REVIEW ARTICLE

Compressed air tunneling and caisson work decompression procedures: development, problems, and solutions

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Kindwall EP. Compressed air tunneling and caisson work decompression procedures: development, problems, and solutions. Undersea Hyper Med 1997; 24(4):337–345.—Multinational experience over many years indicates that all current air decompression schedules for caisson and compressed air tunnel workers are inadequate. All of them, including the Occupational Safety and Health Administration tables, produce dysbaric osteonecrosis. The problem is compounded because decompression sickness (DCS) tends to be underreported. Permanent damage in the form of central nervous system or brain damage may occur in compressed air tunnel workers, as seen on magnetic resonance imaging, in addition to dysbaric osteonecrosis. Oxygen decompression seems to be the only viable method for safely decompressing tunnel workers. Oxygen decompression of tunnel workers has been successfully used in Germany, France, and Brazil. In Germany, only oxygen decompression of compressed air workers is permitted. In our experience, U.S. Navy tables 5 and 6 usually prove adequate to treat DCS in caisson workers despite extremely long exposure times, allowing patients to return to work following treatment for DCS. Tables based on empirical data and not on mathematical formulas seem to be reasonably safe. U.S. Navy Exceptional Exposure Air Decompression tables are compared with caisson tables from the United States and Great Britain.

dysbaric osteonecrosis, oxygen decompression, magnetic resonance imaging, caisson, compressed air, decompression illness/sickness, bends, tunnel, U.S. Navy tables 5 and 6

The number of men engaged in compressed air tunneling and caisson work has steadily diminished as pressure-balanced shields and unmanned excavating systems for caissons have come into use. Except on smaller jobs, where such machinery is not economical, large gangs of men working at pressures over 12 psig (0.86 kg/cm^2) are becoming increasingly rare. Even when automated equipment is used, however, men have to enter the compressed air environment to repair or maintain the equipment in caissons and ahead of the shield, but these exposures are usually for shorter times at higher pressures, similar in many ways to diving exposures.

Historically, surface-supplied diving has generally consisted of relatively short dives, often to greater depths, whereas compressed air work has been confined to pressures less than 50 psig (112 fsw, 3.4 kg/cm^2) for shifts which may range up to 6 or 8 h. For this reason, naval decompression schedules have never been used for compressed air tunnel or caisson workers. The latter have always had their own specialized tables. Decompression sickness (DCS) has always been a problem with compressed air work. However, dysbaric osteonecrosis has been an even greater long-term problem, producing permanent disability. Recently, brain changes manifested by unidentified bright objects as seen on magnetic resonance imaging have been attributed to improper decompression (1).

Historically, caisson tables have lagged behind diving tables in that their originators either had no knowledge of advances made in diving physiology or chose to ignore them. For example, in 1908, Haldane developed rationally derived decompression schedules based on experiment. He introduced stage decompression based on both empirical data and logical reasoning. Nevertheless, in 1922, New York State embodied into law the split shift, which used continuous vs. proven stage decompression, added the trauma of two decompressions per day, and failed to take into account residual nitrogen remaining from the first shift when it came to decompressing for the second time in the same day (2).

For example, using the split shift, a worker might labor for 3 h at 20 psig (1.36 kg/cm^2), decompress in 18 min, and then have a surface interval of 1 h. After this, he would re-enter the tunnel for another 3 h and then decompress, again taking only 18 min (3).

Caisson workers have also had an ingrained tendency to adhere to tradition, whereas divers have had an easier time embracing technologic change. As an example, when Duffner calculated new compressed air tunneling tables for the State of Washington in 1963 (4), he was unable to incorporate stage decompression, but had to go along with the contractors and union, who insisted on continuous decompression, using slower rates as the surface was approached (G. Duffner, personal communication, 1983). Continuous decompression is inefficient and wasteful. For example, if the last stage from 4 psig (0.27 kg/cm^2) to the surface took 1 h, at least half the time is spent at pressures less than 2 psig (0.14 kg/cm^2), which provides less and less meaningful bubble suppression, as Duffner pointed out (4). Historically, continuous decompression evolved from the days when decompression was simply a matter of opening a valve and waiting until the lock pressure equalized with atmospheric pressure. When it was realized that DCS was caused by rapid decompression, the valve was opened fewer turns, and a slower continuous ascent was provided. A further example of tradition at work is the continued use of compressed air to treat DCS in tunnel workers in Great Britain (5,6), when oxygen treatment of DCS was established as the worldwide standard for divers 30 yr ago (7). In the 1996 revision of the *Guide to the Work in Compressed Air Regulations*, O_2 treatment is permitted but left to the discretion of the retained physician (6). The air treatment tables are given and their use described in detail, but O_2 treatment tables are still entirely omitted.

Even more modern attempts at establishing decompression tables for tunnel workers have been based on extrapolations from diving tables and mathematical models thus devised. For the most part, all the air decompression tables now in existence seem to be inadequate. The current British Blackpool tables (8), which represented a quantum jump improvement over the old 1958 British Tunnel Tables (9), still produced DCS in 83% of the workers using the tables during construction of the Hong Kong subway (K.P. Yau, personal communication, 1987). An 8% incidence of aseptic necrosis using these tables was reported during construction of the Dungeness B Power Station cooling water tunnels (10). In the United States, the Occupational Safety and Health Administration (OSHA)-enforced compressed air tunneling tables produced a DCS incidence of 4.85%. Bends occurred in one or more individuals on 42.5% of the working days in Milwaukee when exposures were between 19 and 31 psig (1.29–2.11 kg/cm^2) (11). At pressures greater than 36 psig (2.45 kg/cm^2), they produced a 33% incidence of dysbaric osteonecrosis (12).

Based on my experience, it has been difficult to effect changes in tunneling tables because workers seldom report symptoms of DCS unless they are unbearable or incapacitating. For example, using an anonymous system of reporting symptoms on an 8-ft (2.42 m) finish bore tunnel being driven at a depth of 140 ft (42.4 m) below the surface in 1972, using the OSHA tables, we found that up to 26% of the men on a shift might note symptoms of DCS on any given day, without anyone appearing for treatment (11). On this same project, the official bends incidence, counting only the cases treated, was 1.44%. As noted above, the actual bends rate based on anonymous reporting over a 40-day period was 4.85%. The information anonymously reported was gained by having each worker mark a small piece of paper before going on shift. If he had experienced symptoms of DCS after his previous shift, he would write an "X". If he had been symptom-free, he would write an "O". The only other marking on the paper was the date and shift. He then placed the paper through a slot in a sealed box. From the disparity between the official bends rate and the rate based on anonymous reporting, it is clear that "official" bends rates must be viewed with suspicion.

It became clear to me that the reason for the underreporting is that decompression tables for tunnelers have been so bad for so many years that the pain of decompression-induced bubbles is accepted as being part of the job. More importantly, should a tunnel worker report for decompression treatment too often, he stands a high risk of being removed from compressed air work, and the greater remuneration attendant thereto. During pre-employment physical examinations and informal talks on the job sites, many tunnelers freely admitted to me that they had experienced untreated "air pains" on multiple occasions.

Extremely inadequate tables continue to be used "successfully" from the contractor's point of view, thanks to the phenomenon of "acclimatization" or "habituation" (13–15). After 7–10 days or so of exposure to compressed air, the worker becomes less susceptible to DCS and ceases to experience pain as often. If a hiatus occurs in the project, the acquired resistance is lost in about the same time. A case in point is that when we started a new tunnel project with immediate pressurization to 28 psig (1.90 kg/cm^2) using the OSHA Code, the *treated* bends incidence was 8.6% during the first week. The following week, treated bends fell to a little over 1%. There had been no change in working pressure or other variable introduced. My assessment was that this was due to habituation and not underreporting. Employees with even "normal" susceptibility to DCS tend over time to self-select themselves out of the work force. Habituation makes possible today the continued use of the split shift in Japan (I. Nashimoto, personal communication, 1979), where identical decompressions are used after both shifts with decompression times as little as

15% of what the U.S. Navy schedules call for (11). Nevertheless, regulatory authorities in Japan have failed to adopt more conservative decompressions.

Figure 1 shows a comparison between the OSHA decompression tables for 2- 4- 6- and 8-h exposures, compared to U.S. Navy schedules. To cover the longer caisson exposures, one has to use U.S. Navy Exceptional Exposure Air Decompression tables. The steeper the curve, the safer the table. Thus, the U.S. Navy Exceptional Exposure Air Decompression tables would seem to be safest for tunnel workers, providing longer decompressions over most of their range. It must be pointed out that the final testing of the U.S. Navy Exceptional Exposure Air Decompression tables was done only at a depth of 140 ft (42.7 m) before they were promulgated. Tests were done in a dry chamber with only two to six men in the chamber for each test. On all chamber runs except one, at least one man, and occasionally two or three, suffered DCS (6). Following these tests, the Navy realized that these tables showed a trend for producing DCS between 17 and 33% of the time, and it reserved the tables for emergency use only (16).

Examination of the Blackpool tables shows that they are even less conservative than the OSHA tables, although they do use stage decompression (Fig. 2). From the foregoing, it is apparent that in the United States and Great Britain, contractors routinely decompress their workmen on a daily basis using tables that may be more dangerous than the decompressions the Navy allows only for dire emergencies. With the above facts in mind, it is probable that DCS would be a factor during the performance of an actual tunneling job, and this proved to be the case in Milwaukee.

Milwaukee experience with caisson disease

During the 1960s and early 1970s, the City of Milwaukee constructed a new, ultra-modern tertiary sewage disposal plant. It became necessary to install interceptor sewers from all parts of the city to divert sewage from the inadequate existing treatment facilities to the new plant. Over a period of many years, 80 miles of sewer tunnels were dug, mostly through soft ground. The soil strata in Milwaukee consist largely of glacial till, most of it lying many feet below the local water table. It ranges in consistency from rock, gravel, and clay to fine quicksand lying deep under the city, which is "too thick to swim in and too thin to shovel". The only effective means of mining such material is to use a shield and compressed air. The compressed air forces water out of the sand to the extent that it "stands up" and can be mined. Pressures for mining these tunnels in Milwaukee ranged between 8 and 43 psig (0.54–2.93 kg/cm^2). Thus, it can be seen that all the DCS treated here was from exposures to less than the equivalent of 100 ft (30 m) of sea water. Until 1 August 1970, all the work was accomplished using the split shift.

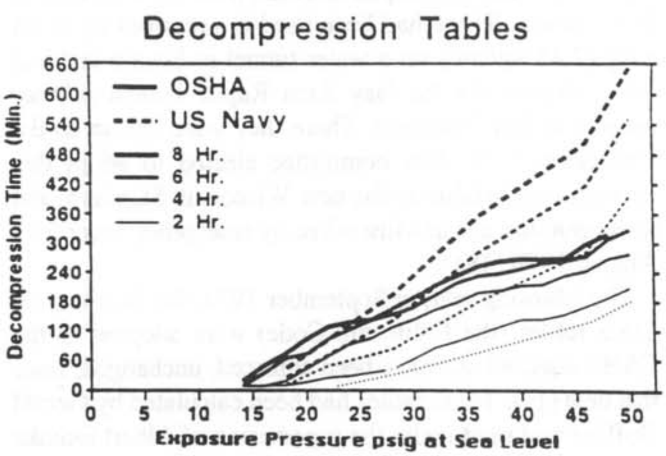

FIG. 1—A comparison between OSHA decompression tables and US Navy schedules. *Dotted* or *solid lines* of increasing thickness indicate increasing exposure times.

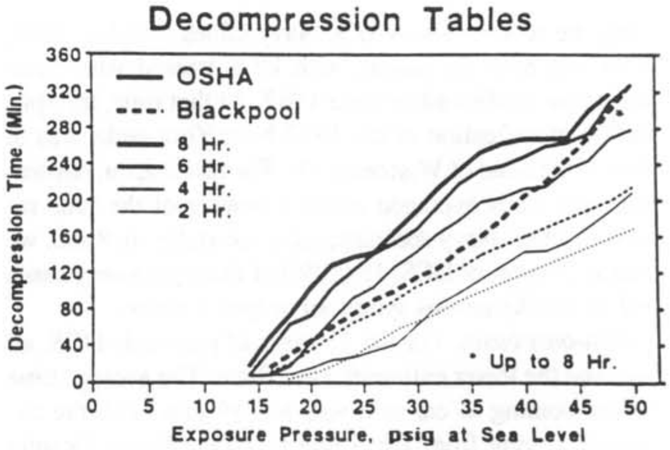

FIG. 2—A comparison between the Backpool tables and the OSHA tables. *Dotted* or *solid lines* of increasing thickness indicate increasing exposure times. (Using the Blackpool tables, any exposures over 4 h have identical decompression times. Thus the decompression for 6 and 8 h are represented by only one line.)

Before my arrival in Milwaukee in 1969, all the cases of DCS had been treated by Dr. Edgar End, the same man who had produced the first truly successful heliox decompression table in 1937. In 1947 he had reasoned that taking a bends patient to 100 ft (3.05 kg/cm^2) and giving him more compressed air to breathe consisted of homeopathy. He felt it would be more efficient to simply compress the patient to 30 psig (67 fsw, 2.04 kg/cm^2) and administer 100% O_2 by mask for 1–2 h. He treated over 200 cases of bends in this manner with excellent results between 1947 and 1968 (E. End, personal communication, 1956, 1968).

Decompression sickness using the split shift

I began treating DCS in Milwaukee in November 1969, using the relatively new U.S. Navy tables 5 and 6. Thus, there has been no patient with DCS treated with compressed air in Milwaukee since 1947. At that time, the split shift, a modification of the 1922 New York code, was in force in the State of Wisconsin (3). For this reason, decompression times averaged about a quarter of the time required by U.S. Navy decompression schedules. In 8 mo. we treated 26 cases of DCS, 15 (58%) of them pain-only cases and 11 (42%) serious symptom or type 2 cases.

Pain-only cases: For the 15 cases of pain-only DCS, all involved the lower extremity save three. The average time before coming to our unit was 8 h 19 min, with the extremes ranging from 1 h 5 min to 20 h 39 min. Despite nearly double the delay to recompression compared to the serious symptom group presented below, 11 of the 15 (73.3%) had complete relief; four patients were left with residual soreness following treatment with tables 5 and 6. The patients were not given more than one treatment. Of those four, three had attempted self-treatment at unknown pressures with air recompression back at the job site. One patient had been treated at Dr. End's facility the previous night with O_2 for DCS in the same knee, and then returned to work with incomplete relief. He reported for treatment only a little over an hour after getting out of the next shift but still had soreness after treatment. One of those patients who had attempted self-treatment before coming to our unit got no relief on arriving at 2. 8 atm abs but achieved dramatic relief when taken to 4 atm abs breathing air. His pain returned upon going back to 2.8 atm abs and was not completely eliminated even with an extended table 6, which followed. Another patient, who had attempted self-treatment with compressed air, waited over 20 h before coming in to our unit. As table 6 proved to be totally inadequate for that patient, he was switched to table 4 breathing 80:20 helium–oxygen by mask instead of air. At 60 ft (2.8 atm abs), treatment was switched from table 4 to an extended table 6. Although nearly completely relieved, he still left the chamber with some residual soreness in one elbow. At the time, I had not heard of anyone shifting from table 4 to table 6 at 60 ft, but I was anxious to try it to avoid tying up our chamber for 38 h and to provide more O_2 treatment to the patient. I also hoped to avoid DCS in the inside tender, which was common on table 4 as used at that time. We thus were able to save 26.5 h of chamber time. The inside tender was also shifted to an extended table 6 at 60 ft and remained asymptomatic following decompression.

Serious symptom cases: Of the serious symptom cases, two were staggers (vestibular DCS), four were chokes (pulmonary DCS), and five had symptoms involving the spinal cord or peripheral nerves. During that time period, tunnel pressures ranged between 20 and 30 psig (1.36–2.04 kg/cm^2). The average time from leaving the lock to starting recompression treatment was 4 h 16 min, with the shortest interval being 39 min and the longest being 8 h. Of the two cases of staggers, the only one to get near relief, which was not complete, reported for treatment 39 min after leaving the lock, but that patient had attempted to treat himself with a brief recompression on compressed air at the job site. In my experience and that of others, if one does not treat vestibular DCS within about 45 min of symptom onset, significant relief while in the chamber cannot be expected.

Four patients had attempted self-treatment with compressed air at the job site, and it should be noted that three of those four failed to get complete relief with treatment on table 6 and had some residual pain. The remaining eight (72.7%) all had complete relief with tables 5 and 6, despite the grossly inadequate split shift decompression schedules followed. Each of the two working shifts per day averaged between 3 and 3.5 h with identical decompression following both shifts. Of note is that all of the serious symptom cases were seen within 8 h. This may account for a good deal of the treatment success. It is not known if any men experienced DCS after the first shift of the day using the split shift. If they did, they immediately treated any symptoms by returning to pressure for the second shift.

Decompression sickness using the OSHA code

Because 35% of the tunnel workers in Milwaukee using the split shift eventually were found to have dysbaric osteonecrosis (17), a new Compressed Air Code Committee was convened by the Wisconsin Department of Industry, Labor, and Human Relations, and I was made its chairman. In 1970 the only decompression schedules in existence for tunnel workers, which had not shown a proclivity to produce aseptic necrosis, were the Washington State tables. These had been used at pressures up to 36 psig (2.45 kg/cm^2) on a water tunnel in Seattle and had been adopted for the Bay Area Rapid Transit subway project in San Francisco. There they were known as the California Code. Our committee elected to adopt this decompression table as the new Wisconsin Standard, and it was put into use in Milwaukee by emergency order on 1 August 1970 (18).

The following year, in September 1971, the Washington State tables (the California Code) were adopted as the OSHA standard and have been enforced, unchanged, since that time (19). These tables had been calculated by Gerald Duffner and used under the supervision of Albert Behnke on the San Francisco Bay Area Rapid Transit project. Using tables associated with such experienced authorities, I expected no further problems with serious DCS. Unfortunately, this proved not to be the case.

Between 1 August 1970 and 8 November 1973, an additional 94 cases of DCS were treated from all the tunneling companies. Based on our anonymous reporting system, we showed a true incidence of 4.85% during a 40-day study period on one contract, during which exposures ranged between 19 and 31 psig (1.29–2.11 kg/cm^2). It is estimated that the treated cases represented less than one third of the actual number of cases that occurred. The official incidence, on the same contract which ran for 51 wk, included only 60 treated cases. This was recorded as 1.44% of 4,168 exposures. Of all the 94 treated cases, 76 (80.9%) were pain-only cases, vs. only 18 (19.1%) type 2 or cases with severe symptoms. Thus it is seen that the split shift had produced proportionately many more type 2 or serious symptom cases than on the single-shift OSHA tables.

Pain-only cases: The average time from leaving the lock and the onset of type I symptoms was 2 h 50 min. The average delay from symptom onset to recompression was 5 h 44 min. Excluding 18 cases (19%) of the 94, where the patient had attempted self-treatment at work or took longer than 10 h to seek treatment, the average delay before all treatment was 3 h 25 min. Eighty-five percent of the pain-only cases involved the lower extremity and 22% had arm or shoulder pain; 7% had both. Table 5 was used 40 times, or for 52.6% of the cases. On eight occasions, table 5 was modified by adding O_2 breathing periods. There were only two instances in which patients completed table 5 with residual soreness. In one case, the patient had experienced pain under pressure coupled with high CO_2 levels in the tunnel and was improperly treated with table 5. Table 6 was used in 36 of the cases, or 47.4% of the patients treated. The overall results for treatment of pain only, using these tables, was excellent, with only 12 patients (15.7%) having residual soreness on completion of treatment. At that time serial treatment was not used for residual pain symptoms alone. Many of these "failures" had mitigating circumstances; two patients had been bent continuously for 2 days and continued to work in the tunnel. Two other cases waited 17 and 18 h each before reporting for treatment, and one case could not be compressed deeper than 30 ft (9 m) because of a total frontal sinus block. One of the patients who was treated with success developed what were considered to be symptoms of oxygen toxicity and was shifted to helium/oxygen between 60 and 30 ft (18–9 m) during decompression. The reason for this is that we wished to continue treatment at pressure in the face of oxygen toxicity without adding nitrogen iatrogenically. A well-inflated blood pressure cuff over the painful area was used in two cases to get rid of residual soreness successfully. Seven patients had attempted self-treatment with compressed air at unknown pressures in the decompression lock at the job site, and they were responsible for three cases that ended up with residual soreness. In any case, self-treatment could never exceed tunnel pressure. The average exposure time in the tunnel for those suffering type I bends was 5 h 41 min. Lack of habituation, i.e., in new starters or workers returning from vacation, was a factor in 16 cases (17%).

Serious symptom cases: The average time from leaving the lock until start of recompression was 8 h 4 min for the type II cases. However, if three outliers who took more than 17 h to appear for treatment are omitted, the average is only 3 h 54 min. The average time from the end of decompression to onset of type II symptoms was 66 minutes. As noted, there were 18 (19.1%) type II cases emanating from the OSHA tables. Of these, 11 had symptoms of spinal cord or peripheral nerve involvement, 4 were chokes, and 2 were staggers. In one case, near unconsciousness or brain DCS appeared when a tunnel worker shorted himself 2 h 3 min on decompression when, without authorization, he rapidly decompressed with no stops following an injury to his hand. The most serious case was a combination of chokes and shock which required the administration of 5.5 liters of fluids including Dextran and plasmanate to keep up with plasma loss. That patient also required a ventilator with positive end expiratory pressure for pulmonary edema, as well as digitalization and massive intensive care. His recompression treatment consisted of a modified table 6 with all its extensions, and the depth maximized to 3 atm (20). Only 5 of the 18 failed to achieve complete relief, the success rate being 72.2%. The usual residual symptom was persistent mild "soreness". All patients save three were treated on table 6. One patient did not tell us about numbness he was experiencing and was inadvertently treated on table 5, but with complete success. The individual with brain DCS who had shorted himself on decompression was treated on table 6A (using an 80:20 heliox mixture) with complete relief. Heliox was used to avoid adding nitrogen to the patient's tissues and to establish a larger gradient for nitrogen gas washout than could be accomplished with nitrox. Another patient with chokes was, for some reason, treated initially on a table 5, but with added O_2 periods at 30 ft (9 m) he achieved complete relief. Nine cases (24%) were pain-under-pressure cases where symptoms appeared before the end of decompression. It is easily appreciated that serious symptoms are usually seen much earlier than pain-only cases. Using the OSHA tables there was no consistent time or depth combination identified that could explain development of type I DCS vs. type II.

No patients treated on tables 5 and 6 were left with serious long-term sequelae, and all of our DCS patients were able to resume full-time heavy manual labor after completion of treatment and discharge from the hospital. I believe that this is related to two factors. First, the exposure pressures never exceeded 100 ft (30 m) of sea water equivalent, and the average time to treatment after leaving the lock was under 9 h. This good success was in spite of very long exposures (4–8 h). *It may be that the pressure at which the nitrogen is delivered to the tissues is more critical than the length of exposure in producing DCS resistant to treatment.* I make this statement because of the remarkable success of low-pressure O_2 treatment, despite the long exposures. In most other large series of DCS cases in divers, where exposure has often been at depths greater than 100 ft, there are usually one or more cases that exhibit permanent disability despite treatment. We fortunately saw no cases that involved permanent work disability.

It was my policy to send patients back to work on the next shift if they had become asymptomatic after chamber treatment. I reasoned that these men had less nitrogen in their tissues after O_2 treatment when they went back to compressed air than their colleagues who had not suffered DCS. If the men had residual soreness or were very tired, I would keep them off work for one or more days. Almost all of the type II cases which were partial treatment failures had only residual soreness with resolution of their serious symptoms.

The average times from leaving the tunnel to the onset of symptoms and arrival at the chamber show that it is rare to have someone come directly from the decompression lock to the recompression chamber. For this reason it does not make sense to insist that the treatment chamber always be at the job site. It is usually better to have it at a central location in the city, preferably at a full service hospital. Central location of the treatment chamber was used with complete success on the San Francisco Bay Area Rapid Transit project and on the Baltimore Metro, as well as in Milwaukee.

It should be noted that there are internal inconsistencies or flaws in the OSHA tables. Note in Fig. 2 that at 26 and 44 psig (1.77 and 2.99 kg/cm^2) 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 (G. Duffner, personal communication, 1979). They are probably due to typographical errors which crept into the transcription of the tables or resulted from a slight displacement of the ruler placed across the mathematically derived nomograms from which the Seattle engineers obtained the decompression times (G. Duffner, personal communication, 1997). Unfortunately, these discrepancies were not detected at the time of their adoption in Wisconsin because the tables were not graphically analyzed until some years later.

Development of new decompression tables

I became increasingly disillusioned with the OSHA tables due to the high DCS rates. When we embarked on a particularly bad section of tunnel, through quicksand 140 ft (42.7 m) below the surface, pressures reached 43 psig (2.93 kg/cm^2). It was discovered 2 yr later that 33% of the men involved in that section had developed dysbaric osteonecrosis (12). It was clear that at pressures over 36 psig (2.45 kg/cm^2), the OSHA tables produced essentially the same amount of dysbaric osteonecrosis as the old split-shift tables (11).

For this reason we sought funds from the National Institute of Occupational Safety and Health to devise safer decompression tables for compressed air workers. This work was carried out at St. Luke's Hospital in Milwaukee. We started this project in 1979, taking 4 yr to complete it. We felt that all previous decompression tables based on mathematical modeling were flawed. In my experience, there is no table in existence that remains as safe or becomes safer as exposure times and pressures increase. The only valid way presently available to construct a decompression table is to use data derived from actual successful dive series in the field. As even naval experience was inadequate to provide decompression data for long-term exposures, I sought the help of Peter Edel in New Orleans, Louisiana. Edel had a computer which had stored data pertaining to 15 yr of successful and unsuccessful commercial dives in the Gulf of Mexico and elsewhere, as well as some of his own experimental data, some altitude experiments, and data obtained from naval sources. These dives included a number of very long exposures. The computer was instructed to draw a line between successful and unsuccessful dives for increasingly higher pressures and longer exposures and then to fill in the gaps using a proprietary neo-Haldanian method with 16 half-time tissues to "connect the dots" and produce smooth curves (21).

A very important consideration in tunnel work is that any decompression schedule must be economically viable. Unlimited decompression time in the name of safety would render the tables unusable in industry. Realizing this, we excluded some extremely long-duration data from the initial calculations. The computer was asked to produce "safe schedules" for periods up to 8 h at pressures up to 50 psig (3.4 kg/cm^2). These tables were labeled Autodec II and were about the same length as the OSHA tables, but they used stage decompression and took deeper stops. It was hoped that these changes would make them usable.

The new Autodec II tables were tested by seven volunteers from local scuba diving clubs. There were six males and one female, and they ranged in age from 26 to 59 yr. This table testing was approved by the St. Luke's Hospital Institutional Review Board for human experimentation. No one was exposed to a decompression schedule shorter than the existing OSHA schedule. Care was taken to space their exposures by 3 days or more to lessen the effects of habituation. Each decompression schedule was tested by them in our chamber after exposure to the longest shift time that could be accommodated in an 8-h working day when the work shift and decompression times were combined. These would be the only schedules used in practice in the field. These schedules would also tend to be the most stressful. While at test pressure, the subjects walked on a treadmill up a 3% grade at a speed of 3 mph for 10 min. Every 10th step, the subject would raise a 5-pound weight held in each hand from a position at his or her side to above the head. Each 10 min of exercise was followed by a 10-min rest. This was an attempt to approximate the workload that a compressed air worker might experience during a normal working day. The subjects sat at rest during decompression. The Autodec II schedules were spot-tested at various pressures up to 34 psig (2.31 kg/cm^2) but were found to produce chokes, DCS in multiple joints in multiple subjects, and in one individual a bone scan showing pathologic activity in the proximal tibia. We then abandoned the testing of Autodec II.

The next generation of schedules computed, Autodec III, used all the data in the computer. The schedules thus produced were prohibitively long, from an economic point of view. As an example, using the OSHA schedule, 4 h work at 44 psig (2.99 kg/cm^2) required 4 h decompression. For the same exposure, the Autodec III schedule required 10 h 46 min decompression. Visual inspection of the new Autodec III tables showed that at pressures greater than 18 psig (1.22 kg/cm^2), commercial compressed air tunneling as we knew it was doomed, because physiology cannot be altered. Decompression times combined with practical working time became too long to be accommodated in an 8-h workday. We had to seek other means of ridding the body of excess nitrogen in a shorter time.

Oxygen decompression

Oxygen decompression has been used by the navies of the world since the 1930s, but [with one exception (22)] was not used in tunneling until 1959(23). The reasons for this were the same ones the U.S. Navy gave for failing to adopt O_2 treatment of DCS. Oxygen was not "sailor-proof" and could cause convulsions, fires, etc. The Navy believed O_2 treatment was both "costly and dangerous" (G. Duffner, personal communication, 1997). The more tradition-bound tunneling world felt the same way. Nevertheless, in 1938–1939, in connection with the construction of the Queens Midtown Tunnel in New York City, Jones et al. (22), working on a project sponsored by the National Institutes of Health and the Bureau of Mines, supervised some 14,000 experimental O_2 decompressions in the men employed on that project. These experiments were done without mishap, despite an O_2 delivery system of poor design, with no overboard dump system. Additionally, the built-in O_2 breathing system had very high breathing resistance. Despite these inadequacies, no fires occurred, and the investigators reported "no serious cases of DCS in those workers who breathed oxygen". In a pilot group of well-trained workers on three shifts of 12 men each, no DCS was experienced using O_2 decompression following 3,884 exposures (22). Oxygen decompression was tried in Japan in 1959, but unfortunately the workers had not been adequately trained, and the contractor did not supply adequate supervision. Moreover, there was no overboard dump system for exhaled gas, which is now considered mandatory. One of the workers apparently lit a cigarette, which resulted in a fire that killed six men undergoing decompression (23). Safety regulators from the United States and England have pointed to that incident as evidence that O_2 cannot be used safely in tunnels. However, despite that accident, O_2 decompression was introduced in Germany in 1972, when the first O_2 tables for regular use by caisson workers were published. Adolf Altner, Chief Safety Engineer, Fachausschuss Tiefbau, Munich, reported that "the rates of DCS decreased remarkably in spite of longer shifts" (A. Altner, personal communication, 1986). In 1974 the French produced O_2 tables (24), and in 1976, Ribeiro (25) used O_2 decompression very successfully in the construction of the São Paulo subway. In 1991, Faesecke developed new O_2 tables for use on the German Kiel Canal tunnels. Using his first set of schedules, he encountered some cases of DCS. When the O_2 breathing periods were lengthened, these problems were eliminated (K. Faesecke, Landesgerwerbeartz State Occupational Health Authority, Kiel, personal communication, 1991). Today in Germany, using decompression tables devised by the German Research Institute for Air and Space Travel (DLR), only O_2 breathing is permitted during decompression of compressed air workers. Air decompression is prohibited by law except in emergencies (26).

Development of the Milwaukee oxygen tables

Oxygen decompression seemed to be the only way of overcoming the impasse dictated by the Autodec III air decompression schedules. We therefore instructed Edel's computer to calculate an O_2 variant of the long Autodec III table (21). As mentioned before, the OSHA table called for 4 h decompression after 4 h work at 44 psig (2.99 kg/cm^2). When intermittent O_2 was breathed, using the new Autodec III O_2 table, decompression time for the identical exposure was now only 3 h 21 min. Most of the other schedules in the table offered similar or greater advantages (21). The formula used in calculating the increased efficiency of O_2 breathing during decompression was proprietary, as were the rest of the computer calculations. However, the resulting shortening in decompression times ranged from 24% to over 70% depending on the exposure times and pressures.

The new O_2 table was tested at the maximum shift length that could be accommodated within an 8-h working time when combined with the required decompression. The schedules were tested with 22 exposures at 2-psig (0.14 kg/cm^2) intervals from 14 psig (0.9 kg/cm^2) up to 46 psig (3.13 kg/cm^2). Three tests were run at 44 psig with different subjects. We did not extend the test to 50 psig (3.4 kg/cm^2), because beyond 46 psig, even the O_2 decompression times exceeded the work shift lengths and would therefore be impractical in use. We did not to want to risk subjects testing tables that would never be used.

Although two subjects had evanescent niggles, no treatable DCS appeared in any of the subjects who tested the Autodec III O_2 decompression tables, and 6 mo. later their bone scans were all negative. Although a few tests at each pressure, even with several subjects, can rule out catastrophic error in the preparation of these tables, it takes hundreds of decompressions in the field to determine what the actual DCS incidence will be. In a sense, these tables had already been "pretested", as they were derived from data based on actual dives that had been made safely. The Milwaukee O_2 tables are the only decompression tables for caisson workers ever tested in a laboratory before promulgation (Fig. 3).

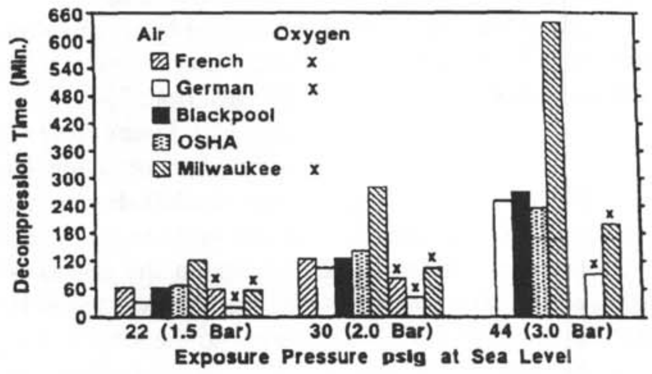

FIG. 3—Total decompression times for 4-h exposures using the French, German, Blackpool, OSHA, and Milwaukee tables. Oxygen decompression tables are depicted with an "X" above the bar; German tables are those in use before 1991.

Regulatory problems

Although so much is known about the incidence of DCS and aseptic necrosis on the existing OSHA tables, they remain in force today. This has largely to do with funding. When the OSHA regulations were first developed in 1971, the mechanism to change them was purposely made difficult and complex as a way to protect the workers from self-serving employers who might wish to lobby for quick changes in an effort to relax rulemaking and reduce expenses. This is a double-edged sword, however. If rules are found to be inadequate or unsafe, there is just as much difficulty in improving them. Anyone wishing a change must first prepare a detailed analysis of the problem and submit it to OSHA. It then goes out for public hearing, which takes more than 90 days. At that point, if sufficient interest is generated, it is sent to a committee of industrial hygienists within OSHA who produce draft regulations. This then must be reviewed by legal counsel and referred back for modification and publishing. All the original regulations and change pathways remain, but the number of persons employed by OSHA has been substantially reduced. There are not enough staff members to manage all the proposed changes, and only those situations with high priority can be addressed. Priority situations involve large numbers of workers who are experiencing significant morbidity and mortality. Because tunnel workers are so few, they have not achieved priority.

Multiple attempts have been made since 1972 to rectify this situation. They have consisted of lobbying efforts by the Carpenter & Joiners Union and the Laborers International Union in Washington DC, letters to congressmen and senators, supporting letters from physicians and physiologists in the diving and hyperbaric field, supporting letters from the Undersea and Hyperbaric Medical Society, direct conferences with the directors and industrial hygienists at OSHA, and publication of the incidence of dysbaric osteonecrosis using the OSHA tables (12). These measures have not been able to effect regulatory change.

This despite a 2 August 1988 internal memo by Ralph Yodaiken, former medical director of OSHA, stating that "the OSHA tables have failed any reasonable test of adequate performance over the past 16 years . . . and oxygen decompression is long overdue in caisson work. The current OSHA tables are outdated and should be replaced in their entirety."

When more funding is approved for OSHA or there are new regulations for proposed rule making, the situation may change. One avenue is to apply for a variance to the regulation, but this involves a great deal of effort on the part of the contractor and must be done with at least 90 days notice. It is easier to use the existing regulations, which are legal and do not expose the employer to any increased liability.

In summary, the Germans, French, and Brazilians have successfully adopted O_2 decompression for tunnel workers with acceptable results. They have had no accidents using it in trained personnel. American O_2 tables are available, but so far they have not come into general use.

Oxygen decompression seems to be the procedure of choice, and it has been shown to provide physiologically safe decompressions for tunnel workers working daily shifts at pressures of greater than 2 atm.

Manuscript received August 1996; accepted July 1997.

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