Doppler ultrasound surveillance in deep tunneling compressed-air work with Trimix breathing: Bounce dive technique compared to saturation-excursion technique.

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Van Rees Vellinga TP, Sterk W, De Boer AGEM, Van Der Beek AJ, Verhoeven AC, Van Dijk FJH. Doppler ultrasound surveillance in deep tunneling compressed-air work with Trimix breathing: Bounce dive technique compared to saturation-excursion technique. Undersea Hyperb Med 2008; 35(6):000-000.The Western Scheldt Tunneling Project in the Netherlands provided a unique opportunity to evaluate two deep-diving techniques with Doppler ultrasound surveillance. Divers used the bounce diving techniques for repair and maintenance of the TBM. The tunnel boring machine jammed at its deepest depth. As a result the work time was not sufficient. The saturation diving technique was developed and permitted longer work time at great depth. Thirty-one divers were involved in this project. Twenty-three divers were examined using Doppler ultrasound. Data analysis addressed 52 exposures to Trimix at 4.6-4.8 bar gauge using the bounce technique and 354 exposures to Trimix at 4.0-6.9 bar gauge on saturation excursions. No decompression incidents occurred with either technique during the described phase of the project. Doppler ultrasound revealed that the bubble loads assessed in both techniques were generally low. We find out, that despite longer working hours, shorter decompression times and larger physical workloads, the saturation-excursion technique was associated with significant lower bubble grades than in the bounce technique using Doppler Ultrasound. We conclude that the saturation-excursion technique with Trimix is a good option for deep and long exposures in caisson work. The Doppler technique proved valuable, and it should be incorporated in future compressed-air work.

INTRODUCTION

Working in a tunnel-boring machine (TBM) in a dry and pressurized environment implies significant health hazards, including barotrauma and decompression sickness (DCS) (1-3). Compressed-air exposure during tunnel work is different from that experienced during diving. The work is characterized primarily by high physical workloads and long shifts. Compressed-air work in a TBM involves elevated pressures in a warm and dry environment. The thermal conditions within the caisson were not caused by the thermal offset following pressure changes. The heat was generated in the hydraulic system of the tunnel boring machine. This heat production was so intense that the temperature of the compressed air in the caisson rose towards 28 degrees Celsius.

During decompression, there is a large drop in temperature, due to the expansion of compressed gases. This causes vasoconstriction and obstruction of inert gas elimination (4). Balldin and colleagues demonstrate that 30% less nitrogen is eliminated with decompression in a dry environment than is eliminated during decompression while immersed (5). Compressed-air work with pressures over 3.5 bar (g) in a dry environment enhances the uptake of inert gas even more due to the high temperature conditions in the work chamber (6). During decompression, gas bubbles form in the tissues and blood due to the super-saturation of dissolved inert gas (6). During decompression, bubbles are present in varying quantities. Large quantities of bubbles are believed to be harmful to the body and are generally considered the initiating factor for DCS (6-9). The risk of developing DCS is correlated with bubble grades (10-12).

From 1998 to 2003, a tunnel was constructed under the Western Scheldt estuary in the Netherlands at great depths, some as deep as 69 meters. Maintenance work had to be carried out in the cutter-head areas using both the Trimix bounce and saturation-excursion techniques. The use of Trimix instead of air might have an extenuating effect on the quantity of bubbles and the development of DCS (13,14). Nishi reports that the risk of DCS in a group of divers with Grade 2 or Grade 3 bubbles post-decompression appears to be smaller with heliox (a mixed gas of helium and oxygen) than it is with compressed air (15,16). In Trimix, helium is added to the compressed air, so that the partial pressure of nitrogen is lower than it is with compressed air. This reduces the effects of nitrogen narcosis (14).

Doppler ultrasound can detect intravascular gas bubbles occurring in the venous circulation after decompression (13,17). The use of Doppler monitoring may provide data about effects of exposure earlier in the cause-effect chain than simply observing the incidence of DCS. The principle of inert-gas bubble detection with Doppler ultrasound is the scatter of ultrasonic waves that induces shifts in frequency and amplitude. A number of factors complicate decompression evaluation with Doppler bubble detection. Bubble occurrence varies widely across individuals and over time (18). Fatigue, obesity, higher age, low fitness, and dehydration are thought to play a role (19,20). To support a common basis for the surveillance of health and safety of compressed-air workers, Nishi recommends standardizing Doppler procedures for dives, monitoring divers, analyzing data, and reporting results (21).

The aim of this study is to evaluate the effects on health and safety of two compression-decompression procedures, i.e. the Trimix bounce technique and the Trimix saturation-excursion technique, by comparing data on bubble grades measured by Doppler ultrasound (assessed one and two hours after decompression). As there is some evidence that body mass index (BMI), age, and high physical workload are correlated with bubble grade (21), we study these relationships as well.

METHODS

Setting

The Western Scheldt tunnel project was unique because of its great depth, in some places up to 69 meters, and because of the weak, wet subsoil (22,23). The tunnel consists of two parallel tubes, each with a length of 6.6 kilometers and a diameter of 11.3 meters. The project was carried out using the hydro-shield boring technique, with groundwater reduction by overpressure in the cutter-head area, where maintenance work had to be carried out. In the Trimix bounce technique (with pressures over 4.4 bar (g)), short working times and long decompression times prevailed (23). Maximal decompression time was set at two hours, because the small decompression chamber imposed an uncomfortable, flexed sitting position. In the deepest parts of the tunnel (with a depth of 6.9 bar (g)), technical problems due to the wear and tear of the tunnel-boring machine necessitated extended working times. These problems gave reason to alter the compression-decompression procedures. The saturation-excursion technique which allows the possibility of an increased working time was introduced (24,25,26). In this project, seven saturation runs were carried out, each with two teams of three divers. The average saturation duration was two weeks, including decompression time. All work and the decompression procedures were carried out under close medical supervision. The medical supervisor documented occupational conditions, any adverse events, and the physical workload ratings along a four-point ordinal scale (light, average, heavy, or very heavy).

Subjects

Thirty-one compressed air workers were involved in the construction of the deeper part of the tunnel (over 44 meters deep). Working divers must have a medical certificate approved by the Dutch Ministry of Social Affairs. The requirements for fitness to dive are stated in the Dutch Social law and meet the European standards. The dive medical assessment comprises a physical fitness test with a minimum aerobic capacity (VO2max of 40ml/kg/min). Seventeen divers had their assessment in our laboratory before the project started. Six divers had a British Health and Safety Executive (HSE) certificate, they were examined elsewhere. On request the medical information was send to us by the foreign diving physicians. Twenty-three compressed air workers were examined using Doppler ultrasound. There was no deliberate selection of subjects for the procedure. There was also no selection according to work-related health complaints and no selection according to determination on body physical characteristics (e.g., body weight). The physical characteristics of the twenty-three compressed air workers are shown in Table I, (see page xxx).

Procedure

Bounce-dive technique: To perform inspection and maintenance tasks, compressed-air workers entered the lock in front of the tunnel-boring machine, where they were pressurized up to working chamber pressure. Trimix breathing was used during the periods of high pressure. Staged decompression was performed using air and oxygen. We tried to minimize the chance of nitrogen narcosis as well as uneconomical decompression times (23). New caisson decompression tables were developed for Trimix breathing. Decompression tables for caisson work must be more conservative than tables for conventional diving work. Remarkably they include oxygen stops starting at 1.5 bar instead of the usual 1.2 bar (g). Breathing oxygen at the decompression stops for twenty minutes, was alternated with air breaks for five minutes. The maximum oxygen load was set at 400 Oxygen Tolerance Units per day, 2,500 per week, and 4,500 per fortnight (23,24,25,27). Fifty-two man-exposures were performed with the bounce-dive technique using Trimix. The bounce dives were made in the range of 46 to 48 meters.

Saturation-excursion technique: With the saturation technique, caisson workers lived in a habitat with a team of six for at least a fortnight. Inside the habitat at 4.0 bar (g) (in one instance 3.7 bar (g)), workers breathed a Trimix mixture of 9% oxygen, 18% helium, and 73% nitrogen. They commuted to the worksite three at a time inside a decompression chamber (shuttle) mounted on a train (transport under pressure; TUP). It took the shuttle approximately one hour to arrive at the TBM. During TUP transport to the front of the TBM, the gas mixture inside was the same as in the habitat. The transfer depth was maintained at 4.0 bar (g), except for once, when a transfer depth of 3.7 bar (g) was chosen. When the shuttle arrived at the TBM , the divers entered the TBM-lock. The divers took on special helmets for Trimix breathing. The lock was pressurized to the working pressure with compressed air. The compression time to the working pressure was approximately two minutes. Most working shifts lasted four hours, not including commuting time. During excursions, workers breathed 12% oxygen, 40% helium, and 48% nitrogen; for bottom pressures over 6.6 bar (g), the mixture was 12% oxygen, 43% helium, and 45% nitrogen. The decompression with Trimix-excursion mix started in the lock of the TBM with a maximum speed of 1 bar/minute. After passing 6 bar (g), the workers were switched to air breathing and were transferred to the shuttle also pressurized with air. Further decompression to saturation storage depth was done in the shuttle during travel to the habitat. During the different phases of the transport process the variations in nitrogen partial pressure were kept minimal. The largest variations were made in the oxygen and helium partial pressures. The transport process between the saturation habitat and the working chamber in the TBM is expressed in Figure 1. The partial pressures are expressed as fractions of the absolute pressure.

Measurements

For health and safety reasons, the diving contractors and the occupational health service involved arranged a Doppler ultrasound survey. Scheduled assessments met medical standards as well as operational demands; enrollments were limited by the restricted availability of

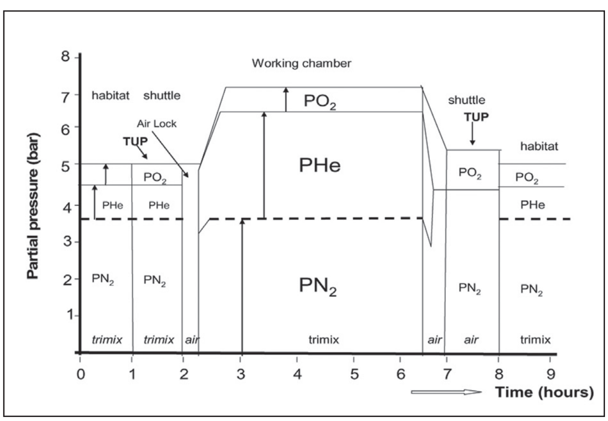

Fig. 1. On the X-axis the sequence of events are shown during the transport process (shuttle) between the saturation habitat and the working chamber in the tunnel boring machine. The partial pressures are expressed as fractions of the absolute pressure. TUP = transport under pressure.

the Doppler technician. Doppler ultrasound assessments were performed approximately one and two hours after completed decompression, in twenty-three of these thirty-one subjects.

Recordings were made according to the Canadian Defence and Civil Institute of Environmental Medicine (DCIEM) protocol with a continuous-wave Doppler DBM9008 array probe of 2.5 MHz (Techno Scientific, Toronto) (13,17). An Aiwa F5 mini-disc recorder was used to record the Doppler signals for later analysis. One Doppler technician was available, who was trained at DCIEM, Toronto. Recordings were made according to the DCIEM protocol. First a one minute precordial recording was made with the subject standing at rest. Thereafter, recordings were made during approximately fifteen cardiac cycles immediately after one deep knee bend (flex).

As soon as heart frequency returned to resting conditions, this procedure was repeated another two times. This was followed by recordings over the subclavian veins, for 30 seconds at rest and 3 times after fist clenching (squeeze) for about 10 seconds (13). A complete recording took about 5 minutes in total. Due to operational circumstances, measurements over the subclavian veins were not systematically recorded, and they are not discussed in this paper.

For recordings inside the saturation chamber, the subjects were trained in proper positioning of the Doppler probe and supervised by the Doppler technician outside the chamber, who also made the sound recordings.

Measurements were performed approximately one and 2 hours after completed decompression, with a spread of 10 minutes before until 10 minutes after the hour, due to the availability of only one Doppler technician.

Defence Research & Development Canada (DRDC) Toronto developed a practical, efficient method for evaluation of Doppler raters, to establish a high standard for grading Doppler signals (14). The Doppler technicians of DRDC, who graded our signals, are characterized as skilled experienced raters, who have a recent and frequent practice in Doppler grading. They rated all available sound recordings according to the Kisman-Masurel code (KM) (13,14).

The Kisman-Masurel method separates the bubble signal into three components. First: bubbles per cardiac cycle, frequency. Second: percentage of cardiac cycles with bubbles for diver standing at rest, or duration of bubbles (number of cardiac cycles with elevated bubble sounds after a specific movement. Third: the amplitude of bubble sounds compared to blood flow and cardiac sounds. Each component is graded on a scale from 0 to 4, forming a three-digit number known as the KM code (13). This three-digit number is then reduced to a single bubble grade from 0 to IV. These grades are further subdivided to give a greater gradation of values.

The bubble grades were transformed into grades according to the Spencer code from Grade 0, the lowest qualification, to Grade 4, the highest qualification (13). The recordings were generally of good quality, but inside the saturation chamber sometimes with electrical interference from other sources. Nevertheless, also these recordings were considered sufficient for grading.

Statistical analysis

Two-sided T-tests were used to analyze differences among divers in terms of age, height, weight, BMI, and VO2 max in the bounce and saturation techniques. Two-sided T-tests were also used to analyze differences in mean diving depth, dive time, and decompression time in both diving techniques.

We used non-parametric methods to analyze the Doppler data, as the data had been collected along a five-point scale. Mann-Whitney U tests were performed to compare bubble grades measured one and two hours after decompression, in both the bounce-dive technique and saturation-excursion technique. In both the techniques, we analyzed the differences in bubble grades measured after one and two hours using the Wilcoxon signed rank test. To study the relationship between bubbles and BMI, age, and high physical workload, we examined Spearman correlations between Doppler grades and the three selected parameters, separately for the measurements after one hour. The data were analyzed with SPSS 13.0.

RESULTS

In total, 52 dives were made by 15 divers using the bounce technique, and 354 saturation excursions were made by 16 divers from the habitat in a depth range between 40 and 69 meters. The personal characteristics of the compressed air workers are described in Table 1.

No differences in age, height, weight, BMI, or VO2 max were found between the

	Bounce technique with Doppler n=15 workers				Saturation Excursions with Doppler n = 16 workers			
	mean	SD	min	max	mean	SD	min	max
Age (yr)	30	5,8	23	40	33	6,2	23	44
Body Height (cm)	182	6,6	171	200	182	4,1	172	191
Weight (Kg)	83	11,4	63	102	83	11,7	63	108
BMI (Kg/m^2)	25	2,8	20	30	25	2,8	20	30
VO_2max (ml/Kg/min)	40	5,3	32	56	40	5,6	31	56

Table 1. Characteristics of twenty three compressed air workers, examined by Doppler ultrasound in two compression-decompression techniques. Eight individual workers participated in both conditions, seven only in the bounce technique and eight only in the saturation technique.

divers in the bounce-technique group and those in the saturation-technique group. We observed no cases of DCS with either technique during the described phase of the construction of the Western Scheldt Tunnel. The two groups differed according to working depth, dive time, and decompression time. The bounce dives were made in the range of 46 to 48 meters. The mean dive time in the bounce technique was 60 minutes, with a mean decompression time of 116 minutes (Table 2). The physical workload in the bounce technique was qualified as average in all cases. The saturation excursions were made in a depth range between 40 and 69 meters. The mean dive time was 210 minutes with a mean decompression time of 59 minutes (Table 2). The workload in the saturation excursions was qualified as heavy. We found a significant difference between the depth, dive-time and deco-time of the two techniques (Table 2). The results were measured in different individuals.

Registrations during the bounce-dive technique

The results of precordial Doppler registrations after bounce-dive exposure are presented in Figure 2. The number of Doppler assessments was restricted by the availability of only one Doppler technician. We detected no bubbles in 21 of 30 precordial Doppler measurements one hour after decompression. We recorded one Grade 1 and one Grade 2 score. Grade 3 scores were recorded five times, and Grade 4 scores were recorded twice. Although the divers were scheduled for Doppler assessment, operational circumstances and the availability of only one Doppler technician permitted recording only fourteen precordial Doppler registrations two hours after decompression. In 9 out of 14 registrations, we observed no bubbles. No Grade 1 scores were observed. We registered two Grade 2 scores and three Grade 3 scores. No Grade 4 scores were observed (Figure 2).

We analyzed the results of fourteen Doppler measurements taken one and two hours after the bounce-technique dives in the same worker-dive combination, using the Wilcoxon signed ranks test. We found no difference in the results after one and two hours ($p=0.58$). In 10 of the 14 cases, we found equal amounts of bubbles in the two measurement points. In two cases, we found a smaller number of bubbles after two hours, in another two a larger number of bubbles after two hours.

Saturation excursions

One hour after the saturation excursions, low bubble counts were found. In the precordial registrations, we recorded no bubbles in 222 of the 236 registrations. Grade 2 scores were found on fourteen registrations. No Grade 1, Grade 3 or Grade 4 scores were observed (Figure 3). Two hours after decompression, no bubbles were detected in 117 precordial Doppler registrations. We examined the results

Table 2. Characteristics of the caisson-work parameters

This table shows the dive time for the bounce technique from 0 to max. 48 meters and for the saturation excursions from 40 to max. 69 meters.

	Bounce technique				Saturation excursions				
	n=52dives				n=354 dives				
	mean	SD	min	max	mean	SD	min	max	p-value
Depth (m)	47	0.1	46	48	61	0.4	40	69	p<0.001
Dive-time (min)	60	9.5	46	77	210	31.7	61	246	p<0.001
Deco-time (min)	116	16.2	97	149	59	20.5	13	124	p<0.001

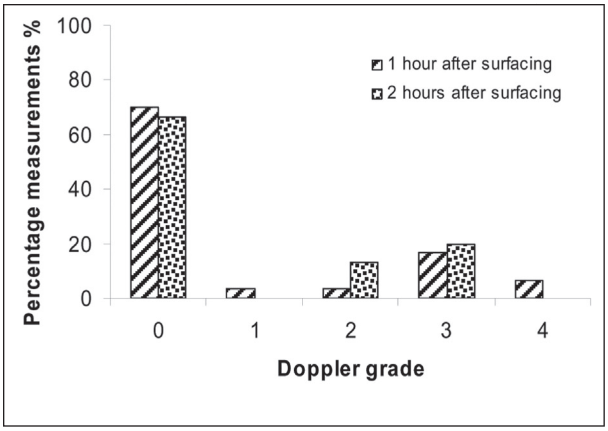

Fig. 2. Precordial Doppler grades after bounce exposures one hour after surfacing (n=30 measurements and two hours after surfacing (n=14 measurements).

hour after decompression for 30 bounce decompressions and 236 saturation excursions. A Mann-Whitney U test revealed a significantly greater amount of bubbles grades in the bounce technique than in the saturation-excursion technique ($p<0.001$). We analyzed, two hours after decompression, precordial Doppler ultrasound measurements in 14 bounce decompressions and 117 saturation excursions. We found significantly higher bubble grades in the bounce technique ($p<0.001$). No significant correlation between bubbles and BMI (Spearman correlation coefficient of 0.097 (ns)(n=31 divers)) and bubbles and age, and physical workload was established.

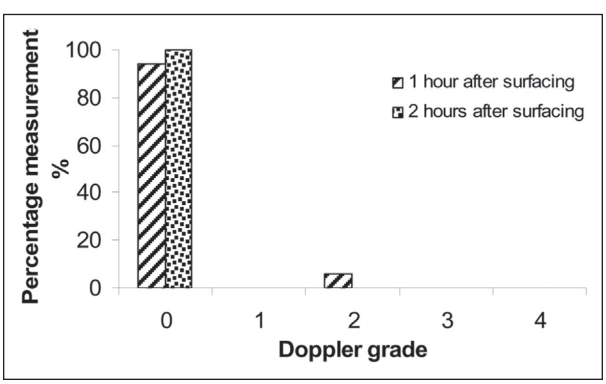

Fig. 3. Precordial Doppler grades after saturation excursions one hour after surfacing (n= 236 measurements) and two hours after surfacing (n=117 measurements).

DISCUSSION

Doppler ultrasound monitoring during the execution of the Western Scheldt tunnel project showed that the saturation-excursion technique was associated with significantly lower bubble grades than the bounce technique was, despite longer working hours, shorter decompression times, and larger physical workloads. During the described phase of the project, there were no decompression incidents with either technique, and bubble grades assessed were generally low.

This study compares two diving techniques in a unique operational project at great depth (maximum 69 meters). Extensive dive time was needed when the tunnel-boring machine became jammed at its deepest point. The saturation technique was introduced for compressed-air work. Instead of compressed air, we used Trimix in both techniques to control the nitrogen narcosis as it was thought that the working conditions (high temperature, heavy work) provided a larger gas uptake. We used custom-made caisson decompression tables, which were more conservative than the existing diving tables were. The existing diving tables are based on the Netherlands Diving Center tables, which were calculated using a neo-Haldanian model. The Tables are designed for a bends-incidence rate lower than 0.5%. They are provided by Dadcodat (Dutch consultants on decompression and hyperbaric physiology) (28).

For reasons of health and safety, we were able to arrange Doppler ultrasound surveys under operational conditions. Planned health surveillance by measurement of Doppler data after exposures at great depths is rarely conducted, and it is therefore one strength of this study.

Compressed-air work in deep tunneling is limited by the occurrence of nitrogen narcosis and reduced working time (28). Kobayashi and colleagues report results of three separate 60-minute chamber-dive experiments at pressures of 6, 7 and 8 bar using a Trimix breathing mixture. The experiments were conducted to evaluate the practicality of using Trimix in hyperbaric caisson work (15). The divers completed the planned exposure according to the Dadcodat decompression schedule. The Dadcodat decompression schedules are the basis for the tables used in this study (28). There were no signs of decompression sickness. Doppler monitoring according to standard procedures revealed no bubbles in any of the divers. Their observations suggest that Trimix is a useful breathing medium for deep caisson work (15). Based on these experiments, we decided to use Trimix for the very deep tunneling work in the Western Scheldt project. In accordance with their results, we observed no nitrogen narcosis, and the rapid decrease in usable work time and the increase of decompression time was far less than it would have been with compressed air at this depth.

Hamilton states that the saturation technique will become more attractive as working depth increases beyond 3 bar (gauge) for situations requiring many hours of work each day (27). The results of the Hamilton study suggest, that it is feasible to apply the saturation technique for deep caisson work (over 3 bar (g) pressure) when long working times are needed. To keep up with the time schedule of the contractors, long working times were necessary in our project. Effectiveness and safety demanded attention to physiology. Although more difficult to implement than the bounce technique, the excursion saturation technique may nevertheless offer some important advantages related to occupational health risks, as we have detected fewer bubbles in the saturation technique compared to bounce technique.

In this study, we performed Doppler registrations after bounce and saturation excursions to evaluate the health and safety of the caisson workers and the new caisson decompression tables. The literature provides evidence that intravascular bubbles may cause damage that could have long-term effects (13). Dives, that produce many bubbles should therefore be avoided. The accuracy of the ultrasonic method is probably low when few bubbles are present. Valves, moving vessel walls, and other moving high-intensity reflectors may cause signals identical to the reflections from intravascular bubbles (18). When more bubbles are present, the method provides a more reliable instrument for monitoring the safety of decompression (10,13,18). We have found about 20% Grade 3 or higher in the bounce technique. So, a number of false-positive and false-negative measures cannot be excluded in this situation. In this study the assessors were blinded to information regarding the dive profiles and other relevant information. Therefore we regard this measurement aspect as having no substantial influence on the study results.

High Doppler scores indicate a high risk of decompression sickness (10,13,18). Sawatzky and colleagues (12) report an association between higher DCS incidence and Spencer bubble grades of 2 or higher. Other research groups have presented similar results (23-26,28). We conclude that in the bounce technique a remarkable result is presented.

With the precordial Doppler ultrasound recordings made one hour and two hours after decompression, we found significantly higher bubbles grades in the bounce technique than we did in the saturation-excursion technique (both $p<0.001$). We had expected these results, because in the bounce dive technique the measurements are being taken at the surface after a long decompression involving a pressure change of 4.7 bar (g) (mean) and a mean decompression time of 116 minutes (Table 2). For the saturation excursion, on the other hand, the pressure change is from 0 to 2.9 bar (g) (mean 21 meters) and a decompression time with a mean of 59 minutes. About 10% of all excursions had depths close to the habitat depth or restricted bottom times that would bring them well within the no-decompression limits. Therefore they were not likely to produce bubbles. As we found only a very few bubbles in the deeper and longer exposures, we consider the inclusion of these 10% low-risk as of no substantial influence on our conclusions.

We found no significant difference between Doppler measurements one and two hours after the bounce-technique dives ($p=0.58$) and those taken one and two hours after the saturation excursions ($p=0.32$). Although in both techniques there was a large quantity of zero grades, the Wilcoxon signed rank test can handle the distribution with many zeros. The test makes no assumptions about the shape of the distributions of the two variables. Unfortunately, we could not perform more than two scheduled Doppler registrations after a decompression. We recommend more measurements in future studies to obtain more information about the development of bubble grades in time.

Although the Doppler measurements yielded a large amount of important information, practical circumstances did not allow recording of all cases. We found no correlation between bubbles and workload or age in either group. This result is not consistent with the recent literature (13,21). Explanations for not finding such a correlation are the modest exposures in the saturation excursion interventions, the limited number of subjects and the high number of zero Doppler grades. The 'healthy worker effect' among the professional offshore diver population, aided by the selection processes in the yearly medical examination could be another explanation for this difference with literature. Especially older professional offshore divers have difficulty passing the medical examinations.

In conclusion, our study revealed a low occupational health risk of both protocols with significantly higher bubble grades in the bounce technique, even two hours after decompression. We recommend the use of the saturation technique with Trimix for deep and long exposures in caisson work. The Doppler technique proved valuable, and it should be incorporated in future compressed-air work.

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