Original articles

Hyperbaric chamber attendant safety I: Doppler analysis of decompression stress in multiplace chamber attendants

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Key words

Decompression, decompression sickness, bubbles, Doppler, nursing, hyperbaric facilities, occupational health

Abstract

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Introduction: Incidences of decompression sickness of 0.76% have been reported in hyperbaric attendants exposed to routine 243 kPa treatment tables. Occupational health risks of this magnitude are not acceptable in routine clinical practice. Significant variations in procedures are therefore found between institutions in an attempt to enhance staff safety. In extreme cases, the use of multiplace chambers has been abandoned. Doppler ultrasound provides an objective tool to assess the sub-clinical decompression stress associated with any particular exposure.

Aims: To assess the decompression stress imposed upon staff exposed to our routine 243 kPa table and to elucidate demographic details within the attendant population that impact upon that stress.

Methods: Design: prospective observational cohort study. Profile: 243 kPa for 90 min with a 20 min decompression on oxygen. Subjects: 28 nursing and medical personnel routinely undertaking patient care under hyperbaric conditions. Procedure: Doppler assessment at 20 min intervals for up to 120 min post-exposure. Scoring: aural grading of intravascular bubbles using the Kisman-Masurel (K-M) scoring system; 163 exposures were scrutinized in this manner.

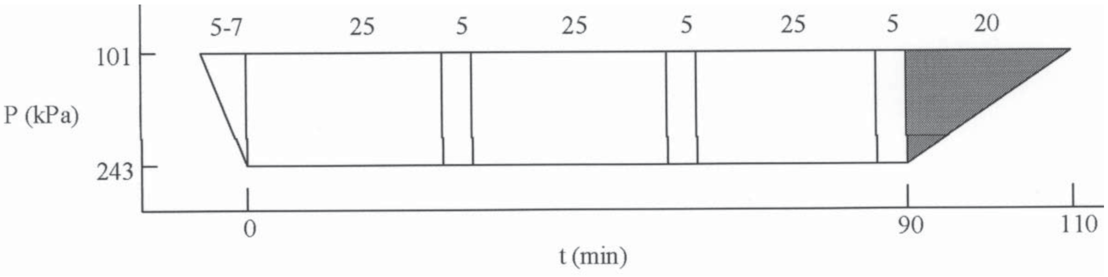
Results: 68% of exposures resulted in 'low' (K-M Grades 0-I), 22% in 'intermediate' (Grade II) and 10% in 'high' sub-clinical decompression stress (Grades III-IV). Female gender and increasing age, weight and exposure frequency showed trends towards higher bubble grades. There were no cases of clinical decompression sickness.

Conclusions: Our standard 243 kPa table conforms to DCIEM definitions of 'acceptable' decompression stress (Grade II or fewer bubbles in ≥50% of the subjects). Significant inter- and intra-individual variability was evident even within this one, tightly controlled dive profile.

Introduction

Hyperbaric oxygen therapy, when provided in a multiplace chamber, involves the exposure of at least one attendant, and a variable number of patients, to increased atmospheric pressure. During treatment the multiplace chamber is pressurized with air and patients breathe 100% oxygen through tightly fitting oronasal 'aviator-style' masks or free-flow oxygen hoods. At the Royal Hobart Hospital (RHH), attendants breathe air throughout the time at pressure then, from the start of decompression, breathe 100% oxygen. The 243 kPa (14 metres' sea water depth, 2.4 ATA) treatment table currently in use was first implemented in January 1997 at RHH and accounts for the majority of attendant exposures to pressure at our facility (Figure 1). It provides strict control of depth and bottom time, with decompression time based on triple the DCIEM air-diving schedule requirement, to minimise the risk of clinical decompression sickness (DCS) in our attendants.[1] Rates of DCS up to 0.76% have been reported in hyperbaric attendants exposed to routine 243 kPa treatment tables.[2,3] In today's occupational health and safety climate it is not acceptable to expose staff members, potentially thousands of times in a career, to health risks of this magnitude.

Figure 1. Royal Hobart Hospital 243 kPa treatment table (RHH 14:90:20)
White = attendant on air. Grey = attendant on oxygen. Patient air-breaks marked to indicate periods of increased attendant activity in-chamber



Important demographic differences may exist between the hyperbaric attendant population (predominantly female, 30–50 years of age, hospital-based nurses, variable fitness, seated for much of the treatment) and the population against whom the safety of commonly used decompression tables is typically validated: predominantly male, 20–40 years of age, fitness-conscious military or emergency services personnel, either exercising during 'wet-chamber' dives or recumbent during 'dry-chamber' dives, and all self-selected volunteers.[4] Accurate assessment of the occupational health risk posed to in-chamber attendants working at hospital-based hyperbaric facilities is, therefore, difficult.

Any exposure to compressed air carries with it the risk of tissue and intra-vascular nitrogen bubble formation on decompression. Theoretically, when these bubbles exceed certain thresholds (e.g., number or bubble radius) the probability of clinical DCS rises sharply.[5–8] Doppler ultrasound is a technique that has been extensively used and refined by organizations such as Defence R&D Canada – Toronto (DRDC Toronto, formerly the Defence and Civil Institute of Environmental Medicine, DCIEM) and Duke University, USA, to assess the decompression stress of new dive profiles and validate the safety of existing empirical or theoretically-derived decompression tables.[5–13] Gas bubbles in the circulatory system occur more frequently than does symptomatic DCS, can be detected even in known 'safe' dive profiles and are able to be graded by readily available Doppler technology.[5–8] The detection of bubbles in this way therefore provides more detailed information about the decompression stress associated with a given dive profile than does the binary outcome of 'DCS versus no DCS'.[8,14]

Various publications on DCS-related staff health risks have kept the issue of "How safe is 'safe'?" topical in the minds of personnel and institutions alike.[15–17] In January 2001 it was therefore decided to attempt to quantify the decompression-related risks associated with the RHH standard 243 kPa table; despite 1,570 attendant exposures up to that time without a case of clinical DCS.

Aims

Primary endpoint: To assess, using Doppler ultrasound, the extent and significance of decompression stress experienced by attendants routinely exposed to the standard RHH 243 kPa treatment table; and compare these results with established DCIEM tolerances for decompression stress.
Secondary endpoint: To evaluate the demographic variation within the hyperbaric attendant population and its relationship to decompression stress.

Methods

STUDY DESIGN

A prospective, observational, cohort study was conducted using Doppler ultrasound to assess sub-clinical decompression stress over 44 months (April 2001 to November 2004). This project was approved by the Research Ethics Committee of the RHH Research Foundation and the Human Research Ethics Committee at DRDC Toronto, Canada.

SUBJECTS

The Royal Hobart Hospital is the major university teaching hospital and tertiary referral centre for the State of Tasmania, Australia. The RHH hyperbaric unit accepts approximately 120 new referrals and performs some 2,000 patient treatments annually. All RHH nursing and medical personnel working in the hyperbaric environment during the study period were invited to participate. Personnel undergoing hyperbaric exposure were all medically certified fit-to-dive in accordance with the appropriate Australian Standard in force at the time. Personnel under the age of 40 years are re-certified biennially, and those 40 years and older annually.

There were no exclusion criteria as this was an observational study undertaken on personnel in the performance of their normal duties. Participation was voluntary and informed consent was gained from all participants. Baseline demographic data were collected for all eligible personnel, irrespective of whether they participated in the Doppler study. These data included age, sex, height, weight and calculated body mass index (BMI), and the frequency with which they underwent hyperbaric exposure.

HYPERBARIC PROCEDURES

All exposures took place in the RHH multiplace chamber (Hydro Electric Commission, Hobart, Tasmania, 1993). The established RHH 243 kPa table was adhered to throughout the study. The attendant was active around the chamber at the beginning of the isobaric phase and for three five-minute periods during the course of the dive whilst the patients received their air-breaks (assisting the patients donning and removing their face masks or oxygen hoods). For the remainder of the time the attendant was seated and relatively inactive unless a problem arose with a patient. The compression phase was generally 5–7 minutes, but could extend to a maximum of 12 minutes if a patient encountered difficulties (usually with middle-ear equalization). In the unlikely event of bottom time exceeding 110 minutes – but being less than 120 minutes – a five-minute decompression stop was mandated at 9 metres, otherwise a linear decompression over 20 minutes was performed.

Personnel were routinely restricted to a maximum of four hyperbaric exposures per week, with no more than three days of consecutive pressure exposure. Additionally, because of Hobart's mountainous terrain (highest habitation 550 m, routine attendant travel to >600 m, sealed roads to 1,250 m), attendants living $\geq$300 metres above sea level were required to remain at sea level for at least four hours before travelling home. In practice, these personnel were rostered for the morning treatment, allowing off-gassing in the afternoon. A minimum 18-hour break was required between hyperbaric exposures to ensure attendants had returned to DCIEM repetitive factor 1.0 (i.e., no residual nitrogen load) prior to their next dive.[1]

DATA COLLECTION

Attendant Doppler sampling was undertaken according to the techniques described by Eatock and Nishi.[18] One Australian author (CVdB) travelled to Canada prior to the study to receive training in Doppler monitoring at DCIEM. All measurements were performed by this individual, or under his direct supervision. Recordings were undertaken using a 2.5MHz continuous-wave Doppler ultrasound device (TSI DBM 9008, Techno Scientific Inc., Ontario, Canada) with a precordial Doppler array probe (TSI-DPA7). Doppler recordings were taken over the precordium and each subclavian vein at 20-minute intervals for up to two hours from the start of decompression (or until any bubbles detected had peaked and clearly started to decline) and recorded onto magnetic audio cassettes. The first recording was performed immediately after the attendant exited the chamber. Each 20-minute recording included the following:

- precordium, at rest – 60 seconds
- precordium, three squats – 30 sec after each
- subclavian veins, at rest – 30 sec
- subclavian veins, three hand clenches – 15 sec after each.

Subclavian measurements were performed bilaterally. A standard questionnaire was completed pre- and post-exposure on days of Doppler scanning. Personnel were also required to report any symptoms arising within 24 hours post-exposure.

DATA ANALYSIS

Doppler recordings were graded aurally using the methodology described by Kisman and Masurel (K-M code).[8,19] This consists of a three-part assessment that analyzes (i) frequency, (ii) either percentage [at rest] or duration [following movement] and (iii) amplitude of detected bubbles, to yield a single bubble grade (0-IV). K-M Grades 0-I may be considered to indicate ‘low’, Grade II ‘intermediate’ and Grades III-IV ‘high’ sub-clinical decompression stress. It was decided in advance that our 243 kPa table would be deemed ‘safe’ if it complied with DCIEM-defined limits of acceptability (Grade II or fewer bubbles in 50% or more of the subjects), or in need of revision if it fell outside these limits.

Aural scoring is known to be observer-dependent; therefore all Doppler recordings were graded by the single author who had undergone DCIEM training. A random sample of 10% of recordings was scored independently at DCIEM and the results compared. No grading discrepancies between observers occurred in this sample.

Bubble grades were treated as categorical data for statistical analysis. The highest K-M bubble grade following each hyperbaric exposure was tabulated for statistical comparison. Analysis was completed using GraphPad Prism® version 4.03 for Windows (GraphPad Software, San Diego, California, USA, 2005). Given the relatively small numbers in this study, bubble grades were dichotomized into ‘acceptable’ (Grades 0-II) versus ‘unacceptable’ (Grades III-IV) and demographic variables similarly dichotomized to facilitate subsequent statistical analysis. The thresholds for division of each demographic variable were as follows: Age < or ≥ 40 years (age when institutional policy mandates change from biennial to annual medical examination), BMI ≤ or > 25.5 (underweight/normal versus overweight/obese), and sex (male versus female). The resulting 2 x 2 contingency tables were subjected to Fisher’s exact test. All tests were two-tailed and $P < 0.05$ was considered statistically significant.

Results

Fifty personnel underwent 1,887 attendant exposures to our 14:90:20 profile between April 2001 and November 2004. Of these, 28 (56%) participated in the Doppler research. These 28 individuals contributed the vast majority of personnel exposures to pressure, performing 1,743 (92%) of the dives. Of these 1,743 exposures, 163 were subject to Doppler analysis (9.4%). Baseline demographic data revealed that the study participants and non-participants were comparable in all respects other than frequency of hyperbaric exposure (Table 1). The reasons for non-participation were invariably logistic (personnel with other commitments following completion of exposure).

Two sub-groups of participants were compared based upon work patterns: regular (multiple exposures per week) versus casual personnel (less than two exposures per week). No significant demographic differences were found between these groups, except for hyperbaric exposure frequency

Table 1
Demographic data (participants versus non-participants)

Variable	**Participants** (n = 28)	**Non-Participants** (n = 22)	***P*-value**
Age (yrs)			
Mean (SD)	37.2 (7.7)	35.6 (5.3)	0.43
Sex; n (%)			
Male	9 (32)	7 (32)	1.00
Female	19 (68)	15 (68)	
BMI ($kg.m^{-2}$)			
Mean (SD)	25.0 (2.8)	24.3 (4.3)	0.51
No. dives in study period			
Range	1–416	1–22	
Mean (SD)	62 (103)	6 (5)	0.015
Total (%)	1743 (92.4)	144 (7.6)	

Table 2
Demographic data of participants
(casual versus regular attendants)

Variable	**Casual** (n = 23)	**Regular** (n = 5)	***P*-value**
Age (yrs)			
Mean (SD)	36.8 (7.2)	39.0 (7.7)	0.57
Sex; n (%)			
Male	8 (34.8)	1 (20.0)	1.00
Female	15 (65.2)	4 (80.0)	
BMI (kg.m^{-2})			
Mean (SD)	25.2 (1.5)	23.9 (2.2)	0.50
No. dives during study period			
Range	1–98	37–416	
Dopplered	*1–8*	*15–26*	
Mean (SD)	28 (27)	219 (172)	<0.0001
Dopplered	*2 (1)*	*21 (5)*	*<0.0001*
Total (%)	648 (37.2)	1095 (62.8)	
Dopplered; n (%)	*57 (35.0)*	*106 (65.0)*	

Table 3
Individual attendants' bubble grades;
BMI - body mass index

	Age yrs	**Sex**	**BMI** kg.m^{-2}	**Monitored** **dives** (n)	**Bubble range** Median	 Mode	 Range
Regular attendants							
1	42–46	F	22.5	26	II	II	O–III
2	32–35	F	23.8	25	I	I	O–II
18	25–27	F	20.5	17	O	O	O–I
21	41	M	26.5	15	O	O	O–III
23	47–50	F	26.4	23	II	II	I–III
Casual attendants							
3	28–30	M	22.5	2	O/I	O/I	O–I
4	34–35	M	26.1	4	I	I	I–III
5	41–42	M	27.5	3	I	I	O–I
6	44	F	23.6	4	II	II	I–III
7	25	F	20.2	1	O	O	O
8	28	F	26.2	1	II	II	II
9	44–46	F	25.2	8	I	O	O–III
10	23	F	22.8	2	O	O	O
11	31	M	21.1	1	O	O	O
12	36	F	33.7	1	O	O	O
13	35	F	22.8	2	O	O	O
14	31–32	F	25.1	5	O	O	O
15	37–38	F	23.3	2	O/I	O/I	O–I
16	31	M	19.0	2	O	O	O
17	35	F	32.3	3	O	O	O–I
19	30–31	M	20.7	2	O	O	O
20	52–53	F	24.2	3	I	I	O–I
22	37	F	25.6	2	O	O	O
24	52	F	28.7	1	II	II	II
25	42	M	31.0	1	II	II	II
26	33	M	30.2	3	I	I	O-I
27	38–39	F	28.4	2	O/I	O/I	O–I
28	41	F	20.3	2	O/IV	O/IV	O–IV

Table 4
Relationship of bubble grade to demographic variables

Variable	**Grade O-II**	**Grade III-IV**	***P*-value**
Age (yrs)			
20–39	76	1	0.0004
40–54	71	15	
Sex			
Male	31	2	0.53
Female	116	14	
BMI (kg.m^{-2})			
≤25.5	93	9	0.59
>25.5	54	7	
Exposure			
Casual	53	4	0.58
Regular	94	12	

Table 5
Times to onset and peak bubble grades

	Onset (precordial at rest)	**Onset** (all sites/states)	***P*-value**
Number (%)	50 (31)	98 (60)	
Mean (SD)	41 (17)	29 (13)	<0.0001
Range (min)	18–80	18–95	
	Peak (precordial at rest)	**Peak** (all sites/states)	***P*-Value**
Number (%)	50 (31)	98 (60)	
Mean (SD)	54 (17)	51 (18)	0.21
Range	18–74	20–95	

(Table 2). Individual attendants' bubble grades are presented in Table 3. The relationships between bubble grades and demographic variables are shown in Table 4. No cases of clinical DCS were identified following any of the 1,887 attendant exposures to this profile during the study period.

Bubbles were first detectable in the circulation an average of 29 minutes post-decompression and peak grades were achieved at around the 50-minute mark. There was a significant delay in onset time of detectable bubbles if only the precordial readings taken at rest were considered. The times to onset (non-zero) and peak bubble grades encountered in our cohort are shown in Table 5.

K-M bubble grades of II or less were encountered in 147 (90%) of the exposures studied when data from all sites/states (i.e., subclavian or precordial, at rest or following movement) were included, with 68% of exposures resulting in 'low', 22% in 'intermediate' and 10% in 'high' sub-clinical decompression stress (Figure 2). These figures changed to 94%, 5% and 1% respectively when only the precordial readings taken at rest were considered – with 161 dives (99%) now having a K-M bubble grade of II or less (Figure 3). These results were within the DCIEM-defined limits of acceptability.

Figure 2
Distribution of maximum bubble grades (all sites and states)

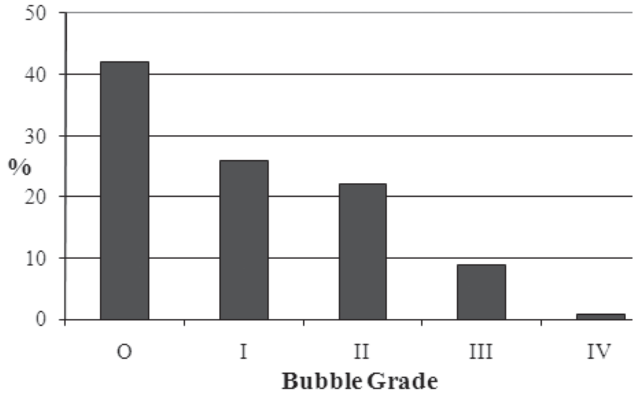
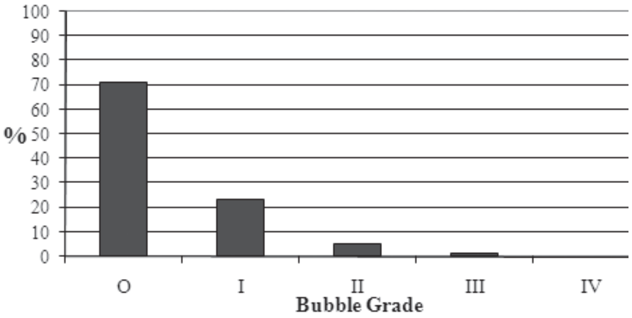


Figure 3
Distribution of bubble grades (precordial at rest)



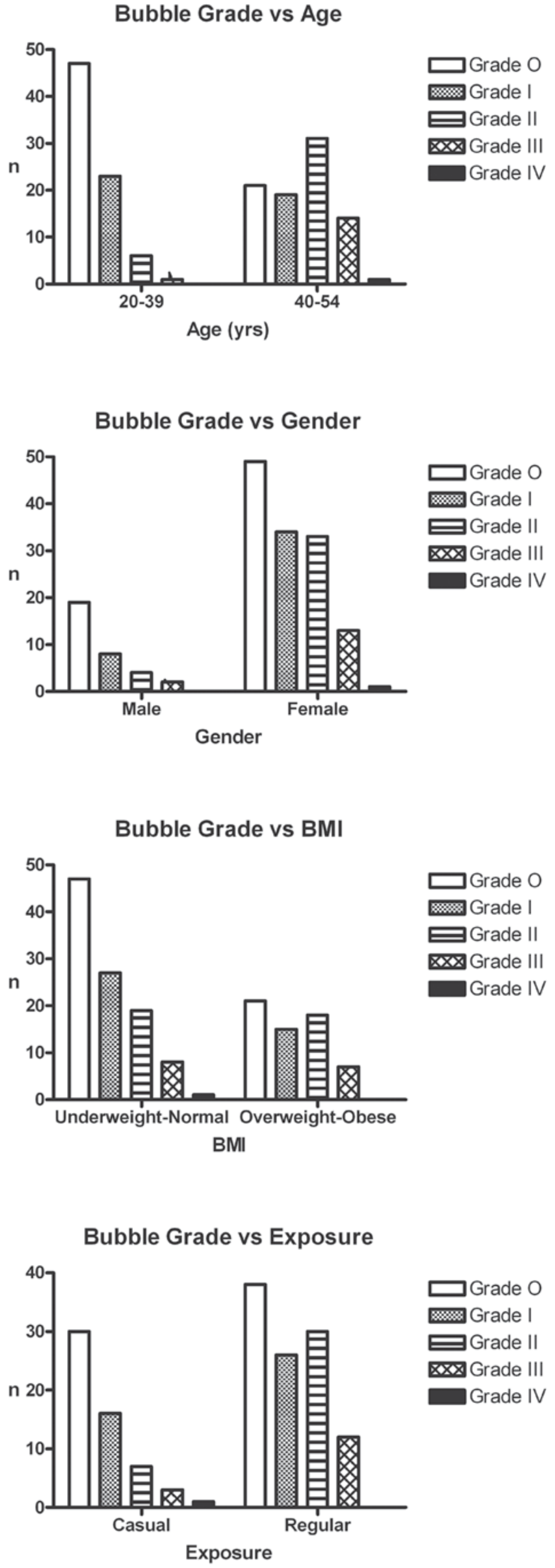
Increasing age, BMI, female gender and frequency of hyperbaric exposure were all associated with a trend towards higher bubble grades (Figure 4). However, only the relationship between bubble grade and age reached statistical significance in this cohort (Table 4).

Similarly, a considerable degree of intra-individual variability became evident as sample numbers on individual attendants increased. Higher bubble grades than usual for a given individual were encountered following injury, illness or exertion; unfortunately the small numbers involved precluded meaningful statistical analysis. Three individual cases may illustrate this point.

CASE A

Attendant 21 (41-year-old male – studied on 15 occasions) scored Grade 0 bubbles on the first 11 occasions. Following a gym-related groin strain he scored Grade II–III bubbles for more than three weeks post-event without further recognized injury (four further sets of Doppler recordings). His injury remained symptomatic throughout this time. This individual stopped working as an attendant because of this unusual and prolonged elevation in bubble grades and subsequently left the service. Follow-up data are not available.

Figure 4
Relationship of bubble grade to demographic variables



CASE B
Attendant 1 (female aged 42–46 years – studied on 26 occasions) sustained multiple musculoskeletal injuries playing netball during the course of the study – including a fractured finger, bilateral ankle sprains, hamstring injuries and numerous contusions. Elevated bubble grades were apparent when pre- and post-injury results were compared. These injuries occurred with such frequency that her true 'baseline' (totally uninjured) level of bubbling was difficult to establish. The majority of bubbles post-injury were detected coming from the affected limb (precordial for lower limb, precordial plus subclavian on affected side for upper limb injuries) with a smaller but more generalized elevation in bubble grades apparent in readings from uninjured limbs.

CASE C
The only Grade IV bubbles in this study occurred on the first occasion that Doppler was performed on Attendant 28 (41-year-old female – studied twice). Review of her pre-exposure questionnaire revealed chronic neck/back pain, a 'slight cold' (but able to equalize middle-ear pressures easily) and performance of 40 minutes of moderately strenuous gym exercise prior to the hyperbaric exposure. Follow-up Doppler 18 hours later gave Grade 0 bubbles. After her next hyperbaric exposure six days later, she had a Grade 0 bubble score. Within the next week she discovered that she was pregnant and ceased work at the chamber. The chronic neck/back ache and upper respiratory tract symptoms remained unchanged throughout.

Smaller fluctuations around an individual's mode were also seen, often not obviously associated with any specific identifiable event but appearing to reflect a 'normal' day-to-day variation.

Discussion

The maintenance of a safe working environment in hyperbaric medicine is of paramount importance to employers and employees worldwide. Most attention has been paid to the incidence of decompression sickness (DCS), and a ten-fold variation in incidence rates (0.076%–0.76%) has been reported from various hyperbaric units.[2,20] No episodes of clinical DCS occurred in over 4,000 exposures to our 243 kPa treatment table during the first fourteen years of chamber operations (January 1992 to December 2005), (95% CI 0.00, 0.09% incidence of DCS).[21] Nearly 10% of the hyperbaric exposures during the study period were subjected to Doppler analysis and demonstrated a bubble grade distribution within DCIEM 'safe' decompression recommendations (Grade II or fewer bubbles in 50% or more of the subjects).

Despite the increasing complexity of techniques used to model dive profiles, to date no theoretical model has been able to offer more than an approximation to the profound physiological subtleties encountered in real life. Hence, the need to develop experimental and investigational techniques to complement the modelling processes has long been recognized.[4,5,9,10] No 'gold standard' test is yet available, however, that can be said unequivocally to measure decompression stress throughout the body.

Of the techniques developed so far, Doppler detection of intra-vascular bubbles has arguably the greatest utility and most extensive evidence base.[4–9,22] The technology is relatively inexpensive, portable, robust and readily available and the skills necessary for standardized data acquisition are easily learned. Bubble detection provides significantly more information about the relative severity of a given exposure than does the simple incidence of clinical DCS. Despite these advantages, Doppler is not without its critics and certain limitations to the technique must be acknowledged.

- It is time consuming and labour intensive.
- It detects moving bubbles within the vascular tree only, which may not be representative of events in other tissues.
- Data analysis is dependent upon aural grading, requires more training to perform reproducibly than does simple data acquisition and is still potentially subject to inter-observer variability.
- The data collected are only semi-quantitative – with a non-linear correlation between grades assigned and bubble size or number.
- Bubble grades are ranked (non-parametric) data and the intervals between the ranks cannot be assumed to be uniform.
- The relationship between bubble grade and risk of DCS is non-linear and dependent on, amongst other things, gas mix breathed (e.g., Heliox versus air).[6]
- Intermittent data acquisition raises the possibility of missing the highest bubble grade.

The issues of where and when to obtain Doppler data post-exposure also remain open to debate. Some authorities contend that, since the final common pathway for venous bubbles is the right heart, precordial readings alone should be adequate. However, the difference noted between our all-sites readings and precordial readings alone of 60% versus 47% suggest a considerable reduction in sensitivity if this approach is adopted, possibly because of the increased complexity of identifying and classifying bubbles in the high-noise environment of the precordium.[5,7,8]

A further potential confounding variable also exists. The administration of oxygen during decompression may, by preferentially enhancing denitrogenation of the fast tissues, introduce a lead-time bias into the evolution of maximum bubble grades.[23] This delay in onset and time to peak may cause Doppler sampling to be ceased prematurely and with a false sense of security. Given the relatively short time to onset of Doppler-detectable bubbles encountered in this group (Table 5), and our policy of ensuring that sampling was continued for two hours or until any bubbles detected had peaked and clearly started to decline, we believe this risk to be minimized.

If these limitations are understood and accepted, then the Doppler detection of intra-vascular bubbles remains a useful tool in the assessment of sub-clinical degrees of decompression stress. To date, no other technology has demonstrated superiority over Doppler in the evaluation of decompression stress.

This was a single-centre study designed primarily to assess the safety of one, highly conservative, hyperbaric exposure profile. This end was achieved and a number of demographic variables were identified as predisposing attendants to increased sub-clinical decompression stress. Of these variables, in this series, older age appears to be the most important criterion to differentiate between individuals' decompression risks. Within a given attendant, injury, illness and peri-exposure exertion also appear to increase decompression stress. A generalized increase in bubble grade (i.e., not just arising from the affected limb) supports the presence of both systemic and local effects in the increased predisposition to bubble formation seen post-injury. The difference between Grade IV and Grade 0 bubbles in Attendant 28 appears due to her vigorous pre-dive physical work-out – although hormonal changes over this six-day period of very early pregnancy (i.e., surrounding blastocyst implantation) may have contributed.

The main limitation of this study was the percentage (56%) of eligible attendants studied. Despite the fact that these participants performed 92% of the dives on this table during the study period, a larger cohort undergoing Doppler monitoring would have enhanced the strength of the study. No attendant actually declined to participate in the study, but other duties frequently prevented casual personnel from remaining in the unit for the requisite two hours post-exposure. Likewise, other demands on technical personnel prevented more exposures being captured with Doppler.

Conclusions

This is the largest Doppler series of a single hyperbaric profile yet published and, we believe, demonstrates that maintenance of a safe workplace for in-chamber attendants does not pose an insurmountable problem. Our institutional policies and procedures appear to provide an acceptably safe working environment and will therefore remain unchanged. Differences between decompression strategies are likely to be the reason for our improved outcomes when compared with previously published series. More research and larger numbers will be needed to resolve issues such as optimal retirement age from in-chamber duties, appropriate stand-down times following injury and restrictions on pre- and post-dive exercise.

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