11 Optimum schedules for caisson decompression

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Abstract
Evidence accumulated over many years indicates that all the current caisson decompression schedules in use are inadequate. The reported incidence of decompression illness (DCI) is considerably lower than the actual. Most previous decompression schemes for tunnel workers have been extrapolated from naval schedules, albeit navies have had very little experience with long-duration dives at shallow depths. Oxygen decompression tables developed in Milwaukee are based on commercial data and eliminate nitrogen several times more effectively than existing schedules. Oxygen decompression appears to be the only viable method of decompressing tunnel workers on a daily basis. These tables appear to be a great deal safer than existing tables, but regulating bodies in the United States, Great Britain and Japan have failed to keep pace with recent developments in decompression physiology. In the past, dysbaric osteonecrosis has been the most feared complication of tunnel decompression. New evidence from Milwaukee, Wisconsin, indicates that there may be the possibility of central nervous system damage secondary to improper decompression. Tables from Japan, the United States, Great Britain, Germany and France are compared with the new oxygen decompression tables. Data regarding central nervous system changes in the brain of compressed air tunnel workers as seen with magnetic resonance imaging are reported.
Keywords: Decompression illness, Oxygen decompression, Caisson decompression, Compressed air, Magnetic resonance imaging, CNS, Dysbaric osteonecrosis.

1 Introduction

Caisson and compressed air work differ from diving in several important ways. Caisson exposures are usually carried out at quite modest pressures never exceeding the equivalent of 50 psig (345 kPa). Bottom times or shift lengths, however, almost always range between 4 and 8h on a daily basis with 6 to 8h exposures being quite common. Furthermore, each exposure tests the decompression schedule being used

Engineering and Health in Compressed Air Work Edited by F.M. Jardine and R.I. McCallum. Published in 1994 by E & FN Spon. ISBN 0 419 18460 0

almost to the limit, as a new schedule is provided for each additional 2 psig (14 kPa). This is done for economic reasons as every effort is made to avoid extending decompression times unnecessarily. For this reason, about four out of five caisson exposures test the table in use to its maximum limit whereas only three in ten water dives tax the table to a similar extent. Diving tables are usually set up in larger 3 m (30 kPa) increments.

Caisson workers' bodies are not supported by water while exposed. In addition to supporting their own weight throughout the exposure, they must carry their tools and the burdens they bear. The air in caissons and tunnels usually contains more contaminants than are present in diver's air. While working at pressure, tunnellers are rarely chilled but are often exposed to heat during concrete pours. On the other hand, divers are typically chilled during their working exposure. In tunnels, chilling takes place during decompression when the workers are seated in a dry chamber. Balldin *et al.* (1969) show that there is 30% less nitrogen eliminated in those decompressing in the dry as opposed to those decompressing while immersed. Finally, despite the fact that caisson exposures are much more numerous than diving exposures, relatively few good data are available regarding the efficacy of the decompression tables used compared to diving decompression schedules.

1.1 The reported incidence of decompression illness

When decompression illness (DCI) rates are tabulated in caisson work, it is usually only treated cases which are reported. These are the official rates which generally give little indication of the actual occurrence of symptoms. Caisson tables have been so extremely bad for so many years that compressed air workers tend to accept symptoms of DCI as an inescapable element of their jobs. For this reason, they rarely report symptoms unless they are unbearable or incapacitating. If they were to report for treatment too frequently, they would be removed from more remunerative compressed air work. Using an anonymous system of reporting on more than one tunnel job in Milwaukee, we found that up to 26% of a shift might be suffering symptoms of DCI on any given day, although none came in for treatment. On one project which had pressures ranging between 19 and 31 psig (131-214 kPa) anonymous reporting revealed that DCI was present on 42.5% of the working days. During that period of time the 'official' decompression illness incidence, representing cases treated, was 1.44%. The present United States Occupational Safety and Health Administration (OSHA) enforced decompression schedules were the tables used when these observations were made.

1.2 Dysbaric osteonecrosis

I consider dysbaric osteonecrosis to be another form of decompression illness as bone is simply another target organ along with spinal cord and brain. Although there have been other theories as to its causation, bone disease appears to be caused by improper decompression. Repetitive human experience has demonstrated that decompression time is the only independent variable in the production of bone necrosis. Short decompressions produce necrosis; long decompressions for the same exposures produce less or none.

1.3 The split shift

The split shift was formalised in the United States when the 1922 New York code was adopted. It was hoped that the shorter exposures would decrease the incidence of DCI. The split shift embodied two rather short shifts separated by a one-hour rest interval on the surface during the middle of the day. Decompressions for both shifts were identical which did not take into account the residual nitrogen from the first shift. The one-hour surface interval was woefully inadequate to allow release of meaningful amounts of nitrogen present in the body. The split shift also exposed the worker to the trauma of two decompressions per day instead of just one. Unfortunately, the split shift is still in use in Japan. It produces a very high rate of decompression illness but contractors have been reluctant to report this to the authorities as they might be subject to disciplinary action should the government become officially aware they had not reported these high rates in the past (Nashimoto, 1986). Figure 1 shows a comparison between the Japanese split shift and the US Navy repetitive dive schedule. The Japanese schedule is totally unphysiologic.

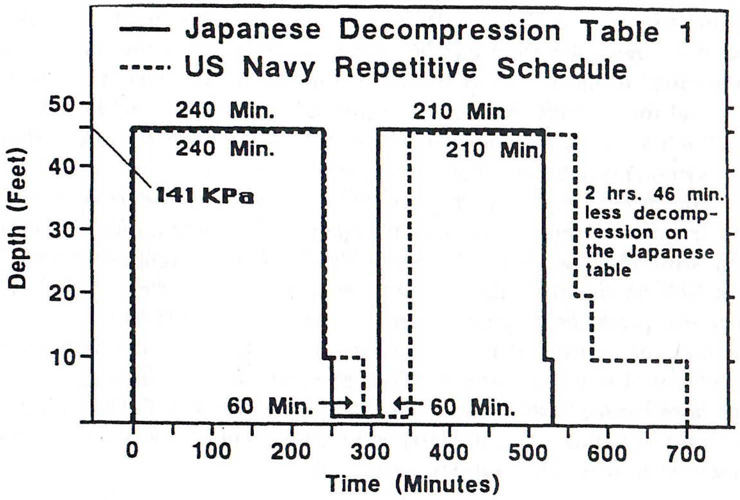

Fig. 1. Comparison between Japanese split shift and USN repetitive dive schedules

2 Shift length

Working shift lengths are typically divisible into 24 hours as tunnelling usually proceeds around the clock. Eight, six and four hour shifts are used, the last at the higher pressures. Because of table inadequacy, the French have drastically shortened

permissible shift length, as pressures rise, to increase safety. In Britain, current practice permits work shift lengths to be longer, as decompression time may be added to a full 8 h work shift. The 1982 edition of CIRIA Report 44 stipulates only that there must be a 12 h surface interval between exposures and that the total of the combined work and decompression exposures be limited to 10 hours per day. My own view is that the time between shifts should be at least 16 h and that 12 h is too short a period for adequate denitrogenation. Even a 16 h hiatus is probably too short, if present theories regarding the half time of the slowest tissues are correct. This implies that employees are not completely free of work-absorbed nitrogen when re-entering compressed air after the first shift of the week. In the US, all work, including decompression, must be completed within an 8 h shift, guaranteeing a 16 h surface interval.

Historically, continuous decompression rather than stage decompression was the norm in compressed air exposures. This emanated from decompression simply being a matter of opening a valve and waiting until the lock pressure equalised with atmospheric pressure. When it become understood that DCI was caused by rapid decompression, the valves were not opened fully, and slower continuous ascent was provided. The present US OSHA decompression tables still utilise continuous decompression at increasingly slower rates for this reason. This complicates matters, as it is very difficult to control such decompressions by hand and a computer or cam-controlled exhaust mechanism is required. Using stage decompression there is no such requirement. Additionally, continuous decompression is also inefficient and wasteful. For example, if the last stage from 4 psig (28 kPa) to the surface were to take one hour, at least one half of the time is spent at a pressure less than 2 psig (14 kPa) which provides no meaningful bubble suppression. In UK, France, Germany and Brazil, the more efficient stage decompression has been adopted.

Behnke (Kindwall *et al.*, 1983) has suggested that saturation habitats be constructed in tunnels with storage pressures for the workman up to 22 psig (152 kPa). This would be the pressure limit because of the cumulative effect of oxygen toxicity from compressed air. At that pressure, the effective oxygen level would be equivalent to 53% at the surface. Much deeper 8 h excursions to working pressure could be made without a decompression obligation. A major problem with saturation exposure is the space required for the living quarters and securing the cooperation of unions for these exposures. Saturation would be feasible only on the largest projects. To this date, it has not been utilised.

3 Modern decompression tables

In 1963, Duffner devised the Washington State tables which have since become the federally enforced OSHA tables in the USA (U.S. Bureau of Labor Standards, 1971). These tables replaced the split shift but retained continuous decompression as opposed to stage decompression.

Because the British 1958 tables were found to produce a 19% incidence of aseptic necrosis on the Clyde tunnels (McCallum, 1967), Hempleman (1973) devised the Blackpool tables in 1966. The Blackpool tables were much longer, adopted stage decompression and required decompression for all exposures greater than 14 psig (97 kPa), as do the American tables.

Duffner was unable to adopt stage decompression in his tables because of the objections of contractors and the unions who refused to stray from tradition (Duffner, 1983). The American OSHA tables also have another major flaw in that for each 2 psig (14 kPa) pressure range a decompression time is provided for shift length 'over 8 h'. These decompression schedules would be disastrous if ever used, as conceivably a foreman could work two 8 h shifts back-to-back in an emergency, totalling 16 h. Were he working at 20 psig (138 kPa), the decompression requirement using the OSHA code would be only 113 minutes. In modern saturation diving with air, such an exposure calls for over 14 h decompression.

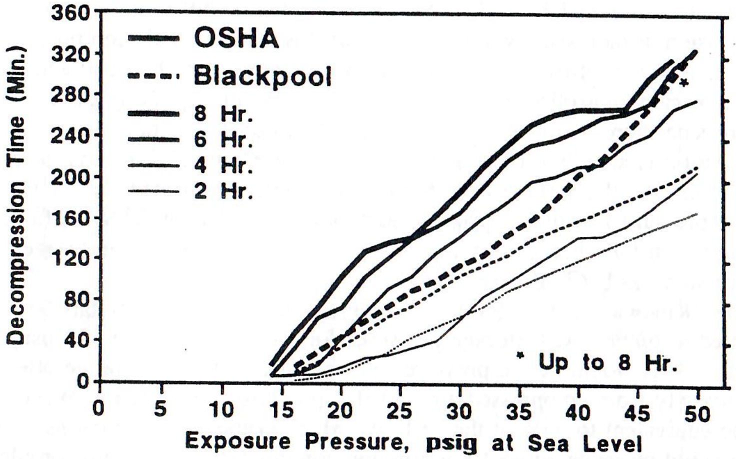

Fig. 2. Comparison of OSHA and Blackpool Tables decompression times

As seen in Figure 2, the OSHA tables call for longer decompressions over most of their range than do the Blackpool tables and therefore should be inherently safer. The steeper the rise of the curve, the greater the safety. Note also the internal inconsistencies in the OSHA schedules which show that at 26 and 44 psig (179 and 303 kPa), the decompression time is the same for both 6 and 8 h exposures. This occurs at several other places in the tables. When these discrepancies were shown to Duffner, he was unable to explain them as they were not so calculated. They are probably due either to typographical errors which crept into the transcription of the tables or resulted from the slight displacement of the ruler which was placed across a nomogram to find the decompression times.

Although the OSHA tables are safer than the Blackpool tables on inspection, they still are not as safe, for the practical exposure times which would be used, as the US Navy Exceptional Exposure Air Tables for which a comparison is shown in Figure 3.

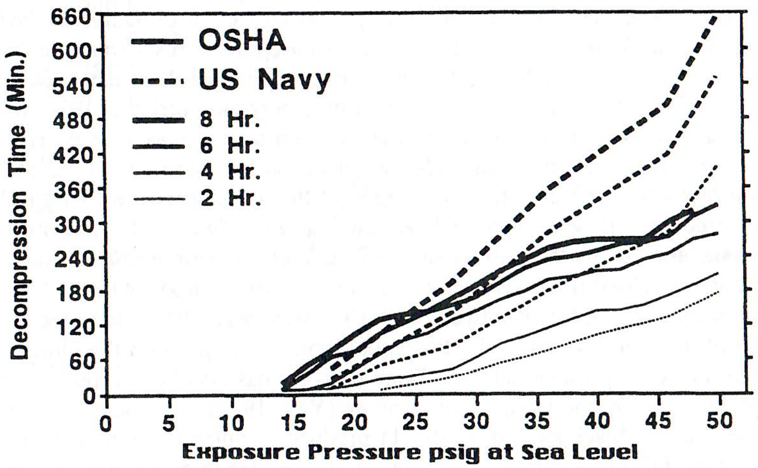

Fig. 3. Comparison of OSHA and USN Exceptional Exposure Air tables decompression times

Thus, it would appear that the US Navy Exceptional Exposure Air Tables would be safest for tunnel work as they provide the longest decompression times over most of their range. However, the US Navy Exceptional Exposure Tables were only tested at the 140 fsw (965 kPa) level before being promulgated to the fleet. On each test there were never more than six men in the chamber and on every occasion at least one man suffered DCI and sometimes two. Realising that these tables showed a trend for producing a DCI incidence of between 17 and 33%, they are now reserved *for emergency use only*. Thus it would appear that in the United States and Great Britain, contractors routinely expose their workman to daily decompressions that are more dangerous than decompressions the United States Navy approves only for dire emergencies.

Considering the theoretical parameters outlined above, we would be concerned about the actual results of using these tables in the field. Experience has shown these concerns to be valid. Previously, the statistics were given for DCI when the OSHA tables were in use. We do not have similar statistics for the Blackpool tables as no anonymous reporting of symptoms has been employed when the tables were in use. A possible exception is Yau's personal communication (1987) that 83% of the men working on the Hong Kong subway project reported decompression illness in association with the Blackpool schedules.

Bone necrosis for all practical purposes appears to be unknown at pressures less than 17 psig (117 kPa) (Walder, 1971). When the OSHA tables were first employed in Washington State, they were used up to a maximum of 36 psig (248 kPa). Ten years later, Sealey (1975) found four individuals with dysbaric osteonecrotic lesions in the shafts of the proximal tibia. No other lesions were found and the tables were felt to be safe from the standpoint of dysbaric bone disease. Subsequent use on the Bay Area rapid transit project was for the most part at pressures never reaching 17 psig (117 kPa) except for one two-week period where the pressures peaked at 36.5 psig (251 kPa) under the Embarcadero. No aseptic necrosis was found on yearly x-ray of the workers but no follow-up examination of them has been carried out. The present OSHA tables were adopted by emergency order in 1970 in Wisconsin and initially no new cases of aseptic necrosis were seen on yearly x-ray of the workmen. However, two years after a tunnel job had been completed at a maximum pressure of 43 psig (296 kPa) 33% of the workmen were found to have dysbaric osteonecrosis when surveyed (Kindwall *et al.*, 1982). Thus, at pressures over 36 psig, the OSHA tables were as ineffective at reducing dysbaric osteonecrosis as were the old split-shift tables used in Milwaukee which produced a 35% incidence of bone disease (Nellen and Kindwall, 1972). Trowbridge (1977) reported an 8% incidence of bone disease when the Blackpool tables were used on the Dungeness B Power Station cooling water tunnels. Bone necrosis has also been reported on the Blackpool tables from the Hong Kong subway (Yau, 1987). It would seem only reasonable that the Blackpool tables should produce as much or more aseptic necrosis as the OSHA tables, as they provide shorter decompression times and longer shifts. They have physiologic advantages over the OSHA tables, however, in that they take deeper stops and use stage decompression.

Looking at experience on the continent, we find that the French air tables are less conservative than the OSHA tables, but that exposure at the high pressures is severely limited (Figure 4). It appears that the French have recognised the inadequacy of the air decompression tables at the higher pressures and have simply curtailed the work shift length and limited the maximum pressure.

The German air schedules are also less conservative than the OSHA schedules and are more limited in shift length and pressure than either the Blackpool or OSHA schedules (Figure 5).

Comparison between the exposure limits of the various tables is made in Figure 6. Notice that the Blackpool tables have an area of diagonal lines between four and eight hours and over one bar (14.7 psig, 101 kPa). This indicates that decompression is the same for any exposure over four hours and depends only on the pressure at that point. The Blackpool tables cut off at eight hours and the US Navy tables cut off at a 12 hour exposure. Note however that OSHA tables are indefinite as they do give schedules for 'any shift over eight hours'. In theory they have no maximum exposure limit. The Navy Exceptional Exposure Air Tables are not shown above 50 psig (345 kPa) where they are not comparable to tunnelling.

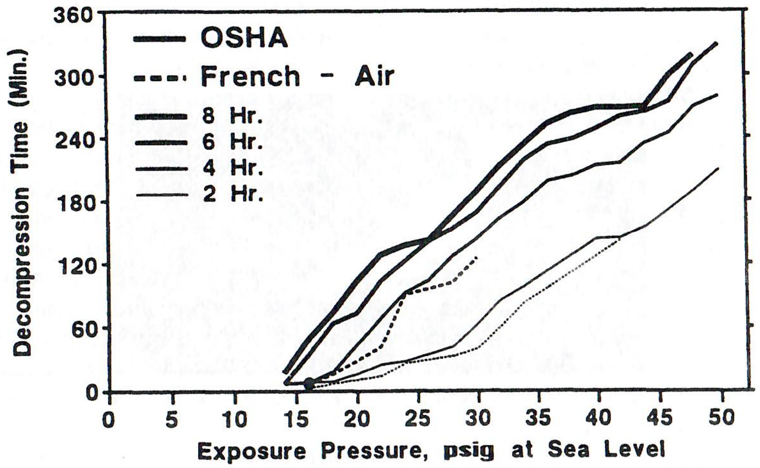

Fig. 4. Comparison of OSHA and French decompression times

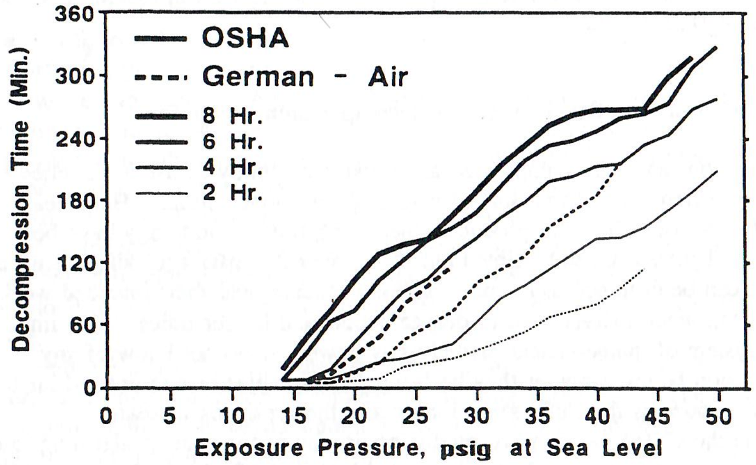

Fig. 5. Comparison of OSHA and German decompression times

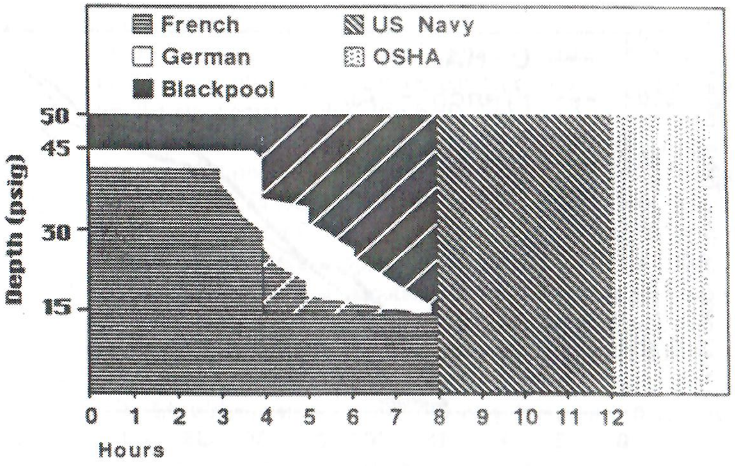

Fig. 6. Comparison of exposure limits

I do not have access to data with regard to the incidence of DCI in workers using the French and German air tables but unless an anonymous reporting system were used to collect those data, they would not be indicative of the true incidence. Since these tables are less conservative than the OSHA tables, we can assume that the incidence of DCI is high.

4 A new approach to development of decompression schedules

Decompression tables for compressed air workers currently in use have relied chiefly on naval experience and some sort of mathematical model, usually Haldanean. It appears that all our efforts to produce tables using this methodology have been flawed. As Duffner himself pointed out to me over 25 years ago, all decompression schedules can be designed to be more or less adequate over their intended working range but fail when extrapolated to deeper depths and longer times. This implies that our system of mathematical modelling is flawed. I do not know of any decompression tables, whether they be Navy Diving tables or compressed air tables that become safer as the shifts grow longer and the pressures increase.

Because the OSHA tables were producing aseptic necrosis at an alarming rate at the higher pressures, we sought funds from the National Institute of Occupational Safety and Health to devise safer decompression tables for compressed air workers. This work was commenced in 1979 and finished in 1983 (Kindwall *et al.*, 1983). As previous attempts at mathematical modelling had failed and naval experience was inadequate on which to base long-term exposures, I sought the help of Peter Edel in New Orleans, Louisiana. Edel had a computer with data pertaining to 15 years of

successful and unsuccessful commercial dives in the Gulf of Mexico and elsewhere, as well as some experimental data. Some of these data were his own and included additional experimental material from commercial as well as naval sources.

It was evident from the start that any decompression tables would have to be economically viable as well as physiologically sound. Unlimited decompression in the name of safety would render the tables unusable in the tunnelling industry. In an effort to meet these requirements, some extremely long duration data were initially excluded from consideration, and the computer was asked essentially to draw a line between the successful and unsuccessful decompressions for increasingly longer times and pressures of up to 50 psig (345 kPa). Gaps in the available data were filled in using a proprietary neo-Haldanean method of calculating tissue saturation and de-saturation. It was assumed that a worst-case situation would be workers decompressing from the second shift of the week when they still had residual gas from the first shift, despite a 16 hour hiatus between shifts.

The first set of decompression tables so produced was labelled Autodec 2 and they were subjected to test by volunteers in our laboratory. The volunteers consisted of six males and one female who ranged in age from 26 to 59 years of age. Each decompression schedule was tested after exposure to the longest shift time which could be accommodated in an eight-hour work day when the workshift and decompression times were combined. In practice, these would be the only schedules which would be used in the field. They would also be the most stressful. The subjects walked on a treadmill up a 3% grade at a speed of three miles per hour for 10 minutes. Every 10th step the subject would raise a five pound weight held in each hand from a position at his side to above his head. Each 10 minutes of exercise was followed by a 10 minute rest. This was to approximate a moderate work effort throughout exposure to compressed air in an effort to simulate the work load of a tunnel labourer. The Autodec 2 schedules were initially spot tested at various pressures up to 34 psig (234 kPa). However, Autodec 2 decompression produced chokes and decompression illness in multiple joints in more than one subject and finally produced a positive bone scan which indicated pathologic activity in the proximal tibia. Further testing of Autodec 2 was abandoned. It had been hoped that Autodec 2, which used decompression times similar to the present OSHA schedules would be adequate, as stage decompression was employed. It was hoped that this alone would provide the necessary safety. In practice, it proved to be a vain hope.

The Autodec 3 schedules were then generated using all of the data available to the computer. This included material from extremely long exposures. The results proved disappointing from the standpoint of economics as the decompression schedules generated by the computer were prohibitively long, although obviously much safer. An example can be given: the decompression requirement for a 4 h work period at 44 psig (303 kPa) is 4 h using the present OSHA schedule. The Autodec 3 schedule required 10 h and 46 min. If this and comparable schedules were the ultimate price for tunnelling at pressures greater than 18 psig (124 kPa), commercial compressed air work as we know it was doomed. Since physiology is unalterable, another way had to be found to rid the body of excess nitrogen in a more timely fashion.

5 Oxygen decompression

Oxygen decompression is nothing new and has been used successfully by the navies of the world since the 1930s. It is a matter of routine in commercial diving. Oxygen decompression carries with it certain risks, not the least of which is fire. For many years the US Navy did not permit oxygen to be used in the treatment of DCI because it was not 'sailor proof'. This was despite the fact that Behnke had shown it to be efficacious in DCI as far back as 1939. However, it was only in 1964 when research disclosed that air treatment of decompression sickness produced a 41.7% failure rate on the initial recompression that research was again directed toward the use of oxygen. By 1967, oxygen treatment of decompression sickness had been approved for use in the US Navy and the failure rate on initial recompressions had dropped to 3.6% (U.S. Navy, 1967). Needless to say they were the same kind of dive supervisors, treating the same kind of divers, using the same chambers, and breathing the same oxygen that had been available in 1939. Suddenly in 1967, oxygen had become sufficiently 'sailor proof'. The only differences were in the recognised requirement and proper training of the personnel.

Oxygen decompression was the first used in compressed air tunnelling in 1938-39 in connection with the construction of the Queen's Midtown Tunnel in the city of New York (Jones *et al.*, 1940). Some 14,000 experimental oxygen decompressions were carried out without mishap on that job despite an oxygen delivery system of poor design with no overboard dump system. Additionally, the oxygen breathing apparatus had very high breathing resistance. Despite these inadequacies, there were no fires and there were also no serious cases of DCI in those workers who breathed oxygen.

The next use of oxygen in compressed air work was in 1959 in Japan. Unfortunately, the workers had not been adequately trained and one of them apparently lit a cigarette that resulted in a fire which killed six men undergoing decompression (Nashimoto, 1967). Despite that unfortunate accident, oxygen decompression was put into use on a regular basis in Germany in 1972 when the first oxygen tables for caisson workers were promulgated. The Germans were pleased with the results and reported that 'the rates of DCI decreased remarkably in spite of longer shifts' (Altner, 1986). Recent German experience with new oxygen tables developed by Faesecke (1991) has been excellent. Le Péchon (1987) reports that the French have had oxygen decompression tables for tunnel workers since 1974, but these remain to be tested on a large project. Ribeiro (1985) has also pointed to very successful results of oxygen decompression used in 1976 in the construction of the São Paulo subway. To date, the German, French and Brazilian experience has been ignored by British and American regulatory bodies and there has been extreme reluctance to adopt oxygen decompression, much as the US Navy was reluctant to accept oxygen treatment of DCI.

6 The Milwaukee oxygen tables

From the physiologic standpoint, it became apparent to us that the only available means of removing nitrogen from the tissues of caisson workers subject to daily decompressions was the use of oxygen. For this reason, Edel's computer was instructed to calculate an oxygen variant of the long Autodec 3 table. From the economic point of view, these new oxygen tables looked very promising indeed. Now, 4 h work periods at 44 psig (303 kPa) required only 3 h 21 min when oxygen was breathed intermittently during decompression. This schedule and the schedules at the lower pressures save considerable time over the present OSHA table (Figure 7).

The new oxygen table was tested in the same way as Autodec 2 at maximum shift length at 2 psig (14 kPa) intervals up to 46 psig (317 kPa). No DCI was seen in any of the test subjects and all of the bone scans were negative six months later. This represents the only set of decompression schedules for compressed air workers ever pre-tested in the laboratory. Obviously, it is clear that two or three tests of the table at each pressure level, even with different subjects, is totally inadequate to project an incidence of DCI. However, DCI did not appear, even at the higher pressures and at maximum shift length. At least, catastrophic error can be ruled out. Decompression times for a 4 h exposure using various decompression tables (both air and oxygen) are compared in Figure 8.

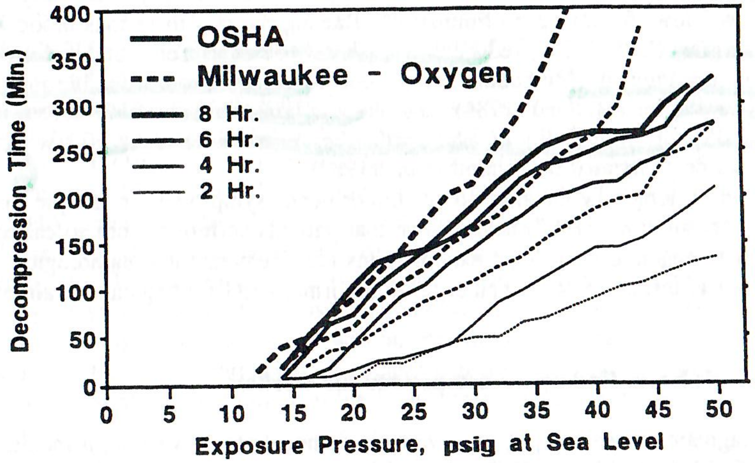

Fig. 7. Comparison of OSHA and Milwaukee oxygen tables decompression times

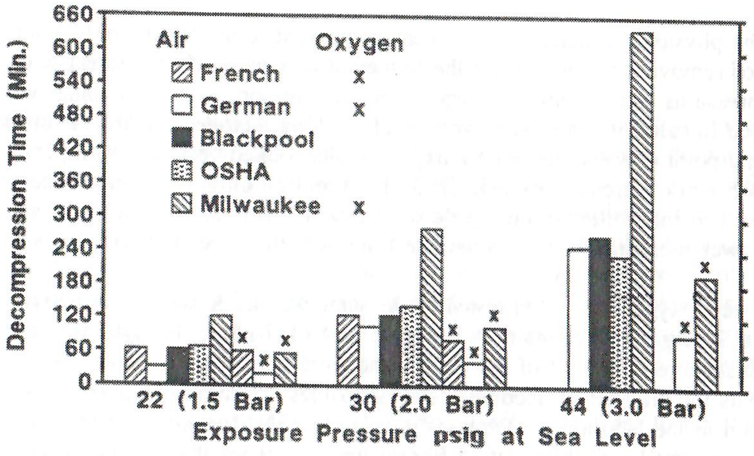

Fig. 8. Comparison of decompression times for 4 h of compressed air work

Oxygen toxicity is not a matter to be taken lightly and its occurrence cannot be ruled out when these schedules are used on a daily basis. However, its appearance is unlikely due to the intermittent nature of the oxygen breathing periods and should oxygen toxicity occur, it is easily reversible. This is not the case with bone and neural damage.

Oxygen decompression offers other advantages beyond simply expanding the 'oxygen window' for nitrogen elimination. Raising the pO_2 in venous blood lessens blood sludging (End, 1939), reduces the stickiness of white cells, and reduces the no-reflow phenomenon (Zamboni, 1990), renders red cells more flexible in passing through capillaries (Mathieu, 1984), and tends to counteract the 81% decrease in the deformability and filterability of white cells after exposure to air at 50 fsw (153 kPa) for 4 h, as demonstrated by Pimlott *et al.* (1987).

We can no longer be cavalier about 'minor bends symptoms' or 'simple limb pain'. Gorman *et al.* (1987) have shown that patients suffering from so called 'Type I' DCI with negative neurologic examinations later demonstrated pathologic psychological testing, a 40% incidence of abnormal EEG findings and brain atrophy.

7 Pathologic brain findings in compressed air workers

Using magnetic resonance imaging, we have demonstrated a very high incidence of unidentified bright objects (UBOs), probably representing lacunar infarcts and gliosis in tunnel workers in Milwaukee, Wisconsin (Fueredi *et al.*, 1991). We compared 19 subjects who had been exposed to various degrees of compressed air with 11 age-matched controls who belonged to the same labour union but who had never been

exposed to hyperbaric air. Foci of increased T-2 intensity (UBOs) deep within white matter tracts were evaluated as to their number and location. Psychometric testing was carried out in both groups to exclude pre-existing brain disease. The 19 subjects in the compressed air group had a statistically higher number of white matter lesions (more than 152) than the control group (22 lesions) (p=0.05). Thirty-seven percent of the compressed air group had more than 20 white matter lesions each, while only 18% of the controls had 10 to 11 such lesions each. The experimental group had a five times higher risk than the control group of having high grade lesions and a high statistical correlation was found between the number and severity of lesions in the compressed air group as compared with the control group when linear trend analysis was performed (p=0.02).

We are aware that these findings are at variance with those of Brubakk (1991) and Todnem *et al.* (1991). They found more UBOs in the controls than in the divers, but it must be remembered they were studying divers. We were examining compressed air workers whose decompression histories were considerably more traumatic. Although UBOs are thought to represent lacunar infarcts and possibly gliosis they are normal findings in an ageing population. In our series, however, the compressed air group and the controls were closely matched as to age. Our compressed air workers scored 'lower' on psychological testing than the controls but the difference was extremely slight and was not statistically significant.

8 Conclusions

It is time that we took a long hard look at our present decompression schedules. It must be noted, however, that the Health and Safety Executive in the UK has been against change in the present tunnelling decompression procedures until there is assurance that 'no new risk is added'. In the United States, the Office of Variance Determination of the Occupational Safety and Health Administration has now admitted that oxygen decompression may be feasible. In 1988, Dr Ralph Yodaiken, Director of the Office of Occupational Medicine of OSHA stated in a memorandum to his staff that the present OSHA tables are 'by modern standards flawed' and that 'the OSHA tables have failed any reasonable test of adequate performance over the past 16 years'. He further noted that 'oxygen decompression can be very safe as proven by the German, French and Brazilian experience'. He concluded 'in summary, oxygen decompression is long overdue in caisson work'. Thus, it is obvious that oxygen decompression will be coming into general use.

As the 21st century approaches, it is clear that the construction industry and its regulators must abandon trying to solve high-tech problems using 19th century tradition.

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