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Complications of saturation diving[1]

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Summary: The experience of 458 man-dives with 731 excursions between 50 m and 300 m carried out by Royal Navy saturation divers is summarized. During saturation decompression there were 6 treated bends and 33 reported niggles. Two bends occurred in dives deeper than 249 m and the remaining 4 bends occurred in dives where decompression began in much less than the saturation stop time after completion of downward excursions. There was one case of vestibular system decompression sickness after an excursion to 300 m. It is concluded that the decompression table is effective in use shallower than 150 m but that the risk increases with greater depth. There is, however, only limited experience in the deeper range. There is no evidence that chamber compression with air to 10 m adversely affects decompression from deeper than 50 m. An account of the medical and physiological conditions affecting divers in these dives is given.

Introduction

Saturation diving implies that divers stay at pressure for sufficient time for their tissues to reach a state of equilibrium with the gases to which they are exposed. The result of such exposure is that any additional time at pressure incurs no additional decompression penalty. The most frequent type of diving is bounce diving in which, after a short period of work, the diver must decompress in stages to the surface. For protracted shallow tasks and for many tasks deeper than 50 m, bounce diving is an unsatisfactory way of working in that it takes longer, uses more divers and exposes them to the risk of more decompressions. The usual approach to saturation diving is for divers to live in a complex of chambers and to make excursions to and from their work site in a sealed and pressurized bell.

There are several major environmental factors in the practice of such diving. Firstly, there must be a continuous supply of oxygen to the system, enough to meet all levels of activity but not so much as to cause pulmonary oxygen toxicity with continuous exposure. Carbon dioxide must be removed by soda lime scrubbers. Helium, being a good heat conductor compared with air, causes an increased heat loss from divers in chambers and from their lungs when in the water; the effect increases with depth. It necessitates the heating of chambers and also of divers' gas supply when at depths much beyond 100 m. Inadequacy or absence of diver heating leads to hypothermia and has been implicated in some commercial diving accidents. The use of helium so distorts speech that it is totally unintelligible unless processed by an 'unscrambler'. The mass of gas required by a diver increases with depth. A diver with a minute volume of 40 litres would require, if working at 140 metres (15 bar), the surface equivalent of 600 litres to maintain his ventilation. For all practical purposes his oxygen requirements would be the same, therefore the waste of gas is great. To overcome this wastage, the exhaled gas is recovered, filtered and scrubbed of CO_2 before oxygen is added for return to the diver.

Methods

The Royal Navy saturation decompression was developed with an approximately normoxic atmosphere of 0.22 bar in nitrogen-free helium. The project began by building down from the surface in a series of 24-hour stages built onto a safe 10 metre stage (Barnard 1976, Vorosmarti *et al.* 1982). The form and timing of these stages was later modified until attempts to return

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without decompression sickness from 180 m reached a complete impasse. Only when the Po_2 was increased to 0.4 bar did the project progress to 250 m (Vorosmarti *et al.* 1978, 1982).

An allowable range of diving depths was established around each storage depth. The development of the RN table and experiments by the US Navy showed there to be a linear relationship between storage depth and the range of excursion in the working range (Spaur *et al.* 1978). Stored at 50 m there is a safe range of 22 m for unlimited duration excursions and at 250 m it is 50 m. The published US Navy (1981) tables for excursion diving were adopted by the Royal Navy.

Nitrogen-free chambers were operationally impractical so it became usual to compress to 10 m with air establishing a Po_2 of 0.42 bar. However, it was possible that the raised PN_2 could contribute to a risk of decompression sickness.

The Po_2 is kept at 0.42–0.43 bar; this means that at 10 bar there is 4% oxygen and at 300 m (31 bar) it is 1.3%. The Pco_2 is kept below 0.005 bar (0.5% surface equivalent). The required temperature for diver comfort increases with depth and lies in the range 24–32°C. Humidity level is a compromise between diver comfort on the dry side and soda lime efficiency for removing CO_2 on the wet side; the usual range is 60–75% relative humidity.

Being a sealed environment, there is an accumulation of byproducts of metabolism and material off-gassing such as carbon monoxide, methane, hydrogen sulphide, methanol and hydrocarbons. Activated charcoal or oxidizing agents are placed in the gas scrubber units to remove contaminants. Some prevention is possible by screening the materials used and taken into complexes.

Results

There have been 364 man sea dives carried out by 79 groups of men to as deep as 300 m for the purpose of trials, training, equipment maintenance and salvage. On 13 occasions men were added to or removed from dives which were continuing. These dives were performed in waters ranging from the North Sea to the Gulf of Mexico and the Falkland Islands. Only 8 dives involving 27 men have been deeper than 151 m, the remaining 71 dives being between 50 and 150 m. The majority of dives have been of about 2 days bottom time, although some have been as long as 20 days.

During these dives there were 737 manned excursions, including 41 working-upward excursions (to a depth shallower than storage). As an excursion usually includes a bellman and two divers, all are included. The divers' in-water time is a variable amount less than the excursion time which has lasted between 18 minutes and 9 hours 55 minutes. Most excursions lasted between one and 5 hours. The maximum number of excursions in one dive was 84 (28 bell excursions).

Since development of the table, 373 decompressions have been made from shallower than 151 m and 85 from 151 to 300 m. The shallower data were used to assess the influence of excursions, both working and as a prelude to decompression, and of nitrogen upon the safety of the decompression table.

Decompressions which began with an upward excursion resulted in 2 bends (2.6%) and 5 niggles (6.5%) (mild transient joint ache) in 77 man-dives; while 296 man-dives in which decompression did not begin with an upward excursion resulted in 2 bends (0.7%) and 3 niggles (1.0%), suggesting that upward excursions may produce problems. However, if the data are divided into groups which did or did not have an interval of at least the decompression stop time after an excursion, before beginning the decompression, a different picture emerges. In 127 decompressions begun in less than the stop time there were 4 bends and 4 niggles, compared with no bends and 4 niggles in 246 decompressions begun after at least a stop-time had elapsed since the last excursion ($P<0.02$, chi-square). Grouping the dives by initial PN_2 failed to show any trend of decompression sickness risks.

During the table development, where the end-point at each stage was necessarily decompression sickness, there were 32 cases of limb bends (Hanson *et al.* 1978). These were confined to the lower limbs in all but 5 cases. In addition 3 of those cases also had associated paraesthesia. There were also 3 cases of serious decompression sickness, 2 of which involved the VIII nerve and the other had cerebral problems presenting like migraine and experiencing visual problems. These serious cases all followed large pressure drops. Since acceptance of the table there have only been 6 lower limb bends. Two of these were in the 70 dives between 200 and 300 m.

Compression to the deeper end of the range results in two potentially debilitating problems, compression arthralgia and high pressure nervous syndrome (HPNS). The arthralgia causes restriction of joint movement and the HPNS causes dizziness, nausea, anorexia, fine tremor, and loss of manual dexterity. They are worsened by depth and rapid compression, but both abate at least partially over hours or days. Most divers have been able to tolerate compression rates of 1 m/min to about 120 m, with a rest for a few hours before continuing at 0.5 m/min. Compression beyond 100 m will, in most divers, cause arthralgia which generally eases over 24 hours. HPNS is not much of a problem until deeper than 180 m, and most get over the worst within a few hours.

During 258 operational man-dives there were 109 cases of medical comment or treatment recorded. The conditions fell into three categories: those caused or exacerbated by the warm, humid and sealed saturation environment, those which would occur anyway, and those related to work.

Skin infections were common with 8 cases each of tinea pedis and tinea cruris or prickly heat, 10 cases of folliculitis or furunculosis and 3 cases of paronychia or cellulitis. There were 9 reported cases of a pruritic red papular rash often lasting a couple of days. Incidental skin problems included a probable herpes labialis, cheiropompholyx, pityriasis seborrhoea and a possible chemical burn from neat Savlon not washed off a suit. Aluminium acetate drops (5%) used regularly were effective in preventing otitis externa, with only 4 mild cases requiring treatment; none of these had to be withdrawn prematurely.

Next in frequency were 33 cases of mostly upper respiratory tract infections. They were mainly pharyngitis, but some became pyrexial and exhibited flu-like symptoms while others developed productive coughs. There were 13 cases of minor trauma although one arm injury led to early decompression for the diver. Back strain occurred in 4 divers; the rest were mostly cuts and abrasions. Two divers suffered chest burns when their experimental closed-circuit hot water suits leaked at one site: this resulted in a blister 5 × 1.5 cm in size in one diver. Another curious injury occurred to a diver who accidentally stuck his thumb over the equalizing inlet port of an air lock. When he was eventually released he had a 1 cm diameter gas bleb on the end of his thumb; this resolved spontaneously over about 6 hours. Additionally, 2 divers suffered from underwater blast and one had to be decompressed prematurely with perforated ear drums.

Six divers had diarrhoea and/or vomiting lasting up to 2 days. There were also 5 cases of seasickness in 2 different dives when decompression was going on while under way. Two imported problems had to be treated – urethral candidiasis and threadworms. The latter led to treatment for all. Three divers experienced toothache during several ascent stages. This was resolved when a piece of enamel lifted off next to a filling in one and when the crown lifted off during an ascent in another. The third case surfaced with toothache. No psychiatric problems have been reported.

It was found that very hot showers could cause red pruritic rashes which in one case went on to urticaria. The urticaria recurred following a later hot shower. Avoidance of hot showers prevented further recurrences.

Discussion

In the depth range to 300 metres no untoward problems beyond the maintenance of thermal balance have been encountered. As yet, no long-term health effects have been identified as a result of saturation diving in this depth range and no increase in the incidence of dysbaric osteonecrosis has been observed. The medical conditions encountered have been largely those one would expect in a warm, humid and sealed environment, namely fungal and bacterial skin infections.

Questions are sometimes asked as to why commercial decompressions are faster than either the RN or USN tables. Perhaps this is mostly because the military are not in a contract race and anyway cannot afford to be seen to be anything but safe. The only way of speeding the decompression is to raise the Po_2. Hennessy (1980) has published a theoretical prediction of bubble-free decompressions related to Po_2. This suggests that decompressing from 250 m with a Po_2 of 0.22 bar would take 12.5 days and with a Po_2 of 0.6 bar would take 6.75 days, but this would be with some risk of pulmonary oxygen toxicity. In practice, decompression from 250 m with the RN table takes about 9.1 days with a Po_2 of 0.42 bar. The USN table with a Po_2 of 0.4 bar takes 9.5 days.

At depths shallower than 150 m the RN saturation decompression table works satisfactorily. Deeper than 150 m there is probably a higher incidence of decompression sickness, especially deeper than 250 m which may require a change in the decompression. There is some association between upward excursions at the start of decompression and the incidence of decompression sickness. However, all 4 bends in dives shallower than 150 m occurred in decompressions which started in less than the stop-time after downward excursions. Compressing saturation systems with air to 10 m does not seem to be detrimental in subsequent decompressions from depths between 50 and 250 m.

The problems of diving much beyond 200 m lend encouragement to using non-diver methods where possible. The reinvented armoured diving suit has its uses, as does the manned submersible. These approaches remove the physiological problems of high pressures and avoid decompression. However, the price is the manual dexterity and the lost mobility of the diver.

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