Venous gas embolism in chamber attendants after hyperbaric exposure.

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Risberg J, Englund M, Aanderud L, Eftedal O, Flook V, Thorsen E. VGE in chamber attendants after hyperbaric exposure. Undersea Hyperb Med; 31 (4): 417-429. An initial occupational survey (OS) was initiated to investigate the prevalence of venous gas embolism (VGE) in chamber attendants assisting hyperbaric oxygen (HBO2) treatments. Nine female subjects were exposed for three consecutive days to the routine hospital procedure of compressed air exposure to 240 kPa for ~115 min with 12 min of terminal oxygen (O2) breathing. VGE was monitored with ultrasound Doppler in 15 min intervals for 2h after the first and third exposure. A follow-up experimental study was completed to investigate whether changed breathing gases and decompression would affect the high incidence of VGE observed in the OS. Ten female subjects were randomly exposed to the routine or revised profile (12 and 24 min of terminal O2 breathing respectively), and a Nitrox profile (breathing gas 40.5% O2 in Nitrogen during 90 min of the isobaric phase). VGE was monitored with transthoracic ultrasound scanner and Doppler. In the OS precordial VGE grade III (Doppler) was observed in five subjects, but median resting precordial VGE was Grade 0 both days and VGE score at all sites were equal Days 1 and 3. In the experimental study, median resting precordial VGE was Grade 0 (Doppler) and Grade 1 (Scanner). VGE Grade III (Doppler) was observed in all series, but VGE scores were not significantly different between the series. We conclude that chamber attendants assisting HBO2 treatment at 240 kPa for ~115 min are exposed to a significant decompression stress using the profiles tested in the present study.

INTRODUCTION

Hyperbaric oxygen (HBO2) treatment has evolved as an important treatment modality for a number of illnesses and injuries (13). HBO2 treatments may be provided in monoplace chambers or in larger multiplace chambers with a capacity for many patients. Chamber assistants accompany patients in the multiplace chamber for technical support, medical care and to initiate emergency procedures in the event of incidents during treatment. When multiplace chambers are used, compressed air is used to increase the internal chamber pressure to a target level, typically 240-280 kPa corresponding to 14-18 meters of sea water (msw). Compression rate is usually adjusted depending on the patient’s ability to equalize pressure in the ears and sinuses. The patient breathes 100% oxygen (O2) from tight fitting oronasal masks or in hoods with short intervening periods of “air breaks” to reduce hyperoxic side effects. While patients breathe O2, chamber assistants breathe the chamber atmosphere, usually compressed air, throughout most of the hyperbaric exposure. To avoid decompression illness (DCI), the chamber attendants usually breathe O2 at the end of the isobaric phase and during decompression.

The UK Royal Navy, US Air Force and US Navy have published HBO2 treatment procedures applicable for institutional use (14,16,18). These are frequently adopted for the treatment of diving-related disorders. However, there is no well-recognized standard for HBO2.
treatment of common non-diving related disease or injury, but a typical "wound healing protocol" would call for 60-90 min of O\textsubscript{2} breathing at 240-250 kPa. The routines for the chamber attendants regarding O\textsubscript{2} breathing and decompression procedures show large variation among centers. Sheffield and Pirone (18) cited a review of DCI incidence in ~29 000 exposures of chamber attendants in North American multiplace chambers. DCI incidence ranged 0.01-0.6%, without obvious differences between different treatment protocols. In 1997 we reported a 0.76% DCI incidence in Haukeland University Hospital chamber attendants (2). The time for O\textsubscript{2} breathing preceding decompression was extended with five min at 240 kPa after this. However, in May 2002, one of the nurses assisting patients having HBO\textsubscript{2} therapy at Haukeland University Hospital suffered a serious episode of neurological DCI. The incident was investigated, but no procedural errors or specific individual risk factors were identified.

Though the observed incidence of decompression illness in Haukeland University Hospital chamber attendants was low, the serious outcome of the last DCI incident underscored the importance of continuous improvement of working procedures. Measurement of DCI would be impractical for evaluating different decompression profiles since expected DCI incidence would be in the order of 1% or less. Measurement of venous gas embolism (VGE) in the heart and peripheral veins has been extensively used for the assessment of decompression procedures, as a positive association has been reported between VGE scores and DCI incidence (15). Measurement of VGE thus allows comparison of decompression stress between different hyperbaric procedures. The objective of this study was to define the prevalence of VGE in chamber attendants during three consecutive days assisting in routine HBO\textsubscript{2} treatment (occupational survey). Based on the survey findings, a follow-up experimental study was designed to investigate the effect on VGE prevalence of reduced decompression rate combined with either prolonged breathing of 100% O\textsubscript{2} or increased O\textsubscript{2} fraction in the breathing gas.

**METHODS**

**Subjects**

Chamber attendants employed by Haukeland University Hospital (as of October 2000 these were all female nurses), were invited to participate in the occupational survey. The inclusion criteria were written consent, availability during the study period and no hyperbaric activity for three days preceding the first exposure. No additional medical examination was required, but all subjects had been medically approved for hyperbaric exposure according to hospital routines. Nine subjects fulfilled the criteria. Their mean age was 52 ± 8 years (range 36-61) and Body Mass Index (BMI) 25.8 ± 2.3 kg/m\textsuperscript{2} (range 22.1 – 28.8). Three were smokers.

In the follow up study (experimental study), the inclusion criteria were identical to the occupational survey, but the extended duration (three weeks) prohibited participation by a sufficient number of nurses. To recruit a sufficient number of subjects, females employed by Haukeland University Hospital or Norwegian Underwater Intervention (NUI) were invited to participate. All subjects signed a declaration of informed consent. Subjects not trained in hyperbaric work were accompanied by a hyperbaric nurse and were examined before the experiment to ensure that they were fit for hyperbaric exposure. Ten subjects, including six nurses, were included. These were aged 50 ± 9 years (range 37-61) and had BMI 26.0 ± 3.0 kg/m\textsuperscript{2} (range 21.8 – 30.8). Two subjects were smokers and two were former smokers.

The occupational survey was approved by the Institutional Review Board (IRB). The experimental study adhered to the Helsinki declaration and the protocol was submitted to the
IRB before the study but due to a miscommunication was completed before final approval. It was designed with hyperbaric exposures equal to or more conservative than the operational procedures used during the occupational survey.

**Hyperbaric exposure**

Hyperbaric exposures were completed within the NUI saturation chamber complex holding six pressure chambers. Four of these were used during the present experiments. A dedicated HBO$_2$ chamber with a treatment capacity for eighteen patients in addition to two chamber assistants was used in the occupational survey. During the experimental study, the use of different chambers allowed simultaneous exposure to different breathing gases, which was critical for observer blinding.

The occupational survey was integrated into the regular HBO$_2$ treatment of the hospital. The nurses assisted patients according to established routines during the hyperbaric exposure. Each nurse was exposed for three consecutive days at ~9 a.m. Chamber pressure was increased to 240 kPa (14 msw) by compressed air at a rate being comfortable for the patients (9 ± 2 min Day 1 and 10 ± 3 min Day 3, not statistically different). During the 100 min isobaric phase at 240 kPa, patients breathed 100% O$_2$ through tight fitting masks or free-flow hoods connected to the built-in breathing system (BIBS) for 3 x 30 min interspaced with 5 min air breaks. The nurses breathed 100% O$_2$ for the last five min of the isobaric phase except for one subject who did so for 10 min. This nurse had earlier been advised to breathe O$_2$ for a longer time due to previous (untreated) symptoms considered compatible with skin decompression illness. Decompression was at a rate of 20 kPa/min, with a total decompression time of 7 min. The nurses breathed 100% O$_2$ during decompression whilst the patients breathed chamber atmosphere. The chamber atmosphere was controlled allowing a F$_{O2}$ of 20-22 %, a P$_{CO2}$ less than 0.5 kPa and a temperature of 20-22 °C.

In the experimental study the subjects were scheduled to participate in three different hyperbaric profiles in random order. The “Routine”, “Revised” and “Nitrox” profiles are shown in Figure 1. Each exposure started with a 15 min linear compression with air to 240 kPa followed by a 100 min isobaric phase. A linear decompression in 7 min (Routine) or 14 min (Revised and Nitrox) ended the 122 or 129 min exposures. Breathing gas was compressed air with the following exceptions. The routine protocol would call for O$_2$ breathing during the last 5 min of the isobaric phase and during decompression (a total of 12 min), while the revised protocol required 10 min of O$_2$ breathing at the end of the isobaric phase in addition to decompression (a total of 24 min). During the Nitrox series, the subjects would breathe 40.5% O$_2$, balance N$_2$, during 3x30 min of the isobaric phase as shown in Figure 1. Oxygen and Nitrox was provided by tight fitting oronasal masks connected to the BIBS-system.

The subjects were scheduled to be exposed once to all three series in random order, and two subjects were examined every day. To allow blinding of the ultrasound investigator, the hyperbaric exposures were timed to bring both subjects to the surface at the same time. One subject elected not to participate in the routine protocol. She remained at surface pressure during the scheduled period for this exposure, but adhered to the post-exposure VGE monitoring as planned.
Since hospital procedures allowed three days of consecutive exposures for chamber attendants, the optimal experimental design would be VGE measurements after each exposure for three consecutive days. Practical constraints did not allow this number of exposures nor measurements. From an operational point of view, it was important to demonstrate low VGE incidence in at least one of the profiles, allowing us to use this in further HBO$_2$ treatment. The Nitrox profile was expected to give a lower VGE incidence than the two other profiles, and it was decided to repeat the Nitrox profile three times with 24h intervals and investigate VGE incidence after Day 3 only. Each subject was thus exposed once for the “Routine” and “Revised” profile, but three times to the Nitrox profile, i.e. a total of 5 hyperbaric exposures. A minimum of three days without hyperbaric exposure separated each series. The subjects agreed to respect minimum stand-off periods before each exposure: hyperbaric pressure 72h, alcoholic beverages 24h, flying 12h, strenuous activity 9h, tea and drinks containing caffeine 2h. Physical activity during and after the hyperbaric exposures was standardized.

Measurements

The two subjects were examined for VGE within 15 min after the end of decompression. Measurements were repeated in 15 min interval for two hours.

In the occupational survey, VGE was examined after the first and third day of exposure. VGE was measured with a continuous wave ultrasound Doppler unit (MultiDopplex, Huntleigh Healthcare, Cardiff, UK). Precordial monitoring was completed with a 2 MHz probe while a 5 MHz probe was used for subclavian vein measurements. Measurements were completed according to the DCIEM protocol (6). An investigator with more than 10 years experience in Doppler monitoring scored the results in real time. The ultrasound investigator was not blinded with respect to hyperbaric exposure.

In the experimental study VGE was measured at three occasions: Once after the Routine and Revised exposure and once after the third day of Nitrox exposure. VGE was measured with a Vingmed Vivid 5 (GE Vingmed Ultrasound, Horten, Norway) ultrasound apparatus, equipped with a 2.5 MHz phase array probe. The subject was placed lying on her left side. The probe was placed in a left parasternal position to optimize a four-chamber projection. If this was unsatisfactory a parasternal long-axis was chosen instead. After a minimum of 30 sec observation for VGE at rest, the subject was asked to flex the right hip and knee 3-4 times to provoke release of VGE. Presence of VGE in the right atrium or passing through the tricuspidal valve was observed for 30 sec and the procedure repeated twice. Following this, the right ventricular outflow tract and pulmonary valves were visualized at rest and after movement with a parasternal short axis projection. Finally a pulsed wave Doppler ray was focused immediately proximal or distal to the pulmonary valve, to obtain an optimal flow signal without disturbances from cardiac walls or pulmonary cusps. Doppler measurements were made in rest and after

![Hyperbaric profiles. Occupational survey identical to top panel "routine" except for variable compression time. Breathing gas air except for grey areas (Routine and Revised: 100% O$_2$, Nitrox: 40.5% O$_2$, balance N$_2$.)](image-url)
movement. Both the ultrasound image and the pulsed wave Doppler audio signals were recorded on video tape. The presence of VGE was scored in real time by an investigator blinded for the experimental exposure. A random selection of tapes from three subjects in each of the three series, i.e. a total of 58 measurements, were re-evaluated after the end of the experiments by the same investigator (secondary investigation) and another observer blinded for experimental situation (independent verification). The secondary investigation and independent verification were completed independently of each other. However, no attempt was made to conceal the initial score during secondary investigation.

**Mathematical model**

A mathematical model developed by Flook (9) and validated in trials of simulated dives and compressed air exposures (10,11) was used to calculate the volume of gas forming into bubbles in the body. The model treats the body as eight parallel compartments having the physiological and anatomical characteristics of identifiable tissues. The volume of gas carried as bubbles in the central venous blood is calculated as a weighted mean of that in venous blood from the tissues. This value is used to predict a median group value for the maximum Kisman-Masurel Doppler score (6) for precordial measurements at rest in each subject. The model was used to compare the decompression risk of the revised profile and the Nitrox breathing profile to the original. The way the model is constructed means that the predictions relate to the average subject, not the individual.

**Data evaluation and statistical analysis**

Presence of VGE in the acoustic Doppler signals (continuous and pulsed wave Doppler) was graded according to the Kisman-Masurel (K-M) grading system as described by the DCIEM protocol (6). The K-M scale is a 5-level categorical scale (Roman 0-IV) with additional subdivision of “+” or “-”, except for 0- and IV+, i.e. a total of 13 different scores. During the occupational survey, each subject would provide data from three monitoring sites (left and right subclavian vein, precordial) at rest and after movement, giving a total of six data points for each subject at any time. Ultrasound images were graded according to the Eftedal-Brubakk protocol (8) with 6 levels (0-5) without further subdivision. The experimental study provided precordial VGE with Doppler rest and movement state as well as image rest and movement state, i.e. a total of four data points for each subject at any time of measurement. Data from both studies were stored in a spreadsheet for further analysis.

The maximum VGE score at any measurement site and for each state (rest/movement) was used for further comparative statistical analysis. Additionally, the highest VGE score (all sites/states) and highest precordial score (movement or rest) was tabulated for statistical comparison. Statistical analysis was completed using the Sigma Stat software (Jandel GmbH, Erkarth, Germany). Change in maximal VGE score between Day 1 and Day 3 for each subject participating in the occupational survey was examined by the Wilcoxon signed rank test. Difference in VGE score between the series in the experimental study was compared using a Friedman’s ANOVA on ranks. Inter-rater agreement of VGE score (initial, secondary and independent grading) was measured by weighted kappa ($\kappa_w$) as described by Altman (1). Except for this inter-rater agreement analysis, all VGE data and statistics from the experimental study are based on the initial grading alone. VGE scores are reported with categorical distribution and median grade. In the series with an even number of observations, a median located between two bubble grades is reported using both levels (e.g. 0/I). Anthropometric data are reported as Mean
± Standard Deviation (SD). Since VGE measurements were completed in intervals of ~15 min, latency to first VGE observation and duration of VGE are reported as the median number of observations. All tests were two-tailed and p<0.05 was considered statistically significant.

RESULTS

No DCI or other complication was observed during or after the exposures.

Occupational Survey

The occupational exposure was estimated to release 2.1 µl gas/ml blood in the central venous blood. Subclavian vein measurements were omitted from two subjects Day 1 due to technical problems.

Table 1. Number of subjects with maximum VGE score. (Occupational survey, N=9) Grade IV VGE not observed.

<table>
<thead>
<tr>
<th>Site</th>
<th>Precordial</th>
<th></th>
<th></th>
<th>Subclavian</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>Movement</td>
<td>Rest</td>
<td>Movement</td>
<td>Rest</td>
<td>Movement</td>
</tr>
<tr>
<td>Day</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Grade 0</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>6</td>
<td>5</td>
</tr>
<tr>
<td>Grade I</td>
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<td>1</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Grade II</td>
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<td>2</td>
<td>2</td>
<td>0</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Grade III</td>
<td>2</td>
<td>0</td>
<td>5</td>
<td>3</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Grade IV</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

VGE results are summarized in Table 1 and Fig 2. Median VGE score was Grade I for precordial and subclavian (movement) Day 3 and Grade III for precordial (movement) Day 1 with range 0-III. Median VGE scores were otherwise Grade 0. VGE were identified in all subjects at one or more sites, either at rest or after movement. Subjects with precordial VGE on Day 1 had the first occurrence of bubbles at the second monitoring session (median value) after surfacing (36 ± 11 min, range 20-50 min) lasting for two observations (37 ± 30 min, range 0-90 min). Subjects with VGE identified in subclavian measurements Day 1 presented first occurrence at the first observation (median value) after the end of exposure (15 ± 7 min, range 10-20 min) lasting for five observations (63 ± 4 min, range 60-65 min). Time of first VGE detection and duration of VGE formation was not significantly different Day 3 compared to Day 1. Except for one subject Day 3, all subjects presenting subclavian vein VGE had precordial VGE as well.

Three and one subjects demonstrated precordial VGE Grade III on Day 1 and Day 3 respectively. Another two subjects demonstrated Grade III VGE both days. Highest precordial VGE score at rest Day 3 was unchanged in five, increased in two and decreased in two subjects compared to Day 1. Similar comparisons for precordial registrations after movement were unchanged in three, increased in two and decreased in four subjects. Maximum VGE grades were not statistically different Day 1 compared to Day 3 at any site (subclavian/precordial) or state (rest/movement). One of the cigarette smokers presented Grade III precordial VGE Day 1, otherwise no Grade III VGE was observed in the smokers.
Experimental Study

Using the mathematical model, the routine, revised and nitrox series were calculated to release 2.1, 1.3 and 1.6 µl gas/ml blood into the bubbles in the central venous blood. A total of nine measurements (two in the routine series, three in the revised series and four in the nitrox series) were omitted due to technical problems, e.g. delays or poor image quality. One subject missed two measurements during the Nitrox series, otherwise no subject missed more than one measurement.

Results of VGE measurements are presented in Tables 2-4 and Figure 3. The median scanner VGE score was Grade 1 for all rest states, Grade 0 for routine movement and Grade 0/1 for revised and nitrox movement states. The single subject who was not compressed at all during the scheduled routine exposure did not present VGE in the monitoring period. The first detection of VGE (scanning images or Doppler) among subjects with VGE, was observed at the first observation (median value) in all series (16 ± 5 min with range 8-20 in the routine series, 17 ± 12 min with range 5-43 min in the revised series and 27 ± 31 min with range 10-95 min in the Nitrox series).

Table 2. Number of subjects with maximum precordial VGE score in rest and movement assessed by imaging technique in the experimental study. N=10 except routine exposure (N=9).

<table>
<thead>
<tr>
<th>VGE grade</th>
<th>Routine (Day 1)</th>
<th>Revised (Day 1)</th>
<th>Nitrox (Day 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest</td>
<td>Movement</td>
<td>Rest</td>
</tr>
<tr>
<td>0</td>
<td>4</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>1</td>
<td>2</td>
<td>1</td>
<td>6</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>4</td>
<td>0</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>5</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
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</table>

Corresponding duration was six observations in the routine series and two observations (median values) in the revised and nitrox series (96 ± 7 min with range 85-103 min; 68 ± 45 min.
with range 0-117 min and 43 ± 45 min with range 0-112 min respectively). Latency for first detection and duration of VGE were not statistically significantly different between the series. VGE in scanning images was detected in 6/9 in the routine series and 8/10 in the revised and in the nitrox series. One subject did not present VGE in any situation while four subjects presented VGE after all exposures as investigated by scanning images. Median Doppler score was Grade 0/I for revised rest state, Grade I for routine movement state, all other situations had a median score of Grade 0. Doppler measurements showed that two subjects did not present VGE in any situation, while one subject presented VGE after all exposures. Table 4 lists the number of subjects showing decreased, unchanged or increased maximum VGE score (rest or movement) comparing the different series. The table does not suggest reduced VGE score in one series compared to the others, and statistical analysis could not disclose any difference in maximum VGE scores between the three series (ANOVA on ranks). The three subjects presenting VGE Grade 4 or Grade III were aged 46-61, had a BMI of 21.8 – 26.4 and one was a smoker.

Agreement between first and secondary grading of scanner images were $\kappa_w$=0.65 and $\kappa_w$=0.72 for rest and movement respectively. Agreement between first and independent grading was $\kappa_w$=0.68 and $\kappa_w$=0.53 while secondary vs. independent grading demonstrated $\kappa_w$=0.60 and $\kappa_w$=0.70 for rest and movement respectively.

Gas embolism was not systematically looked for in the left ventricle or atrium. However, one subject had left ventricular gas embolism during three consecutive measurements when participating in the routine series. This was verified during secondary investigation as well as by the independent observer. Another subject showed possible left ventricular gas embolism on one occasion when exposed to the Nitrox profile. While this was noted during the initial investigation, it was not verified during the careful secondary and independent investigation of the tapes. Verified and possible left ventricular gas embolism was minimal (Grade 1) and occurred during moderate or high venous gas embolism (Grade 3 and Grade 4). Both subjects were referred for clinical cardiac ultrasound investigation for disclosure of possible patent foramen ovale, but the results of these examinations are unknown due to medical confidentiality.

Table 3. Numbers of subjects with maximum precordial VGE in rest and movement state in the experimental study as assessed by pulsed Doppler. N=10 except routine series (N=9)

<table>
<thead>
<tr>
<th>VGE grade</th>
<th>Routine (Day 1)</th>
<th>Revised (Day 1)</th>
<th>Nitrox (Day 3)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Rest Movement</td>
<td>Rest Movement</td>
<td>Rest Movement</td>
</tr>
<tr>
<td>0</td>
<td>5 4</td>
<td>5 6</td>
<td>6 7</td>
</tr>
<tr>
<td>I</td>
<td>2 2</td>
<td>4 3</td>
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<td>II</td>
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<tr>
<td>IV</td>
<td>0 0</td>
<td>0 0</td>
<td>0 0</td>
</tr>
</tbody>
</table>

Table 4. Number of subjects with changed maximum VGE score comparing the different series. N=10 except for routine (N=9)

<table>
<thead>
<tr>
<th></th>
<th>Increase</th>
<th>Unchanged</th>
<th>Decrease</th>
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<tbody>
<tr>
<td></td>
<td>Scanner</td>
<td>Doppler</td>
<td>Scanner</td>
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<tr>
<td>Routine vs. Revised</td>
<td>2</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
<td>Routine vs. Nitrox</td>
<td>3</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Revised vs. Nitrox</td>
<td>2</td>
<td>3</td>
<td>6</td>
</tr>
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</table>
DISCUSSION

VGE measurements are subject to a number of methodological problems (15). Observer bias is a possible confounder in VGE measurements reported from the occupational survey in the present study, as the observer was aware of the subjects’ exposure. Additionally, the results were not verified by an independent observer, and the compression rate was not standardized due to constraints imposed by the practicalities of clinical hyperbaric oxygen treatment. Though observer bias could affect measurement accuracy, the effect on VGE score of a non-standardized compression rate (7 min difference between shortest and longest compression time) would probably be small. The possibility of observer bias was eliminated in the follow up experimental study, as the ultrasound observer was blinded for experimental situation, and the hyperbaric exposures were standardized. However, the accuracy of ultrasound VGE estimation remains controversial. Sawatzky and Nishi (17) reported taped acoustic Doppler signals to agree within $\kappa_w = 0.41-0.79$ for rest and $\kappa_w = 0.25 – 0.72$ for movement dependent on data set and observers. Brubakk and Eftedal (3) compared precordial VGE scores from a “blind” pulsed Doppler and an image assisted pulsed Doppler ultrasound sampled from the pulmonary artery and real-time ultrasound imaging following experimental air dives. Ninety-two measurements were performed using both blind and image-assisted Doppler while a total of 340 samples were available for images and image-assisted Doppler. $\kappa_w$ agreed within 0.68-0.83 for rest measurements and 0.19-0.45 after movement. Eftedal and Brubakk (8) reported good agreement ($\kappa_w = 0.75$) when two experienced observers evaluated VGE in ultrasound images of divers. In the present study, a $\kappa_w = 0.53-0.72$ comparing initial, secondary and independent grading in rest and after movement, indicate “moderate” (0.41-0.6) to “good” (0.61-0.80) agreement (1). $\kappa_w$ obtained in the present study should however be interpreted with caution due to the low number of observations, and a predominantly low (Grade 0-2) bubble grade. Individual disagreements for samples with high bubble grades will accordingly have a relatively large effect on $\kappa_w$.

The different measurement techniques (pulsed Doppler and scanner imaging) used in this study does not allow direct comparison of data. However Nishi et al (15) reported a linear relationship between bubble count (bubbles/cm$^2$ of the scanner image), pulsed Doppler score Grade 0-III and scanner image score Grade 0-3. The grading systems disagreed at very high bubble counts and VGE grades IV/4-5. The low incidence of Grade 4 (scanner) VGE, and no observations of Grade 5 (scanner) or Grade IV (Doppler) VGE should thus allow comparison between the different exposures of the present study.

The objective of the occupational study was to investigate VGE occurrence in chamber attendants during three days of consecutive hyperbaric exposures. Though median VGE scores were low (0 – I), Grade III VGE was observed in six and three subjects Days 1 and 3 respectively. Walker et al (21) measured VGE by Doppler technique in 18 subjects after a 10 msw/90 min and 18 msw/60 min protocol. The subjects breathed $\text{O}_2$ during the 30 min decompressions in both series. VGE Grade III was observed in two subjects following the 18 msw exposure and in one subject after the 10 msw exposure. One subject, not presenting VGE, suffered neurological DCI following one of the exposures (not detailed). Most subjects experienced low grade (Grade 0 or I) VGE. We are not aware of other studies or published mathematical model estimates of DCI incidence or VGE score after conventional “wound healing” protocols, i.e. typically 14-15 msw/60-90 min. The results by Walker et al (21) are consistent with the findings of the present study (Table 3).
Whether repetitive hyperbaric exposures cause physiological adaptation with decreased VGE and decreased DCI incidence is controversial. Baker (cited in (18)) suggested that reducing the frequency of exposure would decrease chamber attendant DCI incidence, though a study on caisson-workers (20) indicate that repeated exposures decrease DCI incidence. While Eckenhoff and Hughes (7) reported unchanged VGE score during twelve consecutive hyperbaric chamber exposures to 150 fsw, Dunford et al. (5) observed decreased VGE scores during 6-8 days of recreational multi-day diving. Results from the present occupational study do not indicate different VGE scores after one or three consecutive exposures.

The objective of the experimental study was to investigate changes in VGE when the PO2 of the breathing gas and decompression rate was changed. We recognize that the use of three consecutive exposures in the Nitrox series can obscure comparison to the single exposure in the Routine and Revised series. However, data from Eckenhoff and Hughes (7) as well as the present occupational study indicate that repeated hyperbaric chamber exposures have minimal effects on the VGE incidence. The volume of gas in the central venous blood, estimated according to the procedure advised by Flook (9), would be expected to be less in the revised and Nitrox profile compared with the original profile. However, using the information gained in the trials reported by Flook (10,11), all three profiles would be expected to give a median precordial K-M Doppler score at rest of Grade 0. Median precordial Doppler VGE score in rest was 0 for the original and nitrox profile and 0/I for the revised profile (Table 3) consistent with the estimates of gas load in central venous blood. However, a relationship remains to be established for the distribution of VGE scores at a given estimated central venous gas load.

The low number of subjects significantly affects the power of the study. To demonstrate improvement with a revised profile (based on a 22% proportion of high VGE score achieved in the occupational survey), 34 subjects would be required for each series in the experimental study. This would be beyond available resources. Rather, a practical approach was taken which required no subjects with VGE Grade III for the revised profile to be acceptable for operational use. (One observation of high VGE in ten would have a 95% CI of 0-47%). Had this target been achieved, a follow-up occupational survey would be required during operational implementation.

![Fig 3. Max VGE score in experimental study. Top panel: Ultrasound images. Bottom panel: Acoustic Doppler signal. N=10 except routine series (N=9). Grade 5 and Grade IV VGE was not observed.](image-url)
of the revised profile. However, as is evident from Table 3, VGE Grade III was observed once in the revised as well in the nitrox series leaving us to reject the revised profiles for future use.

The background for this study was a case of neurological DCI affecting one of the nurses. In the literature, there is a paucity of properly designed epidemiological studies estimating the risk of DCI as a function of chamber exposures. Sheffield and Pirone (18) have published a review of the literature citing a DCI incidence range in inside observers of 0-0.76%. Defining appropriate acceptance criteria for DCI risk should involve employees, employers, the authorities and others sharing responsibility for the activity, and can not be decided on a scientific basis alone. Our hospital has experienced one case of treated DCI and three other cases of decompression related symptoms (transient itching and visual disturbances) in ~4500 exposures since 1994. While the incidence of treated DCI is low when compared to the number of exposures, the risk of decompression related disorder is comparatively high considering the low number of subjects at risk (~20 nurses since 1994). It was thus decided to complement the risk assessment with VGE measurements. The relevance of VGE measurements for health outcome remains disputed, though a recent review by Nishi et al (15) lists a number of studies demonstrating a positive association between high bubble grades and DCI after hyperbaric exposures. Most studies report a markedly increased DCI risk as precordial VGE exceeds Grade II. While DCI is a clinically useful endpoint when assessing table safety, an impractical number of experiments are required to measure statistically significant changes when overall DCI risk is in the order of 2-5%. Nishi et al (15) suggested that VGE measurements could be used to assess the “decompression stress”, allowing DCI safety estimates based on fewer experiments. We recognize, however, that the low number of subjects and experiments reported in the present study calls for caution in interpretations of the results.

A number of measures have been recommended to reduce the DCI risk in chamber attendants. The USN extended the O2 breathing period for chamber attendants in 1993 (14) to lower the estimated DCI risk from 3.3% to 0% (19). The US Air Force adopted the “Nobendem” procedure in 1999, changing oxygen breathing and decompression procedures for chamber attendants “based on a much more scientific approach to denitrogenation” (22). Anecdotal and informal comments from hyperbaric physicians indicate that national and institutional changes in O2 breathing and decompression procedures for chamber attendants are based on empirical data rather than scientific epidemiological or experimental studies. The unchanged VGE score in the three different profiles of the present experimental study illustrates the difficulty of scientifically validating actions taken to make procedures more “conservative”. Out of nine reports reviewed by Sheffield and Pirone (18) on DCI incidence in chamber attendants, only two are published in peer reviewed scientific manuscripts, other references were reports, abstracts etc with variable accessibility. It is thus a striking contrast between the recognition of DCI as a potential problem for chamber attendants and the extent and quality of scientific studies investigating the problem.

A number of measures can be taken to reduce the individual risk for DCI in chamber attendants. Sheffield and Pirone (18) discuss decompression schedule, rotation of attendants, assessment of attendant’s fitness to dive, number of attendant exposure and education of attendants. Individual characteristics (e.g. gender, age, body fat, physical fitness) are claimed to affect DCI risk, any relationship remains mainly unresolved or controversial (12). Carturan et al. (4) identified ascent rate, age, aerobic fitness and adiposity as risk factors for VGE in 47 seven male divers examined after 94 open water dives to 35m. However, this study was not designed to investigate the effect of individual characteristics (e.g. sex, age, physical fitness, body mass index) on VGE, and the number of subjects studied is too low to assess any such relationship.
We were not able to establish a procedure meeting the institutional acceptance criteria. Haukeland University Hospital has decided to continue future elective HBO2-treatment in monoplace chamber to eliminate the requirement and inherent risk to chamber attendants. However, we recognize a need for multiplace treatment of some patients and advise experimental and proper epidemiological studies investigating the risk of DCI in chamber attendants.

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REFERENCE