced into the thorax amounted to 1047 ml at 90 feet and 850 ml at 130 feet depth respectively.

Subsequent studies of blood shifts during simulated breathhold dives in the dry and wet chamber clearly demonstrated that the blood shift occurred only in the wet chamber and must therefore be caused by the hydrostatic pressure. However the face immersion reflex plays a role in breathhold diving causing an increase of the blood shifts into the thorax (SCHAEFER and ALLISON[13]). The apneic face immersion reflex resulting in a marked bradycardia has recently been studied in a hyperbaric helium-oxygen environment (HONG et al.[14]). A potention of the bradycardia during face immersion was noted with increasing pressure in the helium-oxygen environment. A similar potention effect of the bradycardia associated with face immersion could be elicited with a stepwise decrease in water temperature at 1 Ata breathing air.

Extension of diving depth in air-saturation diving

Considerable efforts are presently being made both in Western countries and in East Europe to extend

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[9] K. W. DONALD, *A review of submarine escape trials from 1945 to 1970 with particular emphasis on decompression sickness.* Royal Naval Personnel Research Committee, UPS *290*, 1–26 (1970).
[10] W. J. EATON and H. V. HEMPLEMAN, Royal Naval Physiol. Lab. Report *3/7*, 1–14 (1971).
[11] D. J. GAIT and K. E. MILLER, Aerosp. Med., in press (1973).
[12] K. E. SCHAEFER, R. D. ALLISON, J. H. DOUGHERTY JR., C. R. CAREY, R. WALKER, F. YOST and D. PARKER, Science *162*, 1020 (1968).
[13] K. E. SCHAEFER and R. B. ALLISON, Proc. XXI International Congress of Aviation and Space Medicine, Munich 1973.
[14] SUK KI HONG, T. O. MOORE, D. A. LALLY and J. F. MORLOCK, Physiologist *15*, 171 (1972).

the depth of saturation diving using air or normoxic nitrogen-oxygen mixtures for working from a shallow undersea habitat. HAMILTON, et al.[15] reported recently about two saturation excursion dives at 90 and 120 feet with descending and ascending excursions.

Special decompression schedules were calculated using a 15 compartment decompression model which included half times up to 1280 min.

The decompression from nitrogen saturation were faster than the tolerable limits based on the Tektite experiments (BECKMAN and SMITH[16]). However no untoward effects were observed and the decompressions were uneventful.

Performance tests and evoked brain responses demonstrated a definite adaptation to narcosis in divers saturated at 90 and 120 FSW. Their performance at 200 and 250 FSW showed practically no impairment from control levels.

Decompression

A great variety of decompression tables for shallow and deep dives have been developed by the navies of different countries and commercial diving companies. There is however a marked lack of decompression tables for diving at altitude. BUEHLMANN[17] carried out recently a number of simulated dives in the pressure chamber and real dives in a mountain lake of 1250 m altitude which can provide a basis for decompression tables for different altitudes.

In conjunction with the National Oceanic and Atmospheric Administration (NOAA) sponsored nitrogen oxygen saturation dives at 90 and 120 feet reported by HAMILTON[15], instantaneous inert gas exchange monitoring was carried out by us with a mass spectrometer. Moreover inert gas exchange was also studied in 23 air dives to 200 feet. During decompression schedules used in these experiments, breathing of pure oxygen was instituted at certain time intervals.

In cases with clinical signs of decompression sickness-itching-skin bends, nitrogen bursts in the expired air were observed following a complete initial washout curve of nitrogen while breathing oxygen (SCHAEFER and DOUGHERTY[18]). These findings have been interpreted as nitrogen elimination from existing bubbles due to diffusion gradients from nitrogen bubbles into blood and expired air caused by breathing pure oxygen.

The development of skin lesions has been observed in divers in an ambient helium atmosphere while breathing heavier gas mixtures such as nitrogen-oxygen or neon-oxygen. Based on a series of experiments to clarify the mechanism underlying the occurrence of skin lesions, LAMBERTSEN's group in Philadelphia proposed that steady *counterdiffusion of two inert gases* was responsible for the bubble formation in the skin[18,19].

The question of whether or not free nitrogen is eliminated from the body via the lungs has presented an intriguing challenge to the biological sciences for more than a century. The difficulties did not lie solely in the extraordinary accuracy and sensitivity of the methods required to obtain valid data, but perhaps more importantly in formulating satisfactory concepts. Assuming there is a metabolic source of nitrogen in the body it would influence the calculations of decompression tables.

In a recent study (MUYSERS, SMIDT, v. NIEDING, KREKELER and SCHAEFER[20]), the diffusional and metabolic components of nitrogen elimination were measured in a pressure chamber in which the ambient gas composition as well as the total pressure was varied. A linear relationship between ambient PN_2 and nitrogen elimination through the lungs was established. At zero PN_2 in the ambient atmosphere, nitrogen elimination was present after 18 h and amounted to 0.5 ml/min. This is considered the metabolic component excretion under resting conditions and will be used as a corrective factor in the calculation of decompression tables.

Mass spectrometric analysis of ambient and expired air samples collected during 3 saturation excursion diving experiments showed in all 7 subjects cyclic variations in the ratio of expired/inspired nitrogen while the simultaneously measured respiratory quotient remained constant. Whether these delayed nitrogen excretions were due to release of nitrogen from pools in poorly perfused tissues or altered metabolic processes could not be determined on the basis of existing data.

Heatloss in water

Heat loss in water is one of the most challenging problems in diving. In the 4th Symposium on Underwater Physiology, a review was presented by Surgeon Captain J. S. P. RAWLINS[21] on thermal balance at depth in which heat loss in dry suits, wet suits, and in personnel transfer capsules were discussed. There have been difficulties in estimating body heat loss in water from the changes in skin and core temperature.

[15] R. W. HAMILTON JR., D. J. KENYON, H. R. SCHREINER and P. O. EDEL, Proc. Annual Meeting Aerosp. Medical Association 1973, p. 239–240.

[16] E. L. BECKMAN and E. M. SMITH, Texas Rep. Biol. Med. *30*, 1204 (1972).

[17] A. A. BÜHLMANN, R. SCHIBLI and H. GEHRING, Proc. Fifth Symposium on Underwater Physiology, Freeport, Bahamas 1972, p. 59.

[18] K. E. SCHAEFER and J. DOUGHERTY JR., Proc. Aerospace Med. Ass. 1973, p. 243.

[19] J. IDICULA, D. J. GRAVES, J. A. QUINN and C. J. LAMBERTSEN, Proc. Fifth Symposium on Underwater Physiology, Freeport, Bahamas 1972, p. 49.

[20] K. MUYSERS, U. SCHMIDT, G. v. NIEDING, H. KREKELER and K. E. SCHAEFER, J. appl. Physiol., in press (1973).

[21] J. S. RAWLINS and J. F. TAUBER, Proc. Fourth Symposium on Underwater Physiology (Ed. C. J. LAMBERTSEN; Academic Press, New York 1971), p.435.

WEBB[22] determined body heatlossca lorimetrically during cold underwater swims. Using a water cooled garment for human calorimetry, WEBB added the heat input from warm water and the metabolic heat generated during rewarming, and calculated heat loss in the dives, on the assumption that he had replaced by rewarming in the post dive period exactly what had been lost during the 60 min dives in cold water.

He found that the quantity of body heat loss was just over 200 kcal or approximately 115 kcal/m^2 of body surface. WEBB concluded that changes in surface and deep body temperatures, which he measured, could not be used to estimate heatloss with any set of weighing coefficients he could devise.

Adaptation to diving

Adaptation to breathhold diving has been observed in instructors at the Escape Training Tank in New London[23]. Adaptive changes in lung volumes – increase in total lung volume and decrease in residual volume – was found after 1 year of duty at the tank. The observed change in ratio = total lung volume/ residual volume resulted in a 20–30 foot extension in the safe depth to which the divers could go. (This does not take into account the blood shifts in the tohrax during diving, for which an adaption has not been established).

CO_2 tolerance curves obtained in divers showed a shift to the right and a decreased slope when compared with those of laboratory personnel. The high tolerance to CO_2 is developed during the diving period and lost after a 3 months layoff period. This high tolerance to CO_2 in divers is associated with a high tolerance to low 0_2. The divers show a markedly lower ventilatory response to inhalation of low oxygen mixtures (10.5% O_2 in N_2) than laboratory personnel and accept a much larger oxygen debt during exposure to the low oxygen exposure.

It has been suggested that the basic mechanism underlying the adaptation to high CO_2 and low O_2 in breathhold divers is related to the change in respiratory pattern consisting in a marked slowing of respiration and large increase in tidal volume[23].

The high tolerance to CO_2 has been found to be associated with a reduced autonomic response as indicated in smaller elevations of pulse rate and blood sugar during CO_2 exposure. Blood pressure response to an injection of a cholinergic drug, Mecholyl, was measured in a group of 13 divers and 19 laboratory personnel. The divers exhibited a significant smaller fall in blood pressure than the group of laboratory personnel. These findings suggest that the adaptation to diving produces also a damping effect on the cholinergic system. The stress resistance found in divers is in line with their subjective observations of increased 'relaxation' in the course of prolonged diving training.

Recent studies of the component of exercise hyperpnea in divers and non-divers by LALLY and ZECHMAN[23] showed significant lower ventilatory responses in divers as compared to controls in exercise walking a 10% grade at 1, 2, and 3 mph. Moreover the fast (neural) component of hyperpnea was also less in divers. The respiratory exchange ratio values of divers were significantly lower in divers at 2 and 3 mph suggesting retention of CO_2 during exercise in divers. At these levels of exercise, end tidal PCO_2 was 5–9 mm Hg higher in divers. The authors concluded that the relative hypoventilation observed in divers during exercise is primarily due to reduced sensitivity to CO_2.

Aseptic bone necrosis

During the last years a large number of investigations (mostly radiological) have been made of the joints of men engaged in compressed air work. Incidence of early bone lesions were found to be considerably higher than previously expected and amounted to about 25% in compressed air workers in Britain (GRIFFITHS[25]). Aseptic bone necrosis is now being considered a major hazard in compressed air work.

An extensive survey on divers was carried out by ALNOR[25] in Kiel, Germany, who detected 72 cases of bone necrosis in 131 divers, which represents an incidence of 55%. OTHA (referred to in[27]) found among 301 Japanese divers 152 with bone lesions, an incidence of 50%. In contrast to this high incidence of bone lesions in commercial divers ELLIOTT and HARRISON[27] found only 13 divers with bone lesions out of 250 divers in a survey of divers in the Royal Navy (6%). A more recent study of commercial divers at the Gulf Coast showed 22% incidence of osteonecrosis[28]. The cause of the development of aseptic bone necrosis is not known.

At any rate aseptic bone necrosis is recognized as one of the major hazards in compressed air work and diving operations. Because of the large costs of compensation claims, the diving industry will probably make every effort to replace the human diver in diving operations.

[22] P. WEBB, Proc. Annual Meeting Aerospace Med. Ass. 1973, p. 15.
[23] K. E. SCHAEFER, in *Physiology of Breathhold Diving and the AMA in Japan.* (Eds. H. RAHN and T. YOKOYAMA; National Academy of Sciences, National Research Council, Washington, D.C., 1965, publication 1341, p. 237.
[24] D. A. LALLY and F. W. ZECHMAN, Physiologist *15*, 194 (1972).
[25] P. D. GRIFFITHS, in *Physiology and Medicine of Diving and Compressed Air Work* (Eds. P. B. BENNETT and D. H. ELLIOTT; Bailliere Tindall and Casell, London 1969), p. 452.
[26] P. C. ALNOR, Brun's Beitr. klin. Chir. *207*, 475 (1963).
[27] D. H. ELLIOTT and J. A. B. HARRISON, in *Underwater Physiology.* Proc. Fourth Symposium on Underwater Physiology (Ed. C. J. LAMBERTSEN; Academic Press, New York 1971), p. 251.
[28] CH. J. FAGAN and E. L. BECKMAN, Fifth Symposium on Underwater Physiology, Freeport, Bahamas 1972, p. 29.

Conclusion

The present status of underwater physiology and medicine is reviewed. Emphasis is given to recent studies which provide the basis for extension of depth limits in deep diving such as the Comex dive in 1972 to 2001 feet of simulated depth of water. The results of this study indicates that selected and trained divers can work and live efficiently at 1400 feet of sea water breathing helium-oxygen. The causes of the 'High Pressure Nervous Syndrome' (HPNS) are discussed.

The critical volume hypothesis advanced by MILLER et. al.[6] is cited as one of the explanations for the lack of anaesthetic effects of helium at high pressures. Pressure reversal of a narcotic action a N_2-O_2 gas mixture was recently demonstrated in human subjects.

The depths of submarine escape could theoretically be extended according to MILLER by the use of carbon tetrafluoride as a breathing gas for nitrogen since it is a slower saturating gas.

Recent exploits in breathhold diving dives to 240–256 feet indicate the necessity for bloodshifts into the thorax during the dives which has been demonstrated to take place.

The elimination of nitrogen from existing bubbles during oxygen breathing in decompression has been demonstrated through monitoring of instantaneous gas exchange using a Mass spectrometer. The development of skin lesions encountered during inhalation of heavier gases such as nitrogen and neon in an ambient helium-oxygen atmosphere has been explained with a steady conterdiffusion of two inert gases.

Recent heat loss studies in water indicate that the conventionally used indices of heat loss such as core temperature and skin temperature are inadequate to estimate body heat loss.

The most recent studies of exercise in divers show an adaptation to diving indicated in a lesser ventilating response to a given exercise load. The latest investigation of aseptic bone necrosis underscore the importance of this hazard in compressed air work and diving.

Zusammenfassung.

Es wird eine Übersicht über den gegenwärtigen Stand der Unterwassermedizin gegeben. Besondere Berücksichtigung finden die in jüngster Zeit durchgeführten Forschungen, die die Grundlage für eine Erweiterung der Grenzen des Tieftauchens bereiteten, wie z.B. der 1972 durchgeführte Rekordtauchgang der Comex Gruppe, bei dem eine Tiefe von 2001 Fuss (610 m) in der Kammer erreicht wurde. Nach den in diesem Experiment erhobenen Befunden können ausgewählte und trainierte Taucher in einer Tiefe von 1400 Fuss (427 m) noch gut arbeiten und leben, wenn sie eine Helium-Sauerstoffmischung atmen. Die Ursachen des «Nervösen Hochdruck-Syndromes», sowie die kritische Volumentherorie von MILLER[6] als ein Erklärungsversuch für das Fehlen der narkotischen Wirkung von Helium unter hohem Druck im Vergleich zu Stickstoff werden diskutiert.

CONGRESSUS

USA

International Atomic Energy Agency Symposium on Dynamic Studies with Radioisotopes in Clinical Medicine and Research

in Knoxville (Tennessee, USA), 15–19 July 1974.

This Symposium, a sequel to the symposium on the same subject held by the IAEA in Rotterdam 1970, will be concerned with all those applications of radionuclides in clinical medicine and research that involve investigation of the temporal patterns of uptake, metabolism, clearance or excretion of administered radioactive materials. Abstracts must be submitted by 8 February 1974. Further information and forms to accompany abstracts of papers intended for presentation at the Symposium may be obtained by R. A. Dudley and E. H. Belcher, Medical Applications Section, Int. Atomic Energy Agency, Kärntner Ring 11–13, A–1011 Wien (Austria).

Switzerland

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For further information write to: Professor Dr. K. Wüthrich, Institut für Molekularbiologie und Biophysik, ETH-Hönggerberg, CH–8049 Zürich (Switzerland).