Health and efficiency in trimix versus air breathing in compressed air workers.

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Van Rees Vellinga TP, Verhoeven AC, Van Dijk FJH, Sterk W. Health and efficiency in trimix versus air breathing in compressed air workers. Undersea Hyperb Med 2006; 33(6):000-000. The Western Scheldt Tunneling Project in the Netherlands provided a unique opportunity to evaluate the effects of trimix usage on the health of compressed air workers and the efficiency of the project.. Data analysis addressed 318 exposures to compressed air at 3.9–4.4 bar gauge and 52 exposures to trimix (25% oxygen, 25% helium, and 50% nitrogen) at 4.6–4.8 bar gauge. Results revealed three incidents of decompression sickness all of which involved the use of compressed air. During exposure to compressed air, the effects of nitrogen narcosis were manifested in operational errors and increased fatigue among the workers. When using trimix, less effort was required for breathing, and mandatory decompression times for stays of a specific duration and maximum depth were considerably shorter. We conclude that it might be rational – for both medical and operational reasons – to use breathing gases with lower nitrogen fractions (e.g., trimix) for deep-caisson work at pressures exceeding 3 bar gauge, although definitive studies are needed.

INTRODUCTION

Work under conditions of over-pressure involves risks to health and safety. Possible dangers include barotraumas, narcotic effects from breathing gases, and decompression sickness (DCS) (1-8). In the last decade, several authors have advocated the use of specific gas mixtures instead of compressed air for depths exceeding thirty meters, in order to limit both health risks and decompression times (5-8). Trimix is comprised of nitrogen, oxygen, and helium. In contrast to compressed air, trimix has proven beneficial in terms of low breathing resistance and relatively mild narcotic characteristics within the pressure range of 4 to 7 bar gauge. The drawbacks of the use of helium (e.g., gas breathing facility, higher costs, and voice distortion), are the technically more complicated.

Between 1998 and 2003 a tunnel was constructed under the Western Scheldt estuary in the Netherlands. This project was unique due to the great depth of tunnel (69 meters), and to the weak and wet subsoil (9). The tunnel consists of two parallel tubes, each with a length of 6.6 kilometers and a diameter of 11.3 meters. The caisson work was carried out using the hydro-shield boring technique. This technique involves checking the groundwater at the cutter-head of the tunnel-boring machine by overpressure in order to carry out monitoring and maintenance work. Instead of the planned switch from compressed air to trimix at 3 bar gauge (405.3 kPa abs), the exclusive use of trimix started at 4.6 bar gauge, as the necessary breathing equipment was not available on time.

We report the results of analysis of data that were compiled during the construction of the Western Scheldt Tunnel to evaluate the effects of the use of trimix instead of compressed air on health and work efficiency in deep-caisson work.

METHODS

Decompression procedures

We compiled extended Dadcodat (Dutch consultants on decompression and hyperbaric physiology) caisson-decompression tables which were custom-made for the use of trimix up to a maximum working pressure of 5.1 bar gauge (10-14). These tables were designed for a bends-incidence rate lower than 0.5%. The first operational use of trimix breathing in compressed-air work took place in Nagoya, Japan in 1995 (12,13). Decompression tables were provided by Dadcodat; they are based on the Netherlands Diving Center's tables, which were calculated using a neo-Haldanian model. Since 1978, these tables have been adjusted regularly, using decompression data from practice (15). Because of the Nagoya experience, the trimix tables for this project were designed to be more conservative. Considering the unfavorable working conditions that are involved in caisson work (e.g. high temperatures and high physical workload) the decompression tables for this type of task should be more conservative (e.g. decompression times should be longer) than diving tables are (1,2,6,9). In addition, oxygen stops can start at 1.5 bar gauge instead of the usual 1.2 bar gauge. To prevent acute oxygen toxicity, the breathing of oxygen in decompression stops is alternated with air breathing (15-20). In the case of impaired oxygen supply, back-up tables are available with air decompression only.

We used a trimix mixture of 25% oxygen, 25% helium, and 50% nitrogen. In view of the safety limits of the various gases in this mixture, it can be used up to a maximum pressure of 5.4 bar gauge (9,10) (i.e., 3.2 bar maximum partial pressure for nitrogen) to avoid nitrogen narcosis [21-24], and 1.6 bar maximum partial pressure for oxygen to avoid acute oxygen toxicity. Maximum oxygen load was set at 400 Oxygen Tolerance Units (OTU; equal to UPTD) per day, within limits of 2,500 per week and 4,500 per fortnight (17-20).

Workers and exposures

During the construction of the Western Scheldt Tunnel, 126 caisson workers and professional divers were subjected to compressed air at pressures ranging from 2.2 to 4.4 bar gauge on a total of 1,103 occasions. 24 professional and certified divers were subsequently exposed to trimix during caisson work at pressures ranging from 4.6 to 4.8 bar gauge, for a total of 52 times. Because compressed air and trimix were used at different depths, thereby making a direct comparison of effects impossible, we chose to analyze 318 deepest air exposures, as they were the most comparable to the trimix exposures in this construction project. We included data from caisson workers who were exposed to pressures ranging from 3.9 to 4.4 bar gauge. The characteristics displayed by these men are shown in Table 1 (see pgs. 4 and 5 for all graphics).

The total physical workload depends partly on the compressed air work related parameters (the depth, dive-time and decompression time) and partly on the physical workload of the work itself. The characteristics of these caisson-work parameters are displayed in Table 2.

Health effects

Because of the unique nature of this work, regulations required the continuous presence of a diving physician on site. So the physical and psychological symptoms in the caisson workers during the entire Western Scheldt Tunneling Project were monitored routinely. All adverse events (e.g., industrial accidents, barotraumas, nitrogen narcosis, and DCS) were documented. The harmful effects that high pressure and pressure changes caused on the health of the caisson workers can be explained in terms of partial gas pressure or changes therein.

The harmful effects that high pressure and pressure changes caused on the health of the caisson workers can be explained in terms of partial gas pressure or changes therein. Nonetheless, the susceptibility to nitrogen narcosis varies among individuals and over time. At depths exceeding thirty meters, the use of compressed air is associated with symptoms such as euphoria, exaggerated self-assurance, and poor concentration (21-24). Among the caisson workers in the Western Scheldt Tunneling project, these symptoms manifested themselves as mistakes in the execution of their work, as noted by their supervisors in the data logs.

The risk of DCS is determined by partial gas pressures, exposure times, and decompression procedures; it is probably affected by physical workload as well. For this reason, two diving physicians independently assessed the physical workload registered during all exposures. This information was recorded in the diving company's task forms and working log (Schichtprotocol Vortrieb Kombination Middelplaat Western Scheldt, August 1999–February 2002) and in the log from the Occupational Health Service Organization that was involved. The category of light physical work included such activities such as conducting inspections and welding activities, as well as cleaning cutter teeth, bearings, and workplaces. Heavy physical work involved such tasks as replacing cutter teeth, and diving in bentonite (i.e., sludgy material at the boring front). Differences of opinion about the categorization of activity were resolved through discussion.

Efficiency effects

The gas mixture that is used and the working depth determine the partial gas pressures. Using these data and the exposure time, the prescribed decompression time can be read from the caisson-work decompression tables. Because no relevant work is performed during decompression, longer decompression times decrease working efficiency. Working efficiency may be expressed as economic diving time (EDT), which is calculated by dividing, working time by the sum of working time and decompression time (25). Decompression without any stops results in an EDT of 1. Low EDT values indicate low efficiency in the ratio of working time to decompression time.

Table decompression times for compressed air and trimix (25% oxygen, 25% helium, 50% nitrogen), were derived from Dadcodat caisson decompression tables for a fixed maximum working time of 75 minutes, at maximum pressures ranging from 3.3 to 5.1 bar gauge.

Statistics

To evaluate the reliability of the tables (i.e., BIR < 0.5%), we used the open sequential design of Homer and Weathersby (27). We selected a bends incidence $p0$ of 0.5% that is not rejected more than $\alpha = 0.025$ portion of the time, and an incidence $p1$ of 5.0% that is not to be accepted more than $\beta = 0.025$ portion of the time. The results are plotted graphically. The number of DCS cases is plotted against the number of dives, sequenced over time. The area of rejection or acceptance is then marked by an upper and a lower straight line respectively, depending on the selection criteria.

To compare the efficiency (EDT) of compressed air and trimix we used a two sample T-test assuming unequal variances in the EDT values for compressed air and trimix. We also calculated the table decompression times and the EDT of caisson-work decompression tables after a maximum working time of 75 minutes and pressures ranging from 3.0 to 5.1 bar gauge.

The EDT values for the use of compressed air and trimix were calculated. To support our results, we conducted a paired T-test to assess any differences in the decompression time and EDT values for compressed air and trimix.

Table 1. Physical characteristics of 45 caisson workers exposed to compressed air at 3.9 and 4.4 bar gauge, and 24 caisson workers exposed to trimix breathing in caisson work at pressures between 4.6 to 4.8 bar gauge.

	Compressed air work n = 45			Trimix n = 24		
	mean	min	max	mean	min	max
Age (years)	34	22	51	32	23	44
Height (m)*	1.81	1.71	2.00	1.82	1.71	2.00
Weight (kg)*	82	63	102	81	63	102
BMI (kg/m2)*	25	20	32	25	20	30
VO_{2max} (ml/kg/min)*	40	31	67	40	31	56

Note: BMI = body mass index. VO_{2max} = estimated maximal oxygen uptake
(*) Data were missing for 12 of the 45 compressed-air workers.

Table 2. Characteristics of caisson-work parameters. 45 caisson workers underwent 318 exposures with compressed air. 24 caisson workers underwent 52 exposures with trimix. Physical workloads under compressed air and trimix conditions were described by the diving medical officers and supervisors after the exposures.

	Compressed air n = 318			Trimix n = 52		
	mean	min	max	mean	min	max
Depth (m)	41	39	44	47	46	48
Dive time (min)	63	4	105	60	46	77
Deco time (min)	102	0	164	116	97	149
Physical Workload						
% light	11.0			42.3		
% moderate	15.7			57.7		
% heavy	34.3					
% very heavy	39.0					

Table 3. Imperative decompression times after maximum of 75 minutes of caisson work with air and trimix breathing, respectively, at various maximum pressures.
N.B.: Decompression times include stops and minimum times needed to ascend – at 1 bar per minute.
EDT max: theoretical maximal economic dive time (i.e., working time divided by the sum of working time and decompression time).

	air		**trimix***	
max. pressure (bar G)	deco time (min)	EDT max.	deco time (min)	EDT max.
3.3	70	.51	64	.54
3.6	80	.48	74	.50
3.9	91	.45	84	.47
4.2	105	.42	98	.43
4.5	126	.37	108	.41
4.8	149	.34	126	.37
5.1	167	.31	139	.35

* trimix mixture: 25% oxygen, 25% helium, and 50% nitrogen.

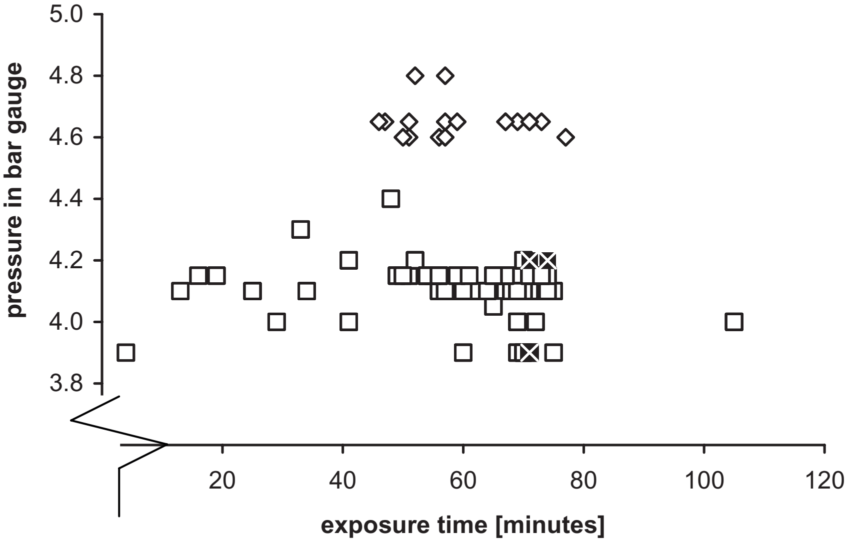

Fig. 1. 318 exposures to caisson work with air breathing and 52 exposures with trimix breathing. Three cases of decompression sickness occurred after caisson work with air breathing.

◇ = trimix

□ = compressed air

■ = decompression sickness after exposure to compressed air exposure

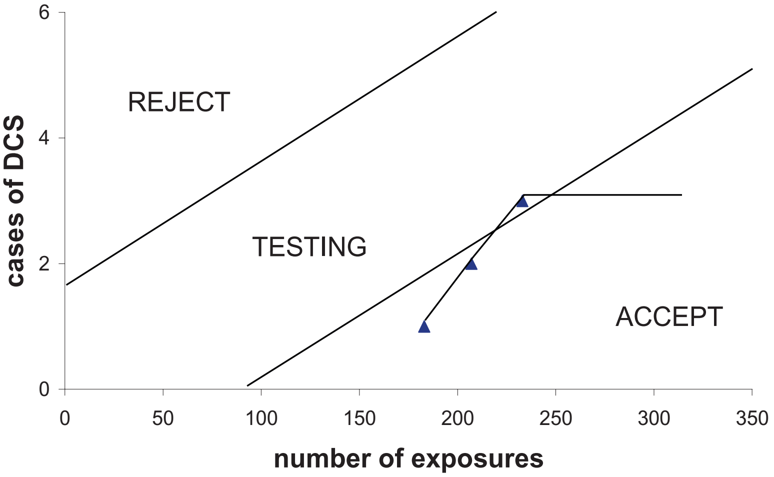

Fig. 2. Open sequential selection rule applied to 307 exposures on 4.2 bar (G)/75-minute schedule for a bends-incidence rate lower than 0.5%.

RESULTS

Health effects

After 318 exposures to compressed air with maximum pressures of 3.9 to 4.4 bar gauge, three cases of DCS were assessed. Symptoms of DCS included progressive aching of the knee, in one case combined with erythema on the chest. All three cases occurred after heavy work, with an applied table time of 75 minutes, and a table depth of 4.2 bar gauge (Figure 1). Following treatment with 100% oxygen according to the standard tables (Comex 12, USN Tables 5 and 6, respectively) the symptoms disappeared without causing any long-term somatic or cognitive defects. Thirty of the forty-five caisson workers (67%) complained of fatigue and difficulty breathing during exposure to compressed air. Supervisors and diving physicians observed concentration and memory problems. In all cases, the oxygen load remained under the previously set maximum of 400 OTU per day (mean: 254 OTU, min–max 3–386).

No DCS or other negative health effects were observed in any of the 52 trimix exposures, which occurred at pressures ranging from 4.6 to 4.8 bar gauge. The mean oxygen dose in this group was 308 OTU (min–max 258–394).

The results of the statistical open sequential design (27) were the intercept of the lower line ($h0 = -1.56$), intercept of the top line ($h1 = 1.56$), and the slope given by $s = 0.019$. The results are displayed in Figure 2. Following this procedure, there was no reason to reject the compressed-air schedule. Had we applied this rule to the 52 uneventful trimix exposures, we would still have been within the testing range.

Efficiency effects

In 318 exposures to compressed air, the mean working time was 63 minutes (min–max 4–105); in 73.1% of the cases work was graded as heavy physical work. The mean decompression time was 102 minutes (min–max 0–164), and EDT values ranged from 0.26 to 1, with a mean of 0.38. As pressure increased rapidly due to the steep first part of the tunnel, the EDT declined significantly. For the deepest air exposure with heavy physical work, four dives were made to 4.4 bar gauge, with a median working time of 33 minutes and EDT values of 0.26. In 52 trimix exposures, the mean working time was 60 minutes (min–max 46–77). None of these cases was graded as heavy physical work. The mean decompression time was 116 minutes (min–max 97–149), and EDT values ranged from 0.27 to 0.37, with a mean of 0.34.

The two-sample T-test assuming unequal variances of EDT values for compressed air and trimix shows a significant difference in EDT, ($p< 0.0001$).

Observation of the workers by diving physicians and supervisors revealed a decreased working pace and efficiency during deeper caisson work, in particularly for cases that involved the use of compressed air. On one occasion, six teeth were removed from the cutter head and reinstalled instead of being replaced by new ones, with none any of the four gang workers noticing this mistake. On other occasions, tools were left behind in the workroom, or dropped in the bentonite, in contravention of the working instructions. Abandoned tools could seriously damage the stone crusher of the tunnel boring machine.

Table 3 describes the table decompression time and the EDT values for the use of compressed air and trimix respectively, after a maximum working time of 75 minutes and pressures ranging from 3.0 to 5.1 bar gauge. Notably, the trimix mixture used here contains 25% oxygen, whereas compressed air holds 21% oxygen. A paired T-test revealed a significant difference in decompression time and EDT for compressed air and trimix, with p values of 0.0085 and 0.0009, respectively.

DISCUSSION

We observed relatively few harmful health effects in a group of caisson workers in the Western Scheldt Tunneling Project. Because of unfavorable working conditions (e.g., high physical workload and high temperatures), the decompression tables for caisson work should be more conservative than tables for diving. The use of compressed air would always introduce some unavoidable risks to safety and health. In addition to exposure time and depth, carrying out heavy physical work is a complicating factor. After 318 exposures to air at pressures over 3.9 bar gauge, three cases of DCS with relatively mild symptoms of aching of joints (bends) were observed. All cases occurred after heavy physical work, with decompression-table values of 4.2 bar and 75 minutes. The compressed-air decompression tables that were used were developed for a bends incidents rate lower than 0.5%. Analysis according the open sequential design of Homer and Weathersby (27) indicated that there was no reason to reject the compressed-air schedule (Figure 2), as the incident rate in the depth-time profile was lower than the threshold value of 0.5% above which adjustment of the decompression tables becomes mandatory (28,29). Heavy physical work in deep caisson work had no unacceptable effects on the health and safety of the compressed-air decompression procedure.

No DCS cases occurred in situations that involved the use of trimix, after a total of 52 exposures with pressures equal to or over 4.6 bar gauge. Other studies (e.g., the study of caisson work for the construction of Piers 1 and 2 of the Hannan Bridge in Japan) have reported similar data (26). The Hannan Bridge project used the same decompression tables that were used in the Western Scheldt Tunneling Project. Although the work-loads in the Japanese project were very heavy, no DCS was reported, thus supporting our optimism.

The relatively low density of trimix makes it less tiring to breathe at greater depths. This is an advantage, especially in heavy work. The use of special breathing equipment (helmet with integrated mask) posed no problems among the group of experienced and certified professional divers. To determine the reliability of the trimix decompression table we applied the 52 uneventful trimix exposures to the open sequential design [27], as shown in Figure 2. The results remained within the testing range, implying that we can accept the table after only eighty uneventful exposures (i.e., exposures in which the acceptance line leaves the 0 cases axis). Because rejection of the table requires more than two cases of DCS, if the second case occurs before the fifteenth exposure (Figure 2), we presume that future data can support our optimism.

CONCLUSION

In conclusion, the Dadcodat decompression table design parameters are apparently reliable, although further testing is needed.In the practical example addressed in this study, exposures to oxygen during decompression always remained within generally accepted limits (16-20). The use of trimix seems to have no obvious advantages in this respect. With regard to the consequences of nitrogen narcosis, however, the picture is different because this effect of nitrogen is a risk to safety as shown by a decreased ability to assess, and by lapses in concentration and coordination. This risk gradually increases with working depth and should be limited as much as possible (21-24). Manifestations of nitrogen narcosis also had an adverse effect on the working efficiency. The use of compressed air was associated with a slower working pace, an increased need for recuperation, and a number of costly operational errors. Although difficult to quantify, we consider these phenomena as relevant adverse economic effects.

Insight into the possible economic profitability of trimix use in practice is offered by the EDT values that were determined within the Western Scheldt Tunnel Project. Despite the late switch from compressed air to trimix at depths of over 45 meters and anticipated unfavorable (i.e., lower) EDT values, these values were ultimately comparable to those associated with use of compressed air at lesser depths. The table-decompression times that were calculated from caisson-work decompression tables indicate that the extra operational costs related to trimix use may be offset by shorter decompression times at depths of 30 meters or more.

In practice, the maximal possible EDT was not obtained. Table times that were longer than the actual required work time were often chosen for both compressed air and trimix. We can only guess as to the reasons for this. Extra risk control of DCS could have been an important factor. Furthermore as workers were paid for each minute under pressure, financial considerations could also have played a role.

Examples from Japanese practice indicate a better management of health and safety risks through the use of trimix instead of air, in deep caisson work projects (11-13). As in the Japanese projects, the workers in our project reported easier breathing and fewer signs of nitrogen narcosis with trimix than they experienced with compressed air. Our data support the use of breathing-gas mixtures of low nitrogen partial pressure to reduce the signs of nitrogen narcosis. Whether the risks of DCS are also lower requires additional data from compressed-air workers. The basic precept to switch between mixtures at pressures no higher than between 3 and 4 bar gauge seems to be supported by our data if we take the question of work efficiency into account.

We conclude that it may be recommended for both medical and for operational reasons, to utilize breathing gases with lower nitrogen fractions (e.g., trimix) for caisson work at depths exceeding approximately 30 meters. More evaluation studies are, however, needed.

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