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Decompression Trials National Hyperbaric Centre, 1999

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Decompression Trials
National Hyperbaric Centre, 1999

Prepared by
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This report describes trials carried out at the National Hyperbaric Centre in Aberdeen during March 1999. The objective of the trials was to determine the probability that during operational diving decompression bubbles were formed to an extent which resulted in Doppler grades in excess of grade 2. The profile chosen for the study was 30 minutes at 130 feet, 39.4 metres, with decompression using Sur-D profile. Twenty divers took part in a total of 30 dives, each diver completing 3 runs separated by 1 week. During the time in the water the divers were required to exercise continuously at a relatively low level of activity. All aspects of the procedure were monitored so that the variability of the exposure could be evaluated. From these data it is possible to conclude that all subjects experienced the same exposure.

The primary conclusion from these trials is that 71.4% of the subjects had bubble grades higher than grade 2 and there is a 95% probability that at least 50% of divers will have grades in excess of 2 for this exposure. The between diver variability is much lower than seen on previous trials and this is believed to result from the constant level of physical activity of the divers during the uptake phase. For Doppler, 67.9% gave grades at rest within one grade of the central; 58.9% gave grade 3 on the scanner. Predicted 95% ranges for the population are 55.5 to 80.5 for Doppler at rest and 45.9 to 72.1% for scanner at rest. Three repeat trials are not sufficient to carry out a proper analysis of the within diver variability and the results do not give a clear cut picture to allow a qualitative statement to be made.

Theoretical analysis shows that the bubbles detected following the end of decompression are predominantly from muscle. The results seem to indicate that the muscle was saturated during the exposure and it is suggested that normal activity during operational dives would also lead to muscle saturations for all except the very shortest bottom times.

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1.0 INTRODUCTION

The trials described in this report are the most recent activity in a long programme of research sponsored by the UK Health and Safety Executive (HSE) into the risks and detrimental affects of diving on the health of the diver with particular reference to long term consequences.

During the course of this programme, and as a direct result of it, the incidence of decompression illness (DCI) for air diving in the North Sea has been considerably reduced from levels ranging to almost 0.5%, depending on the type of diving, down to 0.07% in 1990. Much of the improvement followed restrictions on depth-time exposures detailed in "Exposure limits for air diving operations" 1990.

In 1998 HSE sponsored a workshop attended by invited participants each of whom have some considerable expertise in scientific research into decompression problems. The purpose of this workshop was to peer review the HSE research programme to date and to consider HSE's plans for the direction of future work. The outcome of the workshop was an endorsement of two parallel lines of research:-

> to continue to seek to reduce the risks associated with decompression by setting performance standards which will result in a reduced level of decompression bubble formation;
>
> to pursue a programme designed to investigate and evaluate the long term health effects of diving.

The present study is the beginning of the first line of investigation. Research to date has focused on DCI and nothing is really known about the extent of formation of decompression gas bubbles during operational diving in the North Sea. It is necessary to determine the extent of bubble formation as a base-line against which to evaluate improvement. Before deciding whether or not to initiate a major study of gas bubble incidence off-shore HSE decided to carry out trials designed to reproduce off-shore activity as closely as possible but with the ability to control all aspects of the hyperbaric exposure. This means running the trials in an on-shore hyperbaric facility and the National Hyperbaric Centre was the obvious choice. Unimed Scientific Ltd was asked to take responsibility of the scientific arrangements for the trials.

1.1 THE PROJECT

There were 3 main objectives for this study:

- to see if decompression bubbles form following an hyperbaric exposure which is at the Health and Safety Executive limits for Surface Decompression air diving;
- to look at the range of decompression bubble counts which occur in different individuals when all have had the same exposure
- to look at the range of bubble counts which can occur in an individual following repeat, identical, exposures.

These objectives were achieved by :

- selecting a depth-time exposure which is just within the limits currently in use
- to expose a small group of subjects to an hyperbaric exposure which is identical for all within reasonable operational restraints
- to have each subject complete 3 such trials separated by a sufficient length of time to reduce virtually to zero the possibility of a cumulative effect

This report describes the way in which these carefully controlled exposures were achieved and gives details of the extent of decompression bubble formation.

2.0 PRE-TRIAL PLANNING

Earlier decompression trials resulted in a very wide spread of bubble grades following supposedly similar exposures. The extent of the variability was such that it was almost impossible to form a consistent picture of the relative risks of different exposures. A theoretical study, carried out for the Health and Safety Executive (Flook 1998), highlighted possible sources of variability both between and within subjects. In addition to the obvious need to control carefully the hyperbaric exposure itself, it could be shown that a great deal of variability could arise from diver's skin temperature and from the physical activity of the divers during the time spent at maximum depth and during decompression. Thus much of the pre-trial planning was designed to ensure a closer group of results if possible.

2.1 SELECTION OF HYPERBARIC EXPOSURE

The Health and Safety Executive requested that the hyperbaric exposure used for this trial was a Surface Decompression, Sur-D, with a maximum depth and time on the current Exposure Limits. Two possible exposures were selected 150 feet for 25 minute or 130 feet for 30 minutes. Equivalent depths in metres are 45.45 and 39.4 metres. The decompression procedure was to be that used by a UK diving company in the UK sector. This would mean using the Sur-D table for 42 metres for the 130 feet exposure or 48 metres for the 150 feet exposure.

An initial theoretical simulation of the exposures indicated that 25 minutes at 45.45 metres, decompressing on the 48 metre table, would give more bubbles than would the 30 minute exposure at 39.4 metres, decompressing on the 42 metre table.

Because these trials were intended to give some indication of what might be happening off-shore it was important to choose between these two exposures not only in terms of likely bubble counts but also according to which was most used off-shore. Reference to Gardiner 1997 shows that there are approximately 3 times as many exposures to 39.4 metres than to 45.45 metres for Sur-D decompression.

On this basis it was decided to use 30 minutes at 39.4 metres. Table 1 gives details of the profile.

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Table 1

Decompression from 30 minutes at 39.4 metres

First ascent (mins)	In water stop 9 metres (mins)	Surface interval (mins)	In chamber oxygen (mins)	Time to surface (mins)
2:45	5	3	30	6

The surface interval is taken from reaching surface to reaching 12 metres on the chamber recompression.

2.1.1 Theoretical predictions of bubble formation

The mathematical model described in Flook 1998 was used to predict the extent of bubble formation at the end of the chosen exposure. Divers were assumed to be at rest except during the 30 minutes at maximum depth. Simulations were made for two conditions at maximum depth, for the diver completely at rest and for the diver with muscle blood flow increased to 6 times the resting level. This level of activity corresponds approximately to work at 20% of maximum oxygen consumption for a person of average fitness (Åstrand and Rodahl 1986, Ruch and Paton 1974), a heart rate of about 100 beats/minute. This is a level of activity which should be easily achieved in water and easily sustainable for the required time even by an unfit diver. It should result in the time constant for muscle being decreased from the normal resting value of 50.6 minute to 10.7 minutes and the muscle should be almost fully saturated during a 30 minute exposure.

Predictions were made of the volume of gas which might be carried in bubbles per ml of mixed venous, or pulmonary artery, blood by using a weighted mean of the gas carried in bubbles in venous blood draining all parts of the body. This corresponds to the gas in bubbles which will be detected by precordial Doppler or scanning. The predicted peak gas carried in bubbles in the pulmonary artery for the body at rest throughout the exposure is 0.0020 ml/ml and for the body working at the level described above 0.0048 ml/ml.

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Predictions made by a mathematical model should never be used quantitatively but only to make comparison with what is known and for this we have to refer to the earlier study. Table 6 in Flook 1998 shows that in that study profile H was predicted to have 0.0049 ml/ml gas carried as bubbles. Reference to the bubble grades for that profile shows what is in effect a bimodal distribution, almost half the divers showing no bubbles and 75% of those who did bubble giving grade 3. Unfortunately in that trial the divers carried out a programme of intermittent physical activity which means that the average muscle blood flow, and gas uptake, is very dependent on personal physical fitness. The data could be interpreted as showing that half of the divers were much fitter than the other half and spent less time with a raised blood flow thereby taking up less gas. If we say that those who bubbled are the group to be compared to the predictions for the working diver in the present study, then we might expect bubble grades to centre on a Kisman Masurel Doppler grade 3 in the present study.

A similar result is obtained by converting the predicted gas in bubbles to predicted bubble counts using the relationship derived in the validation of the model against animal experiments (Flook and Brubakk 1996) and quoted as figure 2 in Flook 1998. The relationship between bubble counts and bubble grades published by Brubakk et al (1998) can then be used to convert from bubble counts to Doppler score. Going by this route, which involves a completely different set of assumptions from the previous argument, bubble grades would be predicted to be a little higher at grade 4.

Neither of these ways of using the predictions from the model are ideal. Unfortunately we do not have data for hyperbaric exposure in humans where the activity at maximum pressure is sufficiently well defined to enable a proper estimate of muscle time constant. Therefore we do not have the possibility of making a direct link between predictions and recorded bubble grades for humans. However the less than perfect approaches described above seem to indicate that bubble grades of 3 or more will be common in this study.

Having made these predictions it was decided to go ahead with the 30 minutes at 39.4 metres exposure with the expectation that a significant level of bubbling was likely in most divers.

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2.2 DESIGN OF THE TRIALS

Experience with earlier studies (Flook 1998) demonstrated that in addition to the decompression profile itself the other strong influences on decompression bubble formation are body surface temperature and physical activity throughout the exposure. The design of these trials focused on control of these factors. The dive profile was carried out with attention to the details of depths, times and rate of moves in order to ensure that all subjects experienced the same exposures. Details were recorded by an observer who was independent of the chamber control team whenever it was possible to fit such measurements in with other activities. The results, reported later, include information about the variability of every aspect of the exposure.

Chamber and hot water temperatures were carefully controlled within narrow limits and the variability is report in the results section.

The physical activity and physiological status of the subjects was carefully controlled. The subjects were asked to be ready to begin at least 1 hour before the time planned for compression. This hour was spent with the subject lying at rest on a bunk. At the end of this time resting heart rate was taken. The subjects had all been asked not to drink caffeine or to smoke immediately prior to the trial and to have only a light meal before reporting in. The same restrictions applied right through until the final bubble measurements were recorded. They had access to non-caffeine fluids throughout.

Each subject was asked to take part in two repeat exposures at 1 week intervals. They were also asked not to undertake any diving between the repeat visits and for one week prior to the first visit. It was hoped by this means to remove the influence of other diving experience.

2.2.1 Activity at maximum depth

During the time at depth, in the water, it was considered essential that physical activity continued at a steady level without a break. This because the rate of stabilization at the start of exercise and the rate of recovery when exercise ceases both depend on physical fitness. There could be no attempt to select subjects having a similar level of fitness nor to make an adequate measurement of fitness of each subject before the trials started. It had to be assumed that they had a wide range of fitness and plan accordingly.

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The main object of using physical activity was to drive muscle blood flow so that differences between subjects were minimised. The only sure way to achieve this was to work the muscles so that the rate of gas uptake was high enough to ensure saturation of the muscle during the 30 minutes at maximum pressure. This meant achieving a muscle time constant of 10 minutes or less. As described above this can be done by working the subjects to a level which increases muscle blood flow by a factor of at least 6, to a heart rate of at least 100 beats/minute, though the working heart rate is dependent on fitness to some extent. Given that a higher level of activity could not increase gas uptake beyond saturation and given that saturation seemed to be achievable at a relatively low level of work, it was decided simply to have the divers "swimming" at a "reasonable" pace without stopping, for as much of the 30 minutes as possible. The pace would be monitored, and if necessary controlled, by an observer with the aid of CCTV. Ropes were stretched along the bottom of the tank so that the divers could pull themselves along. They were free to use fins if desired.

During the time at maximum depth when the divers were not engaged in this activity they were getting into the water, putting on their fins and generally being active.

2.2.2 Activity during decompression

Bubble formation is also influenced by physical activity during decompression and this was controlled as much as possible once maximum depth had been left. During the in-water decompression stop the divers were asked to stand still. This was followed by a climb into the transfer chamber just before and during the surface interval. Diving suits and breathing apparatus were removed and transfer to the dry chamber completed during the 3 minutes of the surface interval. During compression to 12 metres, for the oxygen decompression, the divers dried and dressed in the entry lock. Transfer to the living chamber occurred as soon as 12 metres was reached, divers laid down on the bunks and remained at rest for the remainder of the decompression. The activity during the transfer phase could not be controlled but was probably similar for all. Total time from stopping the controlled work to the diver being at rest, on the bunk, was measured and the details are given in the results section. Heart rates were recorded immediately the divers were at rest prior to starting oxygen breathing.

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2.3 QUANTIFICATION OF DECOMPRESSION BUBBLES

The subjects were monitored for decompression bubbles both by Doppler (Nishi 1993) and by ultrasonic scanning (Eftedal and Brubakk 1997). Doppler monitoring is a particulary difficult technique to master and for this reason technicians from DCIEM in Canada were invited to take part in the trials. Thus Doppler monitoring was carried out by the most experienced team in the world. One technician came for the first week and was replaced by a second for the other two weeks.

The most experienced team with ultrasonic scanning is from SINTEF Unimed in Norway and they were invited to send staff to carry out the scanning. Unfortunately they could only cover the first two weeks so the author of this report had to take over for the third week. Fortuitously this arrangement of technician cover for the two techniques worked out in a way which allowed full comparisons to be made to detect any serious difference in scoring between technicians and the outcome is reported in the results section.

Monitoring for each technique was carried out at 15 minute intervals for the first 90 minutes after the end of decompression, thereafter at 20 minute intervals to 120 minutes from the end of decompression. Monitoring was continued longer if neccesary to demonstrate that bubble numbers were decreasing. Thus each diver was monitored every 7.5 initially and every 10 minutes after 90 minutes. Doppler and scanner were in separate rooms and there was no communication about results at any stage. The scientist in charge of the trials removed the data sheets at the end of each session so that the technicians for each technique remained in ignorance of the results from the other technique. All groups were anxious that it be done this way because these trials provide the first opportunity to make a direct comparison between the two techniques.

All monitoring sessions were recorded to allow future audit if required.

2.3.1 Doppler scoring

Doppler scoring was carried out using the Kisman Masurel system fully described in Nishi 1993. The sites chosen for monitoring were precordial and bilateral subclavian veins. This latter site was of interest because the divers were expected to be using their arm muscles a lot as they pulled themselves along the rope. Final bubble grades by this technique are : 0, 1-, 1, 1+, 2-, 2, 2+, 3-, 3, 3+, 4-, 4. In practise, as will be seen from the results, intermediate grades 1-, 1+, 2- and 2+ rarely occur.

Subjects stand throughout this procedure, figure 1. Results are recorded for the subject at rest and following a carefully controlled movement designed to increase blood flow and flush forward any bubbles adhering to blood vessel walls. For precordial bubbles the movement is a deep knee-bend. For subclavian bubbles the movement is a 4 second squeeze of hand and forearm.

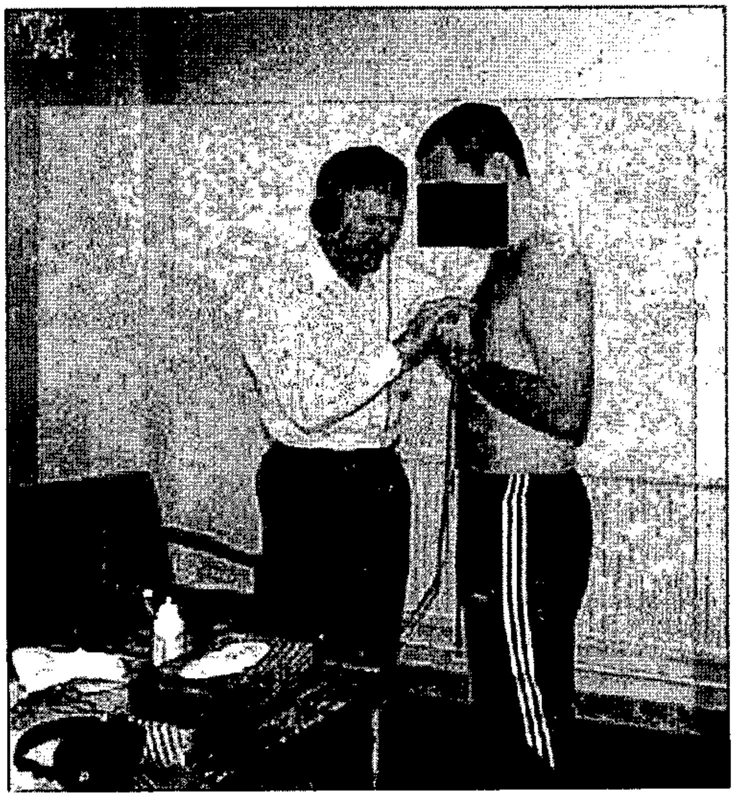

Figure 1 Precordial monitoring by Doppler

2.3.2 Ultrasonic scanning

Precordial bubbles only were used in ultrasonic scanning although on occasion the probe was positioned over the subclavian vein where bubbles were often plainly visible. The scoring system for this is fully described in Eftedal and Brubakk 1997.

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The subjects lie on their left side for this procedure, figure 2. The scoring is done at rest and after movement of the legs. The movement is not so easily controlled in a subject who is lying down however the act of climbing onto the couch is itself movement and, if an good image is obtained quickly, the movement grade is best determined then. A sufficient period of time is then allowed to pass before the resting recording is taken.

There are fewer grades for this technique 0, 1, 2, 3, 4. In practise grade 3 represents a very wide range of bubbling. Grades 1 and 2 are often difficult to define and differentiate. Frequently the bubbles are seen to be obviously going down, or up, in number but still technically fall within grade 3. As will be seen from the results, for the exposure used in these trials these minor problems were probably of little importance.

Figure 2 Precordial monitoring by ultrasonic scanner

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2.4 SUBJECT APPROVAL AND BRIEFING

The trials were brought to the attention of the Grampian Research Ethics Committee who considered the work to be for the purposes of setting a baseline for HSE and therefore not classified as research.

Prior to the trials all subjects had the purpose of the study explained to them and were encouraged to ask questions about it at any time. They were given a written explanation and time to study it before finally volunteering to take part. Each subject was given a code number on agreeing to take part.

The subjects were asked to take no caffeine on the day of a dive; not to smoke from the beginning of the preliminary rest period to the end of bubble counting; to rest during the 2 hours of bubble monitoring and not to eat, take caffeine or shower until the end of monitoring; not to undertake any other dives during the 3 week period of the trials.

At the beginning of each visit each subject was spoken to individually. In addition to using this time to ask about the date of their previous diving exposure, to check that no diving had been carried out in the intervening week, it allowed for discussion of any problems which may have arisen from the previous exposure. This gave them the opportunity to express any disquiet they might have felt and to ask questions.

In fact all showed a close interest and took the opportunity to ask questions throughout. Bubble monitoring was carried out in a suite of rooms which meant that the subjects were in easy social contact with the scientists throughout and there was a continuing dialogue between them about the trials and about the possible implications of the findings.

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3.0 RESULTS

Table 2 lists the characteristics of each diver. As can be seen there is a wide range of ages, shapes and sizes. The date of the last dive quoted in Table 2 refers to the last dive prior to the start of trials. Often the dates are approximate reflecting the fact that, the trials happening at the beginning of the season, many subjects had not dived for several months.

Mean age of the group was 37.6 ± 7.1 years, range from 27 to 54. Mean height was 1.78 ± 0.07 m, range 1.64 to 1.88. Mean weight was 80.45 ± 10.6 kg, range from 65 to 105. 8 were smokers.

Divers were asked about their drinking habits. This is a notoriously difficult habit to define and quantify. Three were non-drinkers, three admitted to drinking every day, usually several pints, up to 6, of beer. The greatest number drank once or twice a week at the weekend, again several, up to 10, pints of beer. One admitted to binge drinking at a frequency of about twice per year. This rough description shows that they probably matched the average diving population

Two of the dives did not go according to plan in that the duration of the surface interval was extended and the decision was taken to follow the chamber oxygen decompression for the next table down. Thus subjects 1 and 14 in week 1 and 25 and 39 in week 2 were excluded from the trials This means they only completed two exposures each.

Subject 24 dropped out after the first week to take up other work. He was replaced by subject 2 who completed two trials.

As a result of these changes only 15 subjects completed all three exposures; 5 completed two exposures.

Table 2

Characteristic of the subjects

Diver number	Age	Height	Weight	Smoker	Date of last dive
1	30	1.83	80.00	No	Feb 99
2	54	1.79	76.36	Yes	1997
3	27	1.64	73.00	No	Jan 99
5	27	1.82	80.00	Yes	Feb 99
6	36	1.83	76.36	No	Nov 98
8	42	1.68	82.73	Yes	Feb 99
10	29	1.88	75.00	Yes	Feb 99
11	39	1.68	65.00	No	Feb 99
12	41	1.78	76.36	No	Nov 98
14	39	1.83	76.36	No	Dec 98
17	39	1.83	79.55	Yes	Dec 98
19	42	1.78	80.00	No	Dec 98
21	37	1.73	79.55	No	Dec 98
24	37	1.82	92.27	No	Feb 99
25	35	1.88	105.0	No	Feb 99
28	42	1.75	87.00	No	Dec 98
32				Yes	
33				Yes	
36	31	1.69	72.00	No	Feb 99
37	31	1.73	67.00	No	Feb 99
39	48	1.80	105.0	Yes	Jan 99

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3.1 THE HYPERBARIC EXPOSURE

The characteristics of the hyperbaric exposure were monitored by the scientist in charge who was independent of the chamber control team. With a short exposure such as this, small variations in the rate of a move or the duration of a stop can be important. It was not possible to monitor all aspects of the exposure on every dive because of other commitments. Little monitoring was carried out during the first week.

The purpose of making these observations was to determine to what extent all subjects had the same exposure. Absolute measures of depth and time are less important than the variations. Pressures were recorded always from the same gauge and times recorded on a stop watch with reference to movement of the same gauge. Table 3 gives details of the average value, the number of observations and the coefficient of variation for the key aspects of the exposure.

Tank water temperature was the most variable of the parameters monitored but this is the least important of those listed because the subject is protected from the tank water by the water flowing in the diving suit. Tank water tended to increase during the course of the day as warm water was dumped from the diving suits.

Suit water temperature tells only part of the story about thermal well-being of the subjects because water flow was also varied to maintain comfort. There was no attempt to influence that. On several occasions there were problems with the water flow causing the divers to feel cold. The problems were immediately rectified. Because the divers' activity was being monitored and timed it was always possible to have a realistic estimate of the length of time for which the divers felt cold. This was almost always less than a minute.

Of the 3 temperatures which were monitored chamber temperature was the most important, because it influences skin blood flow throughout the chamber decompression. The coefficient of variation 4.4% was a little higher than might be considered ideal and chamber temperature did sometimes move more than 1°C from the desired mean.

Table 3

Characteristics and coefficient of variability for the hyperbaric exposure

	Number	Average	Coeff variation
Maximum depth (metres)	10	37.3	0.58%
Duration first move (mins)	17	2.44	3%
Depth in water stop (metres)	12	9.25	2.1%
Duration surface interval (mins)	16	2.77	4.1%
Duration last move (mins)	14	6.56	4.9%
Chamber temperature (mins)	23	21.95	4.4%
Tank water temperature (°C)	28	4.7	13.9%
Suit water temperature (°C)	30	40.1	1.7%

From these results it seems reasonable to conclude that all subjects experienced the same hyperbaric exposure.

3.2 PHYSICAL ACTIVITY

Details of the physical activity during the time in the water are given in Table 4. Subjects pulled themselves along the floor of the tank using a jack-rope and doing some finning. Most reported using their arms with relatively little finning. Movement was continuous throughout the time available, in general both divers kept together. The number of laps were counted and every 10 laps timed. Total duration of activity was recorded. These measurements allowed calculation of, for each diver, the average lap time, total number of laps, total distance covered and total exercise time. Mean values were calculated for each week using all the divers for that week.

Table 4

Physical activity during time in water, means with (coefficients of variability)

	Week 1	Week 2	Week 3
Mean total time (mins)	21.8 (7.7%)	22.3 (3.0%)	23.1 (5.6%)
Mean total distance (m)	541 (14.8%)	541 (14.5%)	581 (5.0%)
Mean average laptime (secs)	15.2 (12.9%)	15.0 (11.2%)	15.1 (7.6%)

Mean total exercise time increased with the week mainly because increased experience with the system led to an earlier start of activity after reaching maximum depth. Activity lasted for a statistically significantly greater time in week 3 compared to week 1 (unpaired Students t test, P = 0.012).

The variability for mean total distance and mean average laptimes are mostly larger than those for total activity time reflecting the range of speeds at which divers moved. There was some attempt to control this within limits but the divers quickly reverted to their natural pace. Given that the objective of the exercise was only to decrease muscle time constant to 11 minutes or less and to increase heart rate to something over 100 beats per minute, to ensure muscle saturation during the 30 minutes on the bottom, there was no need to control the upper limit of activity but only to ensure that a certain minimum level was reached.

There is a significant difference in variance for mean total distance week 1 compared to week 3 and for this reason a non-parametric test, Mann-Whitney, was used to compare total distance. The mean total distance covered in week 3 was significantly greater than that covered in the two previous weeks (P = 0.01).

There were also significant differences in variance for mean average lap time and a Mann-Whitney test was used to compare these. There were no significant differences between weeks. From this it is possible to conclude that the greater distance covered was a result of the longer time available for activity rather than differences in speed.

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Thus more physical activity was performed during the third week than during earlier weeks and if the activity has not achieved the objective of causing muscle to be saturated we might expect to see higher bubble counts during the third week. reflecting a greater gas uptake.

Heart rates were measured at the end of the pre-exposure rest period and again once the divers were in the chamber for the oxygen decompression. This final measurement was taken before the diver started to breath oxygen. Ideally the second measurement would have been taken at the end of the period of controlled activity but this was not possible as the divers were still in suits. The following period of time was taken up with carefully timed activities, to delay any of which would have resulted in the trial being aborted. Thus the final heart rate was measured at the earliest opportunity. The time interval between stopping the controlled activity and measurement of the heart rate was recorded and was 13.09 ± 0.52 minutes.

Resting heart rate before exposure was 73.5 ± 9.99 beats/minute, there was no significant difference between weeks. Final heart rate was 97.9 ± 18.17 beats/min with no significant different between weeks. This final value is close enough to 100 that, following as it does a period of very much reduced activity, it seems safe to assume that the controlled activity achieved the objective of raising heart rates to at least 100 beats/minute.

3.3 BUBBLE GRADES

Monitoring was carried out at 15 minutes intervals for each technique for the first 6 measurements, thereafter at 20 minute intervals. Therefore there is a time difference between the record for the Doppler and that for the scanner. This could be important for results which relate to the early, rising, phase of bubble counts but would be less important for the slow decay phase. There was no attempt to direct any subject to either monitoring technique first, most went first to one on 2 weeks and first to the other on 1 week. Five went to the same monitoring first on all three weeks. This is only of consequence when comparing all scores, it is less important when comparing maximum scores for the two technique. However when looking at time to maximum score it should be remembered that the timing is incremental not continuous.

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3.3.1 Maximum bubble grades - precordial bubbles

Bubble monitoring was intermittant, not continuous, therefore the highest grade recorded is only a maximum and it should not be regarded as a peak value. The true peak of bubbling may have occured between monitoring sessions.

Tables 5 and 6 show the maximum grades recorded at the precordial site both by Doppler and Ultrasonic scanning; table 5 shows the results recorded without movement, table 6 those recorded following movement which, as explained above, is used to flush out bubbles which may adhere to blood vessel walls. Figures 3 and 4 show the same information but presented as a histogram, frequency of occurrence of each maximum grade.

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Table 5

Maximum precordial bubble grades at rest

	DOPPLER			SCANNER		
Diver number	**Week 1**	**Week 2**	**Week 3**	**Week 1**	**Week 2**	**Week 3**
1		3	3-		3	3
2		3-	0		3	2
3	0	0	1	0	0	3
5	1	3-	3-	2	3	1
6	3	3+	3-	3	3	3
8	3-	3-	3-	2	3	3
10	3	0	0	3	0	0
11	3	1	1	2	0	1
12	3+	4	3+	3	3	3
14		3	3+		3	3
17	3	2	2	3	3	2
19	3-	3	3	3	2	1
21	4-	3	3	4	3	3
24	3			3		
25	3		3	3		3
28	2	2	2	1	2	0
32	4-	3	3-	4	3	3
33	3-	4-	3-	3	3	2
36	3-	3-	2	1	3	1
37	3-	3-	0	3	3	1
39	3		3	3		3

Table 6

Maximum precordial bubble grades after movement

	DOPPLER			SCANNER		
Diver number	**Week 1**	**Week 2**	**Week 3**	**Week 1**	**Week 2**	**Week 3**
1		4	3+		3	3
2		3-	1		3	3
3	0	0	1	0	0	3
5	2	3	3-	3	3	2
6	4	4	3+	3	4	4
8	3	3+	3	3	3	3
10	4	0	1	3	0	0
11	3+	2	1	3	1	2
12	4	4	3+	4	4	4
14		3+	4-		3	4
17	3+	3	3-	3	3	3
19	4-	4-	3	3	3	2
21	4	4	4	4	3	3
24	4			3		
25	4		4-	3		3
28	3-	3-	2	1	3	1
32	4	4	3-	4	3	4
33	4-	4-	3	3	3	3
36	3	3+	3+	3	3	3
37	3+	3-	0	3	3	2
39	4		4-	3		3

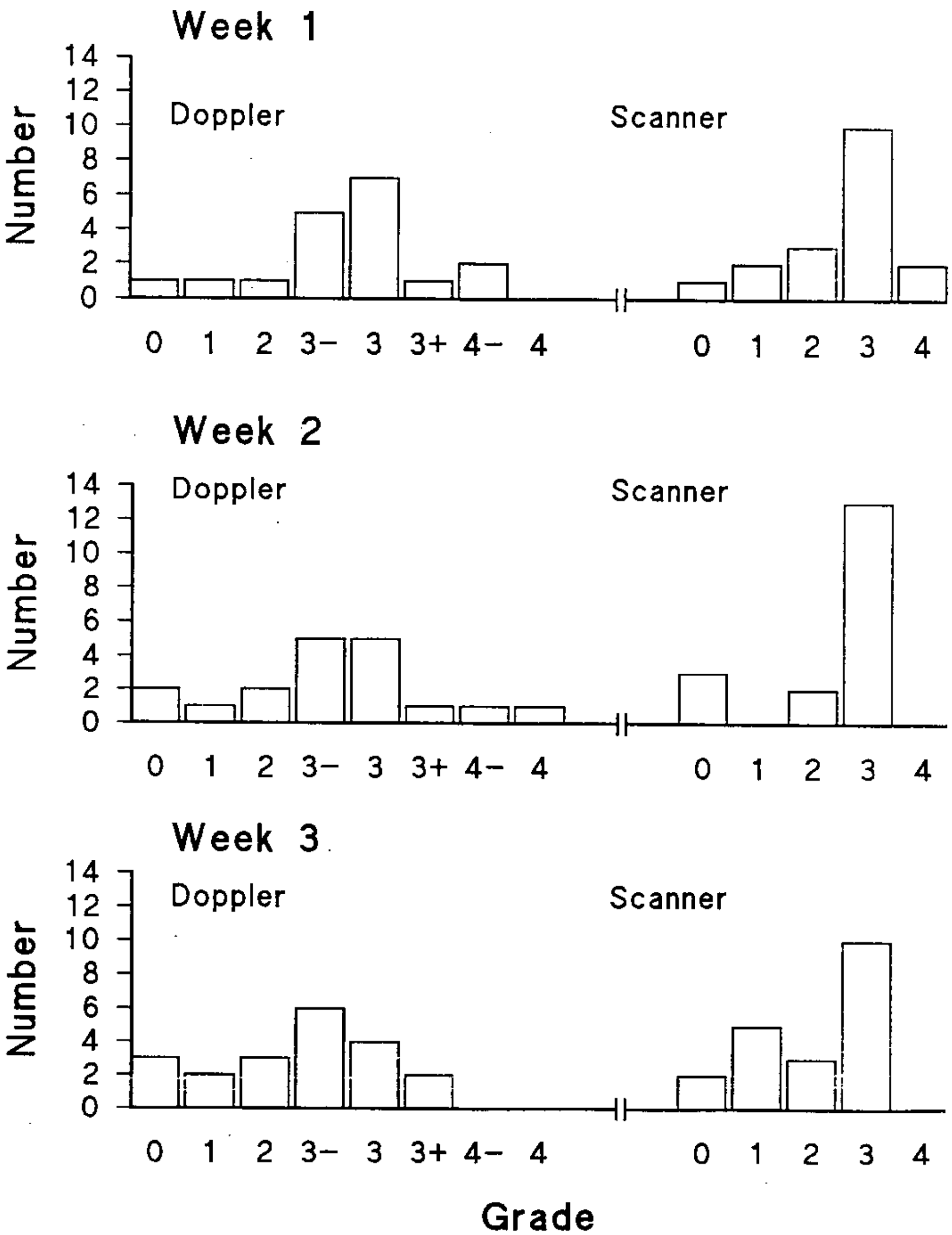

Figure 3 Histogram showing frequency of occurrence of each maximum bubble grade, at rest for both Doppler and scanner

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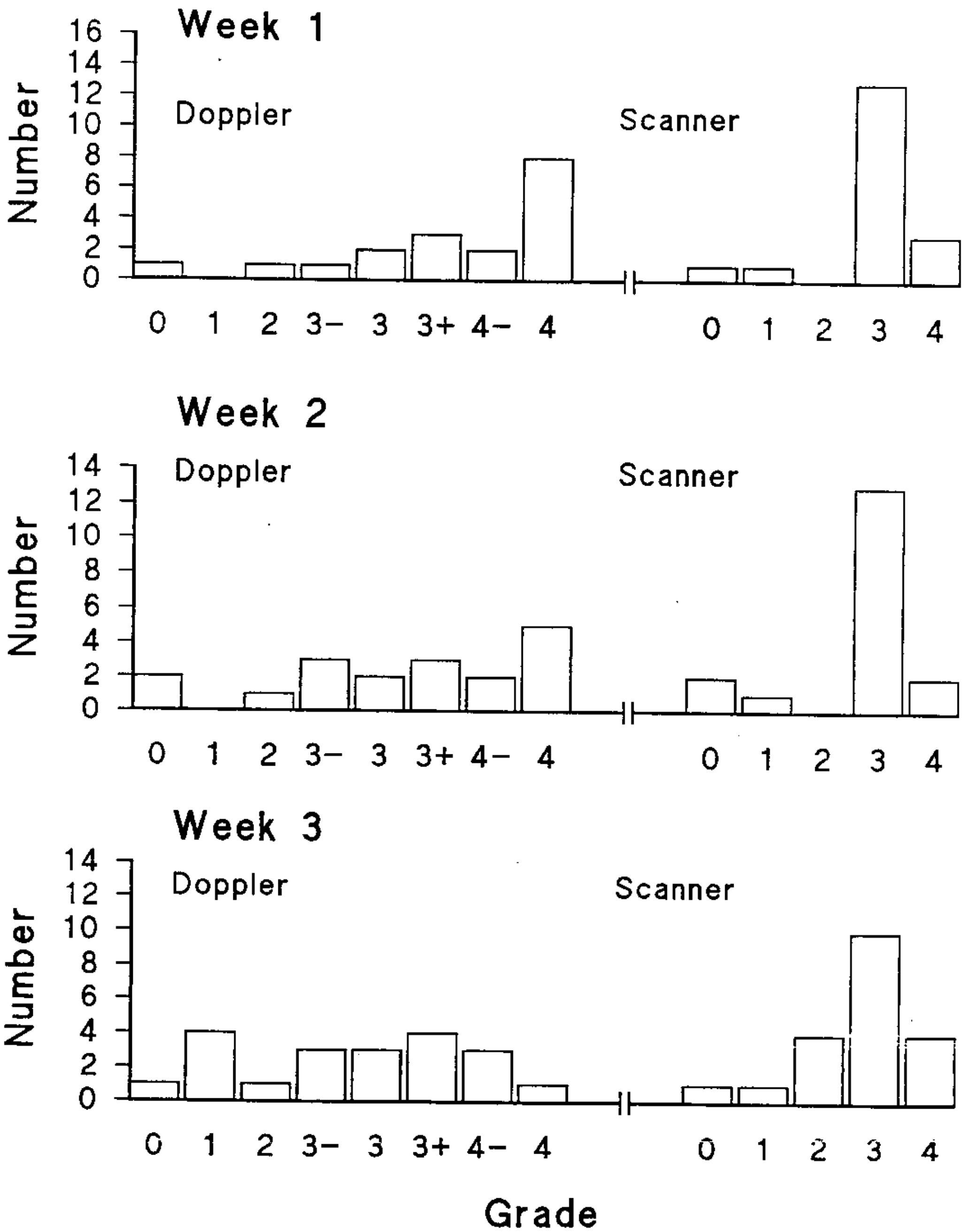

Figure 4 Histogram showing frequency of occurrence of each maximum bubble grade, after movement, for both Doppler and scanner

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The effect of changeover of technicians

Each technique for bubble monitoring was carried out by two technicians, a changeover occurring during the trials. It is necessary to consider the possibility that one person might score results very differently from the other. Doppler was recorded by one person for the first week and a different person for the last two weeks. Scanning was carried out by one person for the first two weeks and a different person for the third week. This arrangement makes it possible to compare three pairs of technicians; Doppler 1 against scanner 1, Doppler 2 against scanner 1 and Doppler 2 against scanner 2. The fact that the change-over week was different for the two techniques means that there is a continuity across all 3 weeks.

For these comparisons all scores have been used, not only the maximum scores. Contingency tables were constructed comparing the complete set of grades for each of the 3 weeks. The statistics used were weighted Kappa statistics (Altman 1991, Fleiss 1981) with the weighting factors chosen to extend across the whole range of bubble grades. It should be noted that this analysis not only tests similarity between technicians but also between the techniques and between the different scoring systems. The test will not allow identification of the source of any difference. However if there is no difference in the "match" between techniques from one week to the next, despite the change of technician, it is probably safe to say that the change of technician has not influenced the scoring.

The weighted Kappa scores for each of the three weeks were: 0.52 ± 0.07, 0.45 ± 0.08, 0.46 ± 0.08, each quoted with the standard error. A Kappa score of 0 means that any agreement is the result of chance; a Kappa score of 1 means perfect agreement. These scores are all significantly higher than zero, therefore the agreement is better than chance. The significance of Kappa values has not been evaluated to the same extent as other statistical tests but according to Altman (1991) Kappa values between 0.41 and 0.60 represent a moderate strength of agreement. The scores are not significantly different from each other in that all lie within 95% confidence limits of any other, 95% confidence limits extending to 1.96 times standard error. There is a larger standard error for the second 2 weeks indicating a greater variability but the significance of this has not been assessed.

Thus the change of technicians appears not to have influenced the data.

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Variability within subjects

The categorical nature of the data makes it impossible to carry out any statistical analyses of the week to week results for individual subjects, it can only be done for the group as a whole. Given that the week to week results have not been influenced by the change of technicians chi-squared tests can be carried out on maximum grades for each of the four conditions: Doppler at rest, scanner at rest, Doppler after movement, scanner after movement. The contingency tables for this test record frequency of occurrence of each grade for each week. The null hypothesis of the chi-squared test is that the distribution of grades are independent of the week in which the measurement was made. Because the number of subjects each week was small the expected frequency in each cell of the contingency table was smaller than ideal for a chi-squared test. To minimise this problem the number of grades for Doppler were reduced in that 3-, 3 and 3 were combined as were grades 4- and 4. For all four conditions the null hypothesis was true. Table 7 gives details of chi-squared value and the number of degrees of freedom for each condition.

Table 7

Results of chi squared test, see text for details.

	Chi squared	Degrees of freedom
Doppler at rest	4.2	8
Scanner at rest	11.1	8
Doppler after movement	11.6	8
Scanner after movement	9.3	8

Once the intermediate grades for Doppler have been removed both techniques have 8 degrees of freedom. For there to be a significant relationship between bubble grade and week (at 5% level) the chi squared values would have to exceed 15.5. Thus taken as a complete group of subjects the bubble grades are not influenced by whether it is the first, second or third week of the trials. This means that taken as a group there is no evidence for either acclimatization of build up of bubbles. It also means that the slight, but significant, increase in exercise carried out in week 3 had no measurable effect on bubble grade.

For the remainder of the analysis of the maximum bubble grades results from all 3 weeks have been combined.

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"Average" maximum bubble scores

Statistical analysis of Doppler or scanner grades is difficult because although the grades are ordered, in that grade 3 means more bubbles than grade 2, the interval between each grade is not known. We have no reason to suspect that, even within either technique, each interval is the same. There is some evidence that increasing grades may fit to a log relationship (Brubakk et al 1998) but as this evidence is itself based on a quantification derived from scanning caution may be appropriate.

The preferred measure of central tendency for categorical data is the median. However where there are an even number of subjects, as in this case, the median score should be taken as the average score of that for rank N/2 and (N+2)/2, for this work ranks 28 and 29. To take an average of Doppler or scanner scores implies a linear rate of change between grades. In practise, in this study the scores for the two adjacent ranks were always the same and therefore no assumptions need to be made in quoting a median.

Table 8 also lists the mode. This is the least informative assessment of central tendency but is the only correct one when there is no knowledge about the interval between grades.

Table 8

Central values of maximum bubble grades

	DOPPLER	SCANNER
	At rest	
Median	3-	3
Mode	3- & 3	3
	After movement	
Median	3+	3
Mode	4	3

Whatever the difficulties in making an analysis of the data it is clear that maximum grades for both Doppler and scanner, at rest and following movement, are mostly centred around grade 3. It is interesting to compare the distribution of bubble grades with that for profile H in the previous study, mentioned in section 2.1.1. There is no evidence of a bimodal distribution in the current study and this is believed to result from the continuous physical activity which allowed the uptake to be independent of physical fitness as described in section 2.2.1.

Variability between subjects

The problems of dealing with ordered categorical data for which nothing is known about the interval between categories, makes it difficult to evaluate the extent of scatter about the central score. I have attempted to get some indication of the closeness of the scores by looking at the percentage of subjects having bubble grades close to the central grade. Table 9 gives the percentage of subjects with a maximum Doppler bubble grade within one grade of the central and with a scanner grade equal to the central grade. For Doppler after movement where median and mode are very different the proportion in categories 3+ to 4 is given. The two techniques are handled differently because the scanner results do not break grade 3 into 3- and 3+.

Once the data has been reduced to this format it is possible to calculate the standard error of the proportion of subjects in the defined central category (Altman 1991) and thereby define the proportion of a population of divers who could be expected to fall within the central group. The basic assumption is that the sample studied is representative of the population. Table 9 also gives 95% confidence limits.

Table 9

Percentage of subjects close to central grade (see text for details)

DOPPLER		SCANNER	
At rest			
Percentage	95% limits	Percentage	95% limits
67.9	55.5 - 80.5	58.9	45.9 - 72.1
After movement			
Percentage	95% limits	Percentage	95% limits
55.4	41.7 - 68.3	64.3	51.2 - 76.8

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This analysis shows that for the hyperbaric exposure as carried out in these trials between 55.5 and 80.55 of divers will have Doppler bubbles at rest centred around grade 3-; between 45.9 and 72.1 % will have scanner grade 3 at rest; 41.2 to 68.3% will have Doppler grades after movement ranging from 3+ to 4; 51.2 to 76.8% will have scanner grade 3 after movement.

The proportion of subjects with grade 3- or higher

A more worthwhile analysis for the purpose of this study is to set confidence limits on the proportion of divers expected to give grade 3- or above for this hyperbaric exposure. Table 10 shows the results.

Table 10

Percentage of subjects with grade 3 and above

DOPPLER		SCANNER	
At rest			
Percentage	95% limits	Percentage	95% limits
71.4	59.5 - 83.4	62.5	49.6 - 75.4
After movement			
Percentage	95% limits	Percentage	95% limits
80.4	69.8 - 91.0	80.4	69.8 - 91.0

These results can be summarised by the statement that the 95% confidence limits indicate that over 49.6% of man-dives will result in bubble grades higher than 3- for the exposure used in this study if the subjects used in this study were a representative sample of divers.

Time to maximum grade

Tables 11 and 12 gives the time to maximum grade for Doppler and scanner at rest (table 11) and after movement (table 12).

Table 13 lists the average time to maximum bubbles together with the coefficient of variation. It must be remembered that the time scale is not continuous in that monitoring was carried out at discrete intervals and that if a subject was being monitored by Doppler he could not have a scanned grade for the same time. This is particularly important when the maximum bubble grade was recorded at the first visit.

The greatly delayed time to peak of subject 5 in week 1 Doppler after movement, highlights one of the problems with understanding the meaning of the results taken after movement. The peak was a grade 2, prior to that recording no bubbles had been recorded after movement although grade 1 bubbles at rest were recorded at 42 minutes. This does appear to be a case in which the actual grade recorded at 157 minutes may not relate at all to the true state but rather to the fact that bubbles were moved on from a stagnant part of the cardiovascular system. Excluding that reading the average time to maximum bubbles always occurred within 30 minutes of the end of decompression,

Table 11

Time to maximum precordial bubble grades at rest (mins)

DOPPLER				SCANNER		
Diver number	**Week 1**	**Week 2**	**Week 3**	**Week 1**	**Week 2**	**Week 3**
1		20	27		12	20
2		20			12	12
3			12			20
5	42	5	20	20	42	12
6	20	20	5	42	12	42
8	20	5	42	12	12	20
10	35			12		
11	27	12	5	20		12
12	42	27	12	21	20	5
14		42	5		5	27
17	8	5	35	15	12	27
19	5	20	27	12	12	5
21	27	27	27	35	20	35
24	20			12		
25	20		27	12		5
28	42	12	20	20	5	
32	27	35	27	20	12	20
33	20	12	20	27	37	27
36	50	35	42	12	27	5
37	72	12		65	5	27
39	12		20	20		42

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Table 12

Time to maximum precordial bubble grades after movement (mins)

	DOPPLER			SCANNER		
Diver number	**Week 1**	**Week 2**	**Week 3**	**Week 1**	**Week 2**	**Week 3**
1		15	12		12	20
2		5	20		12	27
3			12			20
5	157	20	20	120	42	12
6	20	20	20	12	12	42
8	5	20	12	12	12	5
10	50		87	12		
11	27	57	5	20	20	12
12	15	12	12	21	35	35
14		27	5		20	42
17	22	20	35	15	12	27
19	65	35	12	27	12	5
21	12	27	12	20	20	20
24	20			12		
25	20		12	12		5
28	27	27	20	20	35	12
32	12	35	27	5	12	35
33	35	12	35	27	20	27
36	35	5	57	57	57	20
37	72	12		5	5	87
39	12		20	5		12

Table 13

Mean time of maximum bubbles (mins)
Coefficient of variation in brackets

	Week 1	Week 2	Week 3
Doppler at rest	28.7 (0.6)	19.3 (0.6)	22.2 (0.6)
Scanner at rest	22.18 (0.6)	16.2 (0.7)	21.0 (0.6)
Doppler after movement	35.7 (1.0)	21.8 (0.6)	22.9 (0.9)
Scanner after movement	23.7 (1.2)	21.1 (0.7)	24.5 (0.8)

The larger coefficients of variation for time to maximum after movement reflects the possibility of a less direct relationship between the real time course of bubble development and what can be detected after movement. The overall mean time to maximum bubble counts is 23.3 minutes.

3.3.2 Maximum bubble grades - subclavian

Maximum grades for subclavian bubbles are shown in Table 14.

The grades are more widely scattered than precordial grades and there are some differences betweem left and right arm. It is difficult to make any meaningful interpretation of these results. They will be influenced by the relative proportion of motive power which derived from the arms compared to the legs and by use of one arm as the dominant. Subclavian bubbles are more easily detected than precordial and can be useful in alerting the technician to the presence of bubbles leading to a more careful precordial observation in cases of very low bubble numbers.

Table 14

Maximum subclavian bubble grades, left/right

	At rest			After movement		
Diver number	**Week 1**	**Week 2**	**Week 3**	**Week 1**	**Wee 2**	**Week 3**
1		1/3+	1/0		1/4	1/0
2		3/2	2/0		3/2	3-/0
3	0/0	0/0	0/4-	0/0	0/0	0/4
5	1/0	1/2	0/1	1/0	2/4	1/3
6	0/0	0/0	0/0	1/1	0/0	0/0
8	3-/3-	3+/4-	1/3+	3/3+	4-4	1/4
10	0/2	0/0	0/0	1/4	0/0	0/1
11	0/0	1/0	2/1	2/2	1/0	2/2
12	3/4	2/4	2/3	4-/4	2/4	2/4
14		3/3+	2/3+		4/3+	4/4
17	3/3	2/3	3-/3	4-/4	4-/4-	3+/3+
19	1/2	3-/3-	0/1	1/3-	3/3+	0/1
21	3/0	2/0	1/1	4/1	4/1	3/1
24	2/3+			3/4		
25	3+/2		2/0	4/3		3/0
28	0/0	2/2	0/0	0/0	3/4-	0/0
32	3/3	3-/3-	0/3	4/3+	3/2	0/3+
33	0/1	3-/4	2/3	0/3	3/4	3/2
36	3-/0	0/0	0/0	3+/0	1/0	0/0
37	3-/2	2/0	0/0	3/3-	3/0	0/0
39	3+/2		3+/3-	4/3-		4/3

4.0 DISCUSSION

The results, as given in the previous section, show that the trials have been a success. There is a clear answer to the question whether bubbles occur or not and the bubble grades group closely around the central value. There is not the wide, sometimes bimodal, pattern of grades seen in some earlier trials. This indicates that all subjects had essentially the same experience and that identical experience was repeated for all 3 trials. This means that conclusions about between- and within- subject variability can be drawn with some confidence.

The primary conclusion from the results is that in these trials 71.4% gave Doppler grades higher than 2 and 62.5% give scanner grades higher than 2. There is 95% probability that at least 50% of divers might be expected to give bubbles greater than grade 2 on this exposure. In fact table 10 shows that well over 80% could give this level of bubbling. For bubble grades taken after movement as many as 91% will show grades higher than 2. This exposure is on the current time-depth limit for Sur-D decompression but time and depth are not the only factors which determine the incidence of bubbles; some shorter, less deep dives may have less effective decompression profiles. There are currently no decompression tables which have been designed to give a fixed level of risk of bubble formation.

We have to give some considerations to whether or not this exposure is comparable to an off-shore dive. The trials were planned to give saturation in muscle by working the divers continuously during the time in the water. Conditions in the tank are easier than in open water and this is probably reflected in the fact that all divers claimed to be less tired at the end of these dives than at the end of an off-shore dive. Although the task in hand during an off-shore dive might involve intermittent work the subjective assessment of the divers was that in open water they do in fact work continuously against the currents and tides. It seems probable that under real operational conditions the divers do reach muscle saturation during a 30 minute bottom time. This could explain some of the differences seen when decompression profiles which gave low bubble levels in trials proved unacceptable when taken off-shore. The theoretical calculations described in section 2.1.1 indicate that the difference between spending 30 minutes at rest at 39.4 metres and spending 30 minutes engaged in relatively light activity can be almost a factor of three in muscle gas loading.

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There remains the questions of whether or not the subjects used in these trials are representative of the commercial diving population. All are part of the commercial diving community and were not selected in any way. They included a good range of age and stature. There is little reason to suppose that another set of 20 divers would give different results.

4.1 Between diver variability

There is a much lower level of variability between subjects in this study than in any of the profiles analyzed in the previous work (Flook 1998). Table 9 shows that 67.9% of the subjects gave Doppler grades at rest within 1 grade of the central, that is grades 3-, 3 and 3+. For bubble detection by scanner 58.9% gave grade 3. The 95% probability ranges are; for Doppler 55.5 to 80.5 and for scanner 45.9 to 72.1.

There is a popular belief that in a group of subjects there are some who always bubble and some who never bubble. Close examination of table 5 shows that this pattern was not seen in this study. Again this could be a result of the physical activity. Had the pattern of activity undertaken been one where the final gas uptake could have been influenced by the fitness of the diver then there may have been persistent non-bubblers. As mentioned earlier the presence of a bimodal distribution of counts, that is a significant proportion of subjects who do not bubble, could well be a result of some being very much more fit than others.

4.2 Within diver variability

As described in section 3.3.1 there is no satisfactory way to evaluate within subject variability with categorical data of this nature. Chi-squared tests have shown that there is no week to week change in the data for the groups taken as a whole. Examination of table 5 shows that for Doppler scores 11 divers have all 3 scores within a range of two grades. The same consistency is not shown in scanner grades. The only reasonable conclusion from this data is that, although there appears to be some within diver variability we cannot evaluate it from only 3 repeat trials. It would require a sufficient number of repeats to allow each diver's results to be handled in a contingency table.

4.3 The importance of muscle in this profile

The focus in planning the trials was on ensuring muscle saturation and the closeness of the results is believed to be a result of achieving this. It is worth giving some consideration to why muscle is playing what appears to be a dominant role in determining bubble grades. This can be done by reference to the mathematical simulations carried out before trials started. Table 1 in Flook 1998 lists the tissue time constants. Five compartments have time constants shorter than muscle and the slowest of these is 8.6 minutes. Thus all 5 fast compartments will always saturate during a 30 minute exposure. These compartments contribute about 80% of the mixed venous blood in the body when it is not undertaking physical activity, the condition which applied during decompression and during bubble monitoring. Of the remaining 20% of mixed venous blood 65% comes from muscle.

The decompression procedure followed in the trials is sufficient to clear all the fast compartments of bubbles before the end of the chamber decompression. Therefore of the compartments which are bubbling at the end of decompression muscle is dominant. The second largest contribution to mixed venous blood from slow compartments is from fat, 25%, and the 30 minute bottom time was too short to load the fat with enough inert gas to cause bubbles. On this particular exposure muscle is the tissue that we are looking at when monitoring for bubbles following the chamber decompression. Having produced saturated muscle we have ensured a close grouping of bubble grades because no other tissues are involved.

Theoretical calculations relate only to the average man and it is reasonable to assume that in 20 subjects there would be a range of different time constants for the 5 fast compartments but the simulations have in fact considered the worst case because they took all the fast compartments as coming to saturation during the bottom time. This still leaves the possibility that within a group of subjects there will be a range of rates at which bubbles are resolved but on a Sur-D profile the chamber recompression acts as a treatment and all bubbles are squashed during the compression. For the fast compartments 30 minutes in the chamber is long enough to remove all the gas which has been released from these bubbles. It is not long enough to remove all the gas released from the muscle. At the start of decompression muscle contained a volume of gas taken up during 30 minutes with a relatively short time constant. It cannot off-load that volume of gas during 30 minutes at rest, with the longer time constant of resting muscle.

Having followed that reasoning through it becomes obvious how the decompression procedure could be modified to ensure less gas bubbles; a longer chamber decompression with perhaps some relatively mild physical activity.

In addition to the achieving main objectives the trials have shown how it is possible to use a physiological model as an aid in designing trials and how it would be possible to improve the decompression procedure. From there it is a short step to designing decompression profiles which will allow time-depth limits to be extended. Design of decompression profiles in the past have been with reference to DCI incident rates. Once bubbles are taken as the limiting factor a more realistic margin of safety can be applied.

There is one other lesson which can be learnt from these trials; given that the divers did not consider the activity on the bottom to be as hard as the work which they have to do against currents and tides it seems possible that all except the very shortest operational dives result in saturation of muscle.

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5.0 CONCLUSIONS

The primary conclusion from these trials is that 71.4% of the subjects had bubble grades higher than grade 2 and from this it is possible to calculate that there is a 95% probability that at least 50% of divers will have grades in excess of 2 for this exposure. The upper 95% limit is 83.4% who could have maximum grade greater than 2 for Doppler at rest.

The between diver variability is much lower than seen on previous trials and this is believed to result from the constant level of physical activity of the divers during the uptake phase. For Doppler, 67.9% gave grades at rest within one grade of the central; 58.9% gave grade 3 on the scanner. Predicted 95% ranges for the population are 55.5 to 80.5 for Doppler at rest and 45.9 to 72.1% for scanner at rest.

Three repeat trials are not sufficient to carry out a proper analysis of the within diver variability and the results do not give a clear cut picture to allow a qualitative statement to be made. However from table 5 it is evident that no diver has given the same results for all three trials. This could be interpreted to mean that classifying divers as bubblers or non-bubblers may be a little simplistic.

Theoretical analysis shows that the bubbles detected following the end of decompression are predominantly from muscle. The results seem to indicate that the muscle was saturated during the exposure and it is suggested that normal activity during operational dives would also lead to muscle saturations for all except the very shortest bottom times. Therefore decompression tables for air diving should be redesigned to take account of this fact. Using this approach we could expect a safe move towards increased exposure times.

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ACKNOWLEDGMENTS

A study such as that described in this report relies very heavily for its success on a large number of people. The total number of people on whom success depended was approaching 40 of whom 21 were the subjects. Thus there was almost one member of the "back-up" team per subject. Had any one failed to carry out their task conscientiously the results reported here would be less convincing and the conclusions would have to be drawn with less certainty.

There was considerable work to contact potential subjects and organise all to attend, first one week in advance of the trials and then at weekly intervals. Staff of the National Hyperbaric Centre carried out that task with considerable success in that sufficient divers were identified not only initially but also to replace the inevitable drop-outs as some got work elsewhere, broke bones or for other reasons failed to get to the first meeting.

The National Hyperbaric Centre staff responsible for chamber and dive control worked to very tight controls at each stage of the exposure and accepted without complaint the operation of multiple stop-watches to keep check on their performance. Their role was critical to the reproducibility of the results and their success is evident in the results.

The "bubble counters" had to leave their own lives and occupations to spend the time in Britain thus ensuring the highest quality of bubble monitoring. Their success too is evident in the results.

The two bellmen suffered the less than exciting experience of doing exactly the same things 15 times over and volunteered to be monitored for bubbles when their duties should have been completed.

The divers, of course, were central to the whole trial. They were unfailingly good humoured even when ploughing relentlessly up and down an utterly boring tank and when spending hours with chests covered with electrode gel, hungry, experiencing caffeine and nicotine deprivation and without the luxury of a shower at the end of the dive. They were a pleasure to work with.

Thanks are due to all these people; each played a significant role; not one could have been managed without.

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