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Ultrasonic Monitoring of Decompression Procedures [and Discussion]

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Ultrasonic monitoring of decompression procedures

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Early detection of bubbles may provide clues to the mechanism of their formation, and a knowledge of their extent during a decompression may allow the prevention of decompression sickness. We have used ultrasound imaging to study bubble formation in peripheral tissues. The results suggest that:

(*a*) a threshold supersaturation for bubble formation exists;

(*b*) the earliest bubbles are intravascular;

(*c*) before signs of decompression sickness a substantial accumulation of stationary bubbles occurs.

Despite the success of Doppler methods in detecting moving bubbles after decompressions normally considered safe, recent studies have shown that the correlation between number of bubbles detected and symptoms of decompression sickness is often poor. We have used a time integral of the ultrasound images, which avoids laborious image analysis, to follow the extent of both moving and stationary bubbles. Human trials involving a wide variety of decompressions suggest that correct prediction of symptoms is possible.

Introduction

Decompression procedures are calculated with the aim of reducing ambient pressure at the fastest rate possible without the appearance of symptoms. Various methods to achieve this objective have been devised but none are able to predict the outcome of any decompression in general (Boycott *et al.* 1908; Hempleman 1975; Workman & Bornman 1975; Hills 1977). All the methods are in essence similar; pressure is reduced to establish a gradient for gas diffusion into the blood, whence the gas is transported to the lungs and eliminated. The calculation of how, and when, to reduce the pressure rely on the assumption that gas will not separate from solution to form bubbles. However, studies of decompressions following accepted schedules have shown that bubbles are formed (Evans *et al.* 1972; Nishi *et al.* 1981; Gardette 1979). This failure to prevent bubble formation, or even to gauge its extent, means that new schedules have to be empirically tested and the incidence of symptoms reduced to an acceptable level on the basis of subjective reports of the test subjects. Ultrasound provides a means of observing bubbles *in vivo* and thus affords the possibility of achieving an understanding of the factors controlling their formation and also of testing objectively the efficacy of new tables by measuring the extent of formation.

Ultrasound can be used in a number of ways; its attenuation on passage through tissue can be measured, reflexion from interfaces can be used or the change in frequency of reflected ultrasound from moving bubbles, the Doppler principle, can be used (see, for example, Evans 1975). All these methods have been employed, although Doppler techniques to detect moving intravascular bubbles have been the most intensively investigated. This paper will describe the use of one ultrasonic technique, pulse–echo ultrasound imaging, to study the formation of bubbles, and the use of a time integrated developement of this method to monitor the extent of bubble formation during a decompression, with a view to predicting symptoms.

Studies on the formation of bubbles

A high resolution 8 MHz pulse–echo ultrasound system was developed to study bubble formation in small animals (Daniels *et al.* 1979). It uses a 5 mm diameter transducer, pulsed at 2 kHz, to produce bistable B-scan (brightness modulated) images when the transducer is mechanically scanned across a tissue area. The system is able to detect bubbles with diameters down to 10 μm and has an axial resolution of 400 μm and a lateral resolution of 800 μm (Beck *et al.* 1978). Size determination of bubbles, either from the images or from the amplitude of the echo, has been shown not to be a practical possibility; although estimates of the limits to the size can be made. The images are recorded, one every 2 s, on 35 mm film for analysis. Bubble formation is normally monitored by starting imaging 3 min before the decompression and continuing for up to 1 h afterwards. The images are analysed by constructing a control that includes all the tissue interface echoes recorded on the images before decompression and then superimposing this control on each image after decompression, in turn, to reveal where and when new echoes from bubbles appeared.

The first questions posed were whether any particular site predisposes to bubble formation, where the first bubbles form and the relation between bubbles and symptoms of decompression sickness. To answer these questions a series of saturation exposures to pressures of air ranging from 2.8 to 8.3 bar† with anaesthetized guinea pigs were studied. Bubble formation was observed in a cross section of the hind limb of these animals and the first sign of decompression sickness was taken to be any abnormality in the electrocardiogram (e.c.g.). Saturation, defined as that exposure time beyond which no increase in the incidence of decompression sickness occurs, had previously been determined as 90 min. These exposure pressures gave incidences of sickness ranging from 0 to 100%, with the ED_{50} being 5.5 bar. A total of 50 experiments in this series have been completed.

Ultrasound images recorded after a 5.5 bar decompression are shown in figure 1. Bubbles are revealed by comparing the control image, recorded before the decompression, with the images after decompression. The time after decompression is shown at the top of each image. Recompression can be seen to restore the image to its form before decompression. An analysis of ultrasound images, which reveal the spatial and temporal distributions of bubble formation is illustrated in figure 2. The bubble formation revealed by the analysis procedure is considered to be of two types; (*a*) transient when an echo is recorded at a site on only a single image and (*b*) persistent when echoes are recorded on successive images at a single site. Transient events are taken to be intravascular bubbles passing through the plane of scan. Persistent events are taken to represent stationary bubbles on the grounds that the probability of separate bubbles appearing at the same site on successive images is vanishingly small. Stationary bubbles may be either intra- or extra-vascular.

Temporal analyses after an 8.3 and a 6.9 bar decompression are shown in figure 3. Two features are immediately apparent; they are that the number of sites falls with decreasing exposure pressure, and that the first bubbles are transient. The recruitment of sites of bubble formation for this series of decompressions is shown in figure 4. In general, both the rate at which sites occur and the final number recruited are proportional to the magnitude of the decompression. The numbers of transient and persistent bubbles after a number of these decompressions are shown in Table 1.

A comparison of the relative number of bubbles after these decompressions must be taken

† 1 bar = 10^5 Pa.

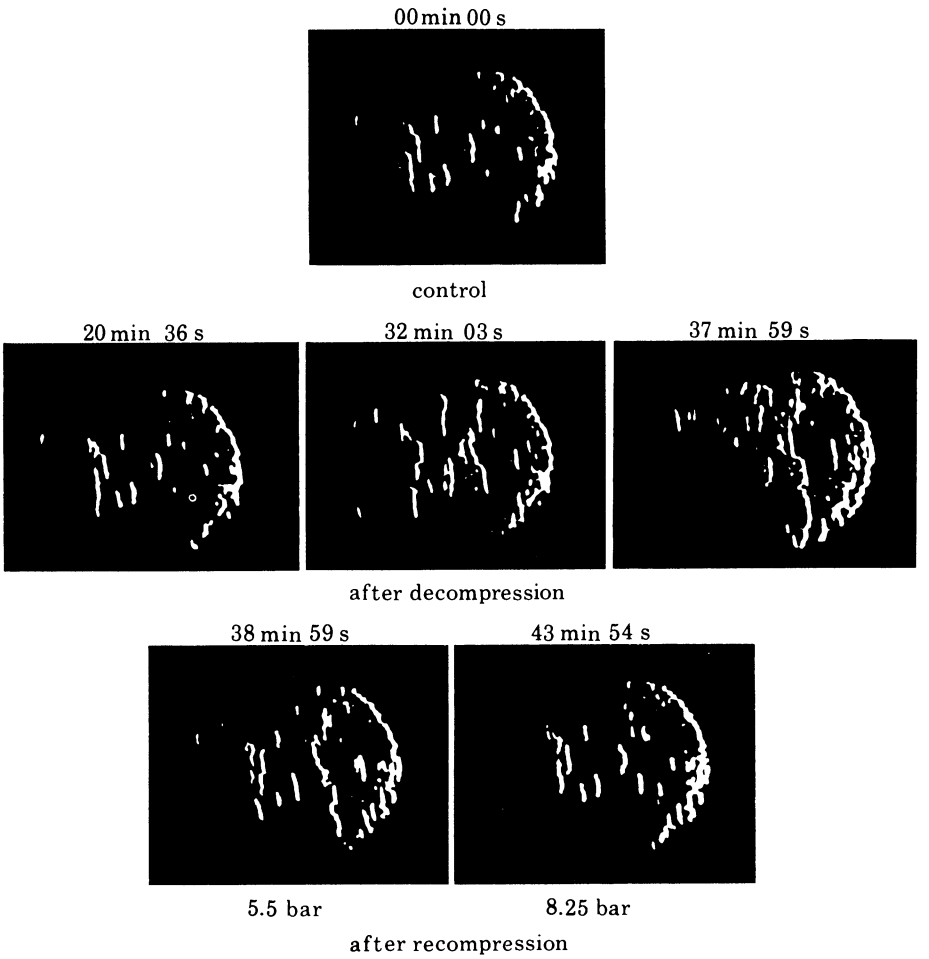

FIGURE 1. Ultrasound images recorded from the hind limb of an anaesthetized guinea pig after decompression from a saturation exposure to 5.5 bar air. The top image is one of those recorded before the decompression to show the pattern of echoes from the tissue interfaces. In all the images the direction of propagation of the 8 MHz sound is from right to left. The curved shape at the right of each image represents the interface between the skin and the acoustic coupling medium. The times shown at the top of the images record time elapsed after the start of decompression, except for the control image. Decompression lasted 60 s. The build-up of bubble formation over a 38 min period after decompression is shown in the three centre images and the effect of recompression in the lower two images. Recompression removed those echoes acquired after the decompression, helping to establish bubbles as the cause of those echoes.

from the 2 min analysis column, i.e. the same number of frames (60) were included in the analysis for all decompressions. The number of bubbles recorded over the maximum analysis shows the extent of bubble formation possible, in five cases (L1, L6, F6, F7, F8) without the appearance of symptoms of decompression sickness.

The proportions of transient and persistent bubbles are about equal, although a tendency for the less severe decompressions to produce transient bubbles can be discerned. The mean number of transient bubbles, over a 2 min period after decompression, falls from 125 to 36 after the 8.3 and 2.8 bar decompressions, respectively. The variation in the number of bubbles observed is greater for the persistent bubbles. Despite the large number of bubbles seen, all the 2.8 bar and two of the 4.1 bar (L1 and L6) divers were asymptomatic.

In the experiment illustrated in figure 1 the bubble formation for the first 7 min after the

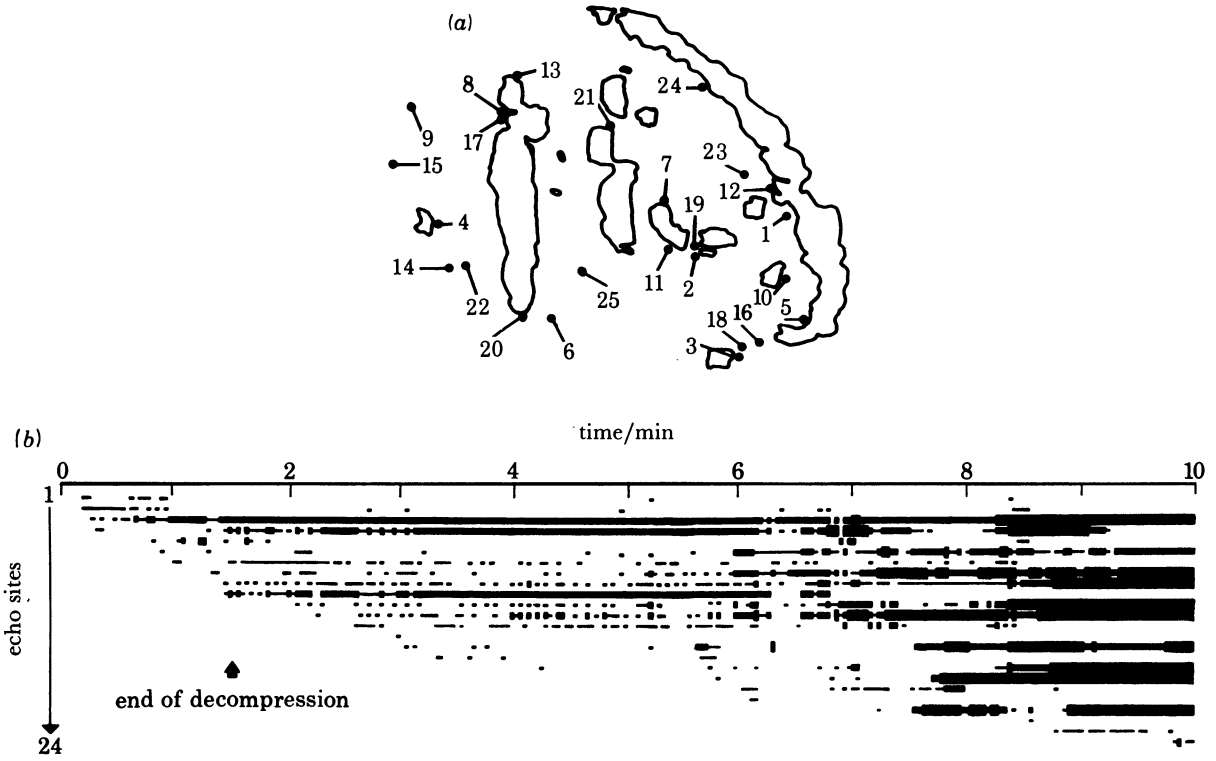

FIGURE 2. Example of the spatial (*a*) and temporal (*b*) analyses of the ultrasound images. In this case, the analyses show the development of bubble formation in the hind limb of an anaesthetized guinea pig after decompression from a saturation dive to 5.5 bar in air. The spatial analysis shows the distribution of sites of bubble formation. These are plotted relative to the tissue interfaces recorded for this area of the leg. The sites of formation are numbered in order of appearance. The temporal analysis shows the time and duration of appearance of echoes at each of the sites. Time is the abscissa and is shown in units of 2 s (one image). The different line widths, which denote the presence of a bubble, represent the estimates of bubble size. Bubbles are classified into one of three size groups: (1) under 100 μm diameter; (2) 100 μm < diameter < 500 μm; (3) over 500 μm diameter, which are represented by increasing line widths (Beck *et al.* 1978; Daniels *et al.* 1979).

decompression was a mixture of transient and persistent, with a majority of the bubbles being transient. However, after 7 min, a change to a predominantly persistent pattern of bubbles can be seen. Approximately 1 min after this change the first signs of decompression sickness were observed. In addition to this change in the nature of the bubble formation a stepwise recruitment of sites of formation is often observed. This is illustrated in figure 5, which shows three 4.1 bar decompressions, two asymptomatic and one after which decompression sickness occurred. The second steep rise in the number of sites on the symptomatic dive was followed, after 14 min, by the onset of decompression sickness. Both these features are illustrated in figure 6 for a more severe 8.3 bar decompression (C7).

Our conclusions from the results of these decompressions can be summarized: (*a*) the initial bubbles are intravascular; (*b*) both the number of bubbles and the number of sites of formation are dependent on the magnitude of the decompression; (*c*) before symptoms of decompression sickness occur an accumulation of stationary bubbles is observed.

Another question posed was whether a critical level of gas supersaturation is necessary before bubbles will form. Ultrasound imaging to detect bubbles should provide a more sensitive test for this than studies based on symptomatology. To investigate this question a second series of

saturation air dives were performed. For these the exposure pressures were 0.69, 1.03, 1.38, 1.72 and 2.07 bar. In addition, two series of control experiments were performed in which the guinea pigs were treated in the same manner apart from exposure to pressure. In all, 10 animals were used for each exposure pressure and control; a total of 70 animals. The experiments were done in a random order and were analysed blind. A standard analysis period of 15 min and 400 images for each animal was adopted. The total number of new echoes recorded over the analysis period are given in table 2.

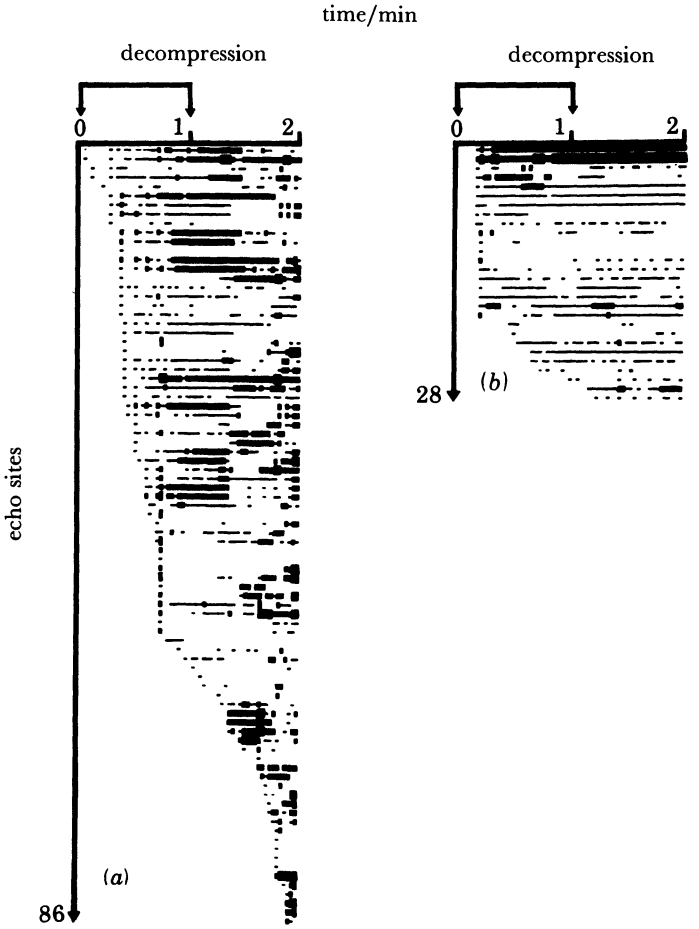

FIGURE 3. Temporal analysis of the ultrasound images for the first 2 min after (*a*) 8.3 bar decompression, and (*b*) 6.9 bar decompression. For each, the individual sites of appearance are plotted as the ordinate and time in units of 2 s (one image) is plotted as the abscissa. The three different line widths represent, in order of increasing width, class 1, 2, 3 bubbles. (Reprinted from Daniels *et al.* 1980.)

The counts recorded from the control experiments represent echoes from tissue interfaces, which were not accounted for by the control image constructed for the analysis. This is caused by animal movements different to those that occurred in the 3 min period before decompression, in which the normal tissue interfaces were imaged, and represents the 'noise' level in the system. Another factor that complicates the analysis was the variation in the mass of the guinea pigs used (360–560 g). The mean masses for the seven experimental series were: 525, 424, 529, 432, 531, 442, 421 g. It was expected that the lighter, less fat, animals would exhibit less bubble formation than heavier animals, for the same decompression. So a mass correction was included when these data were analysed.

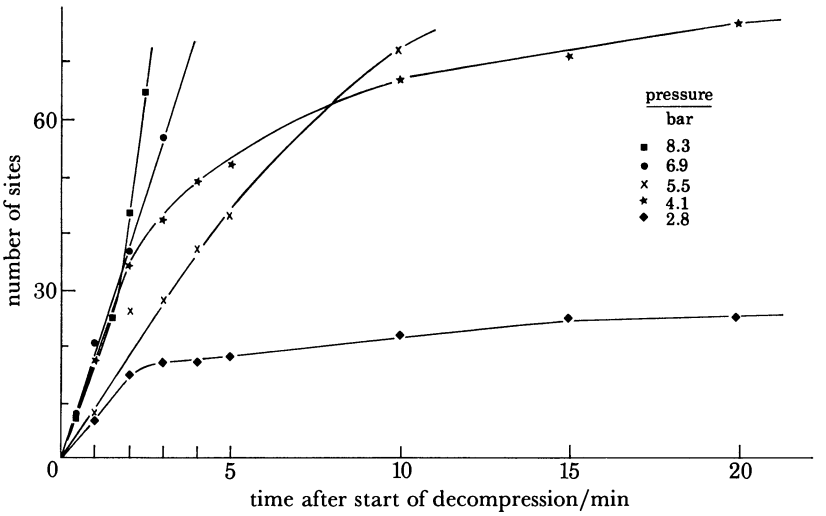

FIGURE 4. Recruitment of sites of bubble formation in the hind limb of anaesthetized guinea pigs after air saturation dives. The lines are drawn by eye and the points represent the average over a number of decompressions. Details of the bubble formation is given in table 1.

TABLE 1. ANALYSIS OF BUBBLE FORMATION AFTER SATURATION AIR DIVES

		number of bubbles			
		transient		persistent	
dive number	pressure / bar	2 min analysis	maximum analysis	2 min analysis	maximum analysis
D2	8.3	190	—	171	—
C7	8.3	60	—	9	—
C16	6.9	47	—	68	—
D9	6.9	77	—	72	—
C19	5.5	65	313 (6 min)	73	311 (6 min)
C13	5.5	12	67 (6 min)	9	38 (6 min)
L5	4.1	63	1100 (16 min)	121	1402 (16 min)
L1	4.1	35	1029 (16 min)	37	1134 (16 min)
L6	4.1	64	742 (16 min)	47	850 (16 min)
F6	2.8	43	696 (22 min)	39	502 (22 min)
F8	2.8	66	197 (22 min)	58	152 (22 min)
F7	2.8	0	1599 (22 min)	0	645 (22 min)

The data were analysed by fitting to three alternative models:

(i) $Y = a + b_1 X + b_2 X^2 + b_3 M$ (a polynomial);

(ii) $Y = a + b_1 X_1 + b_2 X_2 + b_3 M$ (a formal threshold model),

where

$$X_1 = \begin{cases} X, \text{ if } X \leqslant D, \\ D, \text{ elsewhere,} \end{cases} \quad X_2 = \begin{cases} 0, \text{ if } X \leqslant D, \\ X - D, \text{ elsewhere} \end{cases}$$

and D is the change point (threshold) to be determined;

(iii) $Y = a + b_2 M + \exp(c + b_1 X)$ (an exponential),

where Y is the echo count, X is the exposure pressure and M is the mass.

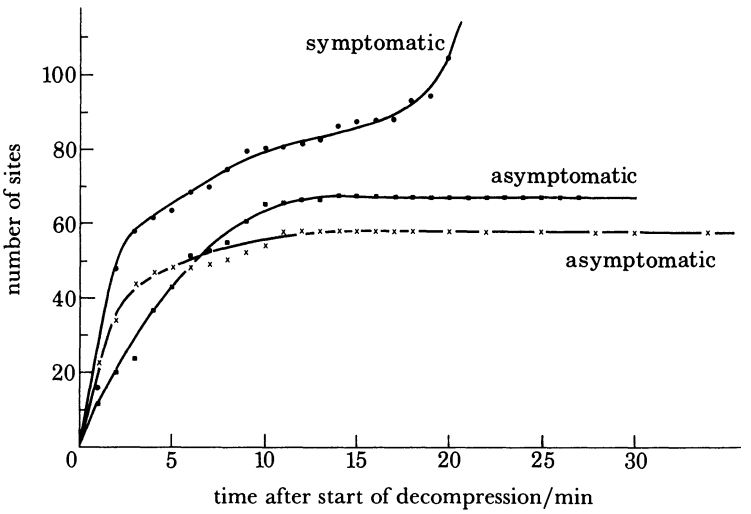

FIGURE 5. Recruitment of sites of bubble formation in the hind limb of anaesthetized guinea pigs after three decompressions from saturation exposure to 4.1 bar.

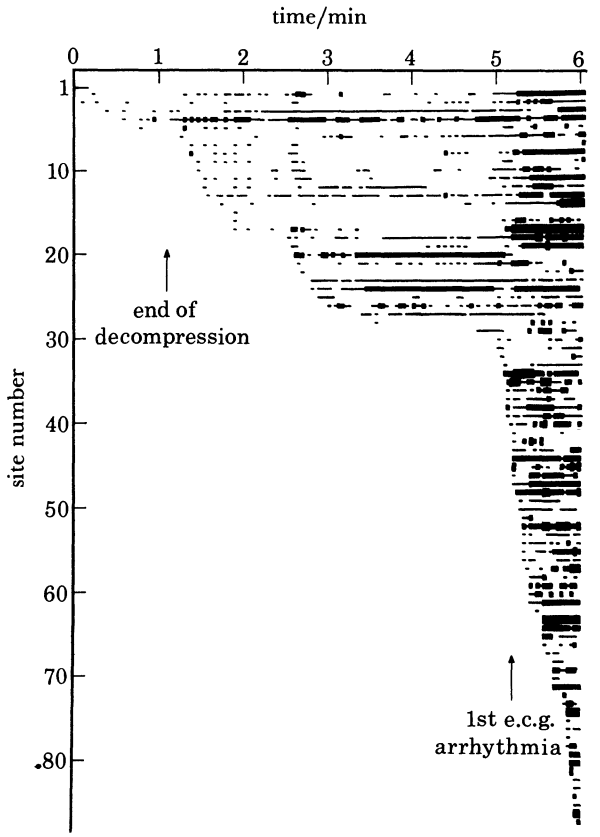

FIGURE 6. Temporal analysis of ultrasound images recorded after decompression from a saturation exposure to 8.3 bar in air. (For details, see legend to figure 2.)

TABLE 2. ANALYSIS OF TOTAL ECHO COUNT RECORDED FROM THE HIND LIMB OF ANAESTHETIZED GUINEA PIGS OVER A 15 MIN PERIOD AFTER DECOMPRESSION

		exposure pressure/bar				
control	control	0.69	1.03	1.38	1.72	1.07
165	42	374	64	114	1112	1689
261	101	71	108	149	22	97
412	110	227	375	1157	62	901
834	146	433	256	792	209	1436
82	8	373	48	982	96	1147
36	373	291	445	1289	527	68
79	166	549	2	435	1563	55
293	128	322	289	153	28	803
118	1	268	642	267	164	454
565	317	11	3	43	480	635
285 ± 76†	139 ± 37	292 ± 48	223 ± 65	538 ± 142	426 ± 157	728 ± 173

† The errors given are the standard errors in the mean.

TABLE 3. ANALYSIS OF VARIANCE SQUARES

	Residual squares	Mean squares	Degrees of Freedom
Model i	69.41	1.052	66
Model ii	69.65	1.055	66
Model iii	65.74	0.996	66

The models were fitted with the method of least squares with the aid of the program BMD-P run on the Oxford University VAX 11/780. (Dixon 1977) to give the final expressions:

(i) $Y = -169.7 - 463.5\,X + 175.4\,X^2 + 1.411\,M$;

(ii) $Y = -1196.26 + 406.4\,X + 1.35\,M$, with change point $D = 1.9$;

(iii) $Y = -427.14 + 1.319\,M + \exp(0.542 + 1.890\,X)$.

Analysis of variance gave the residual and means squares shown in table 3.

Table 3 shows that all the models gave a good fit to the data and model (iii) was marginally the best. In the absence of any strong reasons for its retention, model (i) has been discarded because it is the most difficult to furnish with a physical reality. The threshold yielded by model (ii) was 0.9 bar, with 95% confidence limits of 0 and 1.6 bar. The width of these limits is felt to be a reflection of the limited data set and so they could be improved upon. The exponential model (iii) does appear a reasonable alternative to a threshold.

To test further the question of whether the threshold concept is correct a series of double dive experiments were performed. It was known from previous work that the incidence of decompression sickness could be increased by multiple decompressions, even in conditions of an apparent reduction in gas supersaturation (Griffiths *et al.* 1971). This was thought to be due to bubbles formed on the first decompression. So if the exponential model was correct, but we did not see the low level of bubble formation from the lowest exposure pressures because of the signal/noise ratio in the method, their presence might nevertheless be detected by their effect on bubble formation in a second test decompression, after an initial decompression from a low pressure. The test exposure chosen was 15 min at 6.9 bar. A threshold of 0.9 bar had been suggested and so two initial saturation exposures of 0.82 and 1.38 bar were chosen. The

interval between dives chosen was 15 min, on the basis that this interval gave the greatest increase in symptoms after the second decompression. The results from these experiments are shown in table 4. In these experiments mass variation was eliminated by selecting animals from a pool as their mass reached 500 g. The order of the experiments was randomized. A period lasting 10 min after the 6.9 bar decompression was analysed in all cases.

TABLE 4. ECHO COUNTS AFTER DOUBLE DECOMPRESSION

control 1 6.9 bar	control 2 6.9 bar	0.82+6.9 bar	1.38+6.9 bar
3559	3114	3308	1518
2115	819	5673	1047
2612	2197	2427	1840
1933	1976	2675	803
2720	3870	3324	1251
2501	2120	595	531
2391	1024	505	1674
1949	2554	1472	290
675	—	3604	476
2352	—	1298	1961
2281±232†	2209±356	2488±503	1139±190

† The errors given are the standard errors in the mean

Statistical analysis with the Snedecor F-test and the Student t or Welch d test, as indicated by the F-test, showed that there was no difference between the two groups of controls ($P > 0.8$) nor was there any difference between the controls and the 6.9 bar decompression when preceded by the 0.82 bar decompression ($P > 0.7$). However, the 6.9 bar decompression when preceded by the 1.38 bar decompression yielded a significantly lower echo count ($0.001 < P < 0.01$).

These results suggest, therefore, that the 0.82 bar decompression is indeed sub-threshold. The reduction in the echo count when the first decompression was 1.38 bar is at first sight unexpected in the light of the results of Griffiths *et al.* (1971). However, the increase in symptoms observed on previous work was explained on the basis of a central redistribution of peripheral bubbles by the second compression, which leads to very rapid bubble growth in vital central areas after the second decompression (Gait *et al.* 1975). It may be suggested, therefore, with these much less severe exposures, that the decrease in the echo count observed reflected a reduction in the nuclei available for their formation.

The evidence supports the view that a threshold to bubble formation exists, and that for decompression to the surface it is 0.9 bar. A threshold to bubble formation is not unreasonable by analogy with other changes of state, which similarly require a threshold state to be exceeded. It remains to be determined whether this threshold is expressed as a pressure ratio or as a fixed pressure drop or represents a fixed quantity of gas. An established threshold to bubble formation allows the magnitude of pressure reduction to be set and in principle offers the possibility of bubble free decompressions.

MONITORING BUBBLE FORMATION WITH INTEGRATING PULSE–ECHO ULTRASOUND

The most widely used ultrasound monitoring method relies on the Doppler principle to detect moving, intravascular bubbles. The method was first developed during animal experiments in which bubbles were monitored in a number of different blood vessels (Powell 1972; Spencer

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et al. 1969; Gillis *et al.* 1968). Eventually, studies of bubbles in man were concentrated on the detection of bubbles in the pulmonary artery as a measure of the number of bubbles in the total venous return, the 'pre-cordial' position (Smith & Spencer 1970; Spencer & Clarke 1972). A very large number of decompressions have now been monitored by using pre-cordial Doppler (Bayne *et al.* 1977; Gardette 1977; Nishi *et al.* 1981; Nashimoto & Gotoh 1977). Early methods have been improved by the adoption of a standardized counting method and in many cases the discrimination of bubble signals from the background has been improved by use of signal processing techniques. The findings from three major studies are shown in table 5. The number of decompressions exhibiting bubble scores 0–IV are shown and the number showing decompression sickness is shown. The grading system for the bubble scores is:

0, no bubbles;
I, less than one bubble per cardiac cycle;
II, one bubble per cardiac cycle;
III, much more than one bubble per cardiac cycle;
IV, continuous bubbles.

The normally accepted critical bubble score is grade III, at which point it is considered that decompression sickness is likely to occur.

Table 5. Correlation of Doppler detected bubbles with decompression sickness for a total of 556 decompressions

Doppler bubble scores	number	number of decompressions showing symptoms: none	minor	pain	serious
(*a*) 0–II	129	91	31	7	—
III or IV	23	13	—	7	3
(*b*) 0	201	185	—	16	—
I–II	28	19	—	9	—
III or IV	3	1	—	2	—
(*c*) 0–II	132	131	—	1	—
III or IV	40	34	—	6	—

Sources: (*a*) Nashimoto & Gotoh (1977); (*b*) Gardette (1977); (*c*) Nishi *et al.* (1981).

From table 5, it can be calculated that overall, a 13% incidence of decompression sickness ('pain' or 'serious') occurred with bubble socres of grade II or less. Furthermore, one study showed an 8% incidence of sickness with no Doppler bubbles detected. These findings are borne out by a fourth study (Bayne *et al.* 1977) in which the Doppler signals from 86 decompressions were analysed blind and divided into two groups; (1) recommendation of treatment on the basis of a high bubble score; (2) risk free by virtue of a low bubble score. Four recordings were rejected because their quality was too poor for analysis; of the remainder 36 fell into group 1 and 47 into group 2 (risk free). The decompressions in group 1 yielded 5 cases of decompression sickness and those in group 2, 3 cases.

These studies of the correlation of the number of bubbles in the venous return and the occurrence of decompression sickness suggest that this is not the critical factor. The pulse–echo imaging experiments had shown a tendency for a change in the nature of bubble formation, to a predominantly stationary pattern, before the onset of symptoms. It was thought, therefore, that if a way could be found to avoid the laborious, detailed analysis of the images, then a basis for predicting symptoms might emerge.

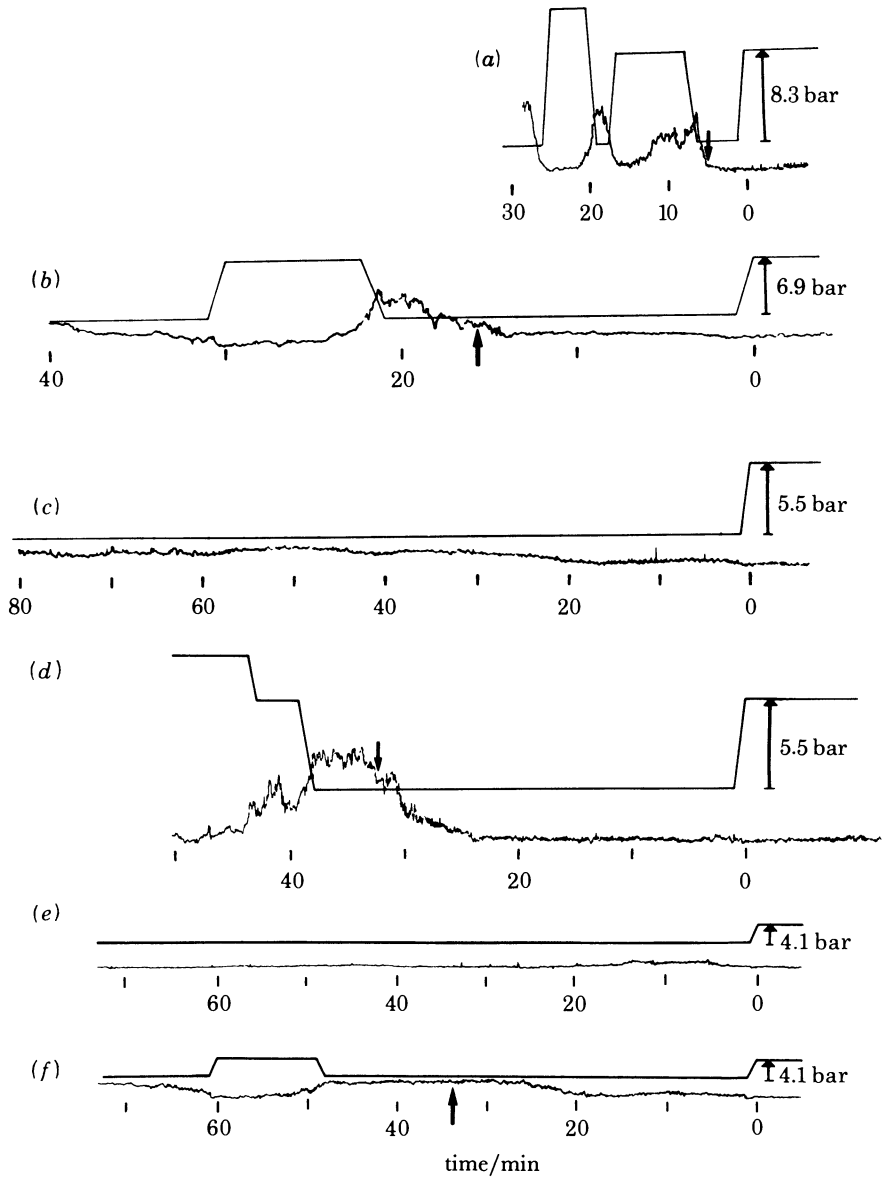

FIGURE 7. Outputs from the integrating pulse–echo ultrasound system for guinea pigs after decompression from saturation exposures to (*a*) 8.3, (*b*) 6.9, (*c*) 5.5, (*d*) 5.5, (*e*) 4.1 and (*f*) 4.1 bar in air. The pressure profiles are shown with each integrator so that the effect of recompression can be seen. For decompressions that gave rise to symptoms of decompression sickness, the onset of symptoms is denoted by an arrow.

A means of integrating the ultrasound images has been developed in which the echoes composing each image are electronically counted (Daniels 1978; Daniels *et al.* 1981). Before a decompression the echo count from the control images is noted and is set to be a fixed subtraction from each of the succeeding counts. In principle this leaves a zero remainder. However, in practice the echo count fluctuates because of animal movement and so it is arranged that a small non-zero remainder is displayed. The display is both digital and appears as a trace on a pen recorder. Bubbles appearing in the plane of scan of the ultrasound will cause a rise in the echo count, transiently for intravascular bubbles passing through the scan plane and persistent for stationary bubbles. The ability to predict decompression sickness from

this measure of the extent of bubble formation has been tested with guinea pigs given saturation air dives described previously.

The results from a number of such experiments are shown in figure 7. In each case the integrator output (echo count) is shown with the appropriate pressure profile. The output can be seen to increase after decompression and to fall in response to a recompression, as expected. For the less severe decompressions a significant increase in the output before the onset of decompression sickness can be seen. The asymptomatic 4.1 bar decompression showed no change in the output. Results from 50 such experiments suggested that for all but the most severe decompressions (8.3 bar) ample warning of sickness was given by observing the magnitude of the integrator output and the speed with which it increased. These results led us to develop a system for monitoring human decompressions.

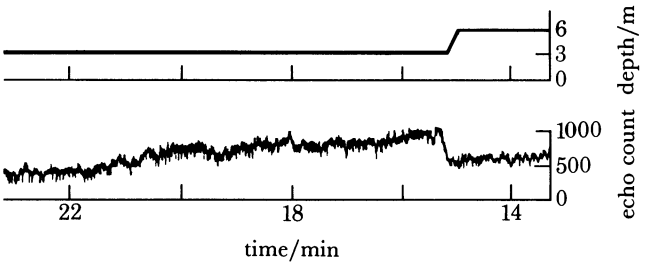

FIGURE 8. Integrator output recorded from the back of the right knee of a man after decompression from a 60 min exposure to 30 m s.w. The decompression lasted for 45 min and required stages at 9, 6 and 3 m s.w. The portion of trace shown was recorded as the pressure was reduced from 6 to 3 m s.w. Time is shown increasing from right to left from 14 min after the start of the decompression.

For human experiments, the single mechanically scanned ultrasound probe was not suitable and was replaced by a 64 element linear array transducer. This, together with the appropriate electronics, gives 20 images per second, as opposed to one every two seconds for the mechanical system. It can also be attached directly to the diver, without the need for a complicated liquid acoustic coupling arrangement. The ultrasound frequency was reduced from 8 MHz to 5 MHz to increase the penetration of the sound. Two signal processing modes were incorporated into a new integrating unit; namely an average output over 1–20 images could be selected and a running average over 1–8 outputs was available. In practice, the best combination of these to reduce the variation due to movement was to average over 2 images and output the running average over all 8 stores. A total of 56 human trials of this apparatus have been completed.

An example of the new integrator output is shown in figure 8. This was recorded from the back of the right knee during decompression from a 60 min exposure at 30 m s.w. (metres of sea water). The decompression lasted 45 min and required 3 stops; at 9 m s.w. for 5 min, at 6 m s.w. for 10 min and at 3 m s.w. for 30 min (Royal Navy Table 11). A transient rise in the integrator output was recorded, beginning 15 min after the start of the decompression and lasting 7 min. This coincided with the stage in the decompression from 6 m s.w. to 3 m s.w. The decompression was asymptomatic and no other signs of bubble formation were recorded. This rise in the integrator output was associated with the appearance in the ultrasound images of discrete bubbles in the region of the popliteal vein. A further 15 decompressions following the Royal Navy Table 11 have been monitored and the results of these are summarized in table 6.

Overall, 10 of these decompressions gave rise to bubble formation detected by the integrating pulse–echo system. In two cases the subjects complained of minor skin itching. The rise in the integrator output was not large for any case, that shown in figure 8 is typical. Although bubble formation had been demonstrated on a high proportion of decompressions (62%), which are considered among the safest used, the relation between the integrator output and impending symptoms could not be defined because no overt signs of decompression sickness were observed. Accordingly, a series of decompressions using the U.S. Navy Standard Air Dive Table were monitored.

TABLE 6. ANALYSIS OF BUBBLE FORMATION DETECTED BY INTEGRATING PULSE–ECHO ULTRASOUND IMAGING DURING AIR BOUNCE DIVES USING ROYAL NAVY TABLE 11 (BR2806)

number of men	depth / m s.w.	duration / min	number with bubbles	number with decompression sickness	number requiring therapy
1	30	15	0	0	0
10	30	20	6	1	0
4	30	60	3	1	0
1	50	60	1	0	0
16			10	2	0

In these experiments a mixture of dry and wet exposures and repeat dive experiments were monitored. The results from 19 experiments are summarized in table 7.

For the six wet exposures the subjects swam while using normal Scuba equipment in the 'wet pot' attached to the main pressure chamber. Immediately before their decompression the subjects left the water, entered the dry chamber and attached the transducer. They were then monitored as normal. An example of the integrator output after one of these experiments is shown in figure 9. This shows a small transient rise in the integrator output some 40 min after the start of the decompression. No symptoms were reported after this decompression. The only case in which any therapy was required was after the 180 min exposure to 30.5 m s.w. After this decompression a rise in the integrator output began after 32 min and continued for 33 min. The output had not returned to the normal level by the end of the monitoring session. After surfacing the subject reported itching in his forearms during the period in which the rise in the integator output was seen. This had been during a pause in the decompression at 6 m s.w. The following morning the subject reported stiffness and an ache in his middle finger joint. He was recompressed to 10 m s.w. for 25 min and breathed oxygen intermittently. The subject was monitored with the ultrasound during the recompression therapy. The integrator output fell during the stay at 18 m s.w. and did not rise after the final decompression. The ache in the subjects finger was not relieved.

A higher proportion of these experiments (75%) showed bubbles than the decompressions using the Royal Navy Table 11. However, these experiments were deliberately more provocative, and included wet and repeat dives, which are known to potentiate bubble formation. So a direct comparison of the two decompression tables is not valid. Nevertheless, it may again be observed that bubble formation was routine after decompressions that are in worldwide use. It should be noted that in all 35 of these experiments symptoms were only seen in divers who had been observed to have bubble formation. The only conclusion that can be drawn from these two sets of experiments, as regards symptoms, is that the prolonged elevation in the integrator output

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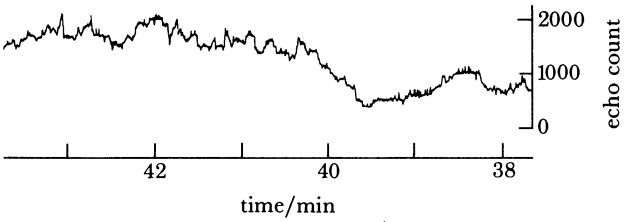

FIGURE 9. Integrator output from the right thigh of a man after decompression from a wet dive of 25 min duration to 30.5 m s.w. Time is shown increasing from right to left from 38 min after the decompression.

TABLE 7. ANALYSIS OF BUBBLE FORMATION DETECTED BY INTEGRATING PULSE–ECHO ULTRASOUND IMAGING DURING AIR BOUNCE DIVES USING THE U.S. NAVY STANDARD AIR DIVE TABLE

number of men	depth / m s.w.	duration / min	number with bubbles	number with decompression sickness	number requiring therapy
6	30	25	3	0	0
3	30.5	25	3	1	0
2	30	25+10	1	0	0
6	30.5	25 (wet)	6	2	0
2	30.5	180	1	1	1
19			14	4	1

TABLE 8. ANALYSIS OF BUBBLE FORMATION DETECTED BY INTEGRATING PULSE–ECHO ULTRASOUND IMAGING DURING EXPERIMENTAL DECOMPRESSIONS

number of men	depth / m s.w.	duration	gas mixture	number with bubbles	number with decompression sickness	number requiring therapy
1	80	15 min	Trimix 20:40:40 O_2–N_2–He	1	0	0
2	540	6 d	Heliox $p(O_2) = 0.4$ bar	2	1	1
2	61	6 d	Nitrox $p(O_2) = 0.4$ bar	2	0	0
2	23	24 h	Nitrox $p(O_2) = 0.5$ bar	2	2	2
7				7	3	3

after the decompression that required some therapy was unique among these 25 experiments. It may be tentatively suggested that an accumulation of stationary bubbles is critical before symptoms in man develop, as had already been suggested by the small animal experiments.

The next series of experiments involved monitoring a number of experimental decompressions. These were expected to provide a greater opportunity for relating the integrator response to the occurrence of symptoms. The results from seven experiments are summarized in table 8.

A wide variety of dives have been monitored, ranging from a saturation Heliox exposure at 540 m s.w. to a 15 min bounce dive to 80 m s.w. Bubbles were seen during all these decompressions and all three instances of decompression sickness required therapy. The most dramatic rise in the integrator output was seen after the decompression from saturation at 23 m s.w. with Nitrox (figure 10). The rapid, two stage increase in the integrator output

occurred 30 min after decompression from 23 m s.w. to 10 m s.w. The elevated level was maintained for 100 min with very little reduction. Approximately 8 h after this increase the subject reported pain in his right knee. The accumulation of stationary bubbles had been observed in his left thigh. Recompression relieved the symptoms.

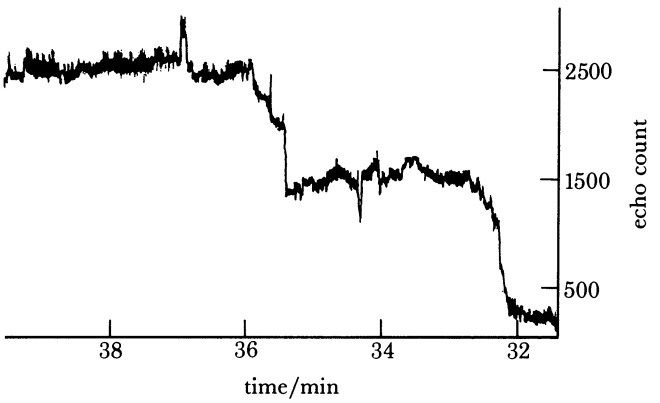

FIGURE 10. Integrator output from the left thigh of a man after decompression to 10 m s.w. following a 24 h saturation exposure to 23 m s.w. Nitrox ($p_{O_2} = 0.5$ bar). This portion of the trace begins 30 min after the decompression.

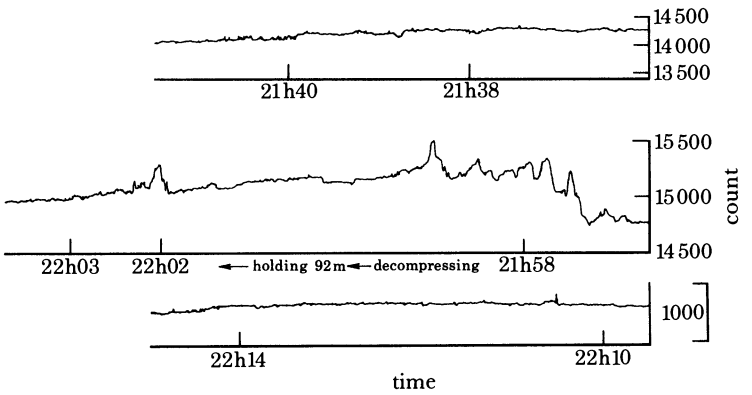

FIGURE 11. Integrator output from the left thigh of subject A during decompression from a saturation exposure to 540 m s.w. Heliox ($p_{O_2} = 0.4$ bar). This portion of the trace was recorded at 92 m s.w.

Monitoring bubble formation during the long decompressions from deep saturation exposures introduces additional problems. Clearly the entire decompression cannot be monitored. However, it has been established by experiment that provided the subjects are well trained in the use of equipment and establish a routine of scanning they can reproducibly position the transducer for daily scanning sessions. A portion of the integrator output recorded from one of the subjects monitored during the decompression from 540 m s.w. is shown in figure 11. This was recorded at 92 m s.w. and shows a transient increase in the integrator output. There were no symptoms recorded at this time. However, towards the end of the decompression, at 10.7 m s.w., this subject reported difficulties with his vision, which lasted 4 min and left him with severe headache. A recompression to 25 m s.w. was immediately begun. During this recompression we were able to monitor the second subject and the integrator output is shown in figure 12. A considerable fall in the level can be seen during the recompression, and while

at pressure the level stabilized at the control level. The final decompression to surface pressure caused a rise in the integrator output of both subjects but surfacing was accomplished with no further incidents. The clinical evaluation, after the dive, of the difficulties in vision was that the subject had experienced an arterial gas embolism. Before this incident at the end of the decompression it had been noted that both these divers had accumulated stationary bubbles and might be expected to have problems.

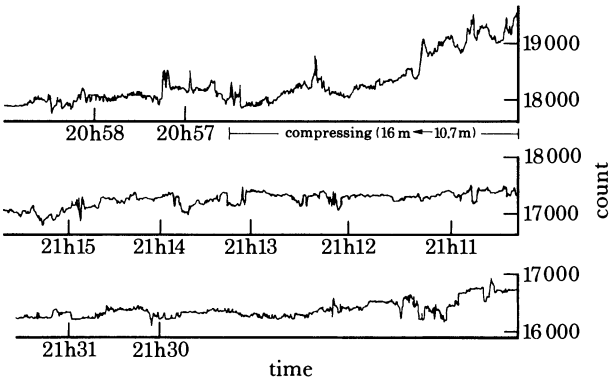

FIGURE 12. Integrator output from the right thigh of subject B recorded during the decompression from saturation at 540 m s.w. Heliox. The trace starts at 10.7 m s.w. and shows the effect of recompression to 25 m s.w. The recompression had been required to alleviate symptoms of decompression sickness experienced by subject A.

The results from these experiments have shown that we can routinely detect bubbles during decompression but that symptoms appear to be related to the accumulation of stationary bubbles specifically. It may be suggested, with reference to the decompression from 23 to 10 m s.w., that we can predict symptoms without having to monitor the area ultimately affected. Finally, it can be suggested that the extent of bubble accumulation before symptoms is less during long saturation decompressions than after short decompressions. It remains to be established whether safe limits to the extent of bubble formation can be defined for decompressions in general.

CONCLUSIONS

The technique of pulse–echo ultrasound imaging has been shown to have applications both for studying the factors responsible for bubble formation and in monitoring the extent of bubble formation during a decompression. At present the detailed analysis of the ultrasound images is a laborious procedure. However, recently available techniques of computer assisted analysis may be expected to dramatically reduce the time necessary for analysis. This will help to elucidate the relative importance of gas tension and the absolute quantity of gas to the formation of bubbles. These factors will determine the manner in which ambient pressure can safely be reduced. It may be that although bubble free decompressions are, in principle, possible, they would require unacceptably long decompression times. In that case it will be necessary to be able to predict the magnitude of bubble formation and to keep this below a level established as safe. Finally, the ability to monitor the extent of bubble formation during a decompression and to relate this to the likelihood of decompression sickness provides a means of objectively testing new decompression procedures and of reducing the extent of empirical testing presently needed.

Many of the experiments described in this paper were done by Dr J. M. Davies, Mr K. C. Eastaugh and Mr C. P. Armstrong. The human trials were all done with the cooperation of the Admiralty Marine Technology Establishment Physiological Laboratory. Thanks must be give to many of the members of staff at that laboratory who volunteered to be subjects. Valuable statistical assistance was given by Dr I. G. Vlachonikolis of the Department of Biomathematics, Oxford University. This research was supported by grants from the Medical Research Council, the Wellcome Trust and the Science Research Council.

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Discussion

A. Evans (*Decompression Sickness Research Laboratory, University of Newcastle upon Tyne, U.K.*).

(1) Did the transducer array function properly at very high operating pressure?

(2) What anatomical structures were surveyed during the human experiments, and did the results give any indication that bubbles appearing in any identified tissues were particularly correlated with subsequent symptoms?

(3) Is it possible to say if the new echoes arise from

(*a*) the growth of pre-existing gas nuclei;

(*b*) bubbles formed *de novo* or

(*c*) bubbles moving into the surveillance plane?

(4) Could the appearance of intermittent echoes be due to mechanical movement of transducer or subject?

(5) Has it been possible to demonstrate any effect of acclimatization by ultrasonic surveillance?

(6) Has there been any comparison between the predictive value of ultrasonic imaging and the conventional Doppler technique?

S. Daniels. (1) The operation of the linear array transducer has been tested at pressures up to 540 m s.w. and no discernible effect on its response was found.

(2) The transducer has been used in a variety of locations on the upper leg, from the knee upwards. A typical cross section reveals the inter-muscular interfaces and bone surfaces (where the density of the tissues changes sharply). In addition, arteries can often be detected owing to their pulsatile movement. Like the small animal work, the experiments with men have not revealed any special liability to bubble formation in any tissue.

(3) At present the experimental evidence favours bubble formation *in vivo* as proceeding from the growth of pre-existing micronuclei. It is not possible to deduce from a two-dimensional ultrasonic section whether transient echoes represent bubbles passing through the plane of scan or bubbles arising in that section. However, given the large number of such transient echoes that are seen, it appears most likely that the majority of transient echoes represent bubbles passing through the plane of scan.

(4) Control experiments, such as those described in the series of experiments examining the threshold question, have suggested that the total number of echoes from movement (less than 17 per minute) represent a small fraction of those due to bubbles. Preliminary experiments with men have suggested that movement artifacts can be further reduced by using electromyographic recording to differentiate changes in the number of echoes due to movement from those due to bubbles.

(5) To date, no experiments have demonstrated acclimatization to decompression in small animals, nor have any ultrasonic studies been performed on tunnel workers where the statistics on the incidence of decompression sickness suggest that some acclimatization to decompression occurs.

(6) Dr Davies (1983) has used Doppler bubble detection and ultrasound imaging together, in bounce dive experiments with goats. He found that the number of bubbles detected by the Doppler device did not correlate with the appearance of symptoms of decompression sickness, but that the extent of bubble formation as measured by ultrasonic imaging did allow prediction

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of symptoms. Recently, in cooperation with NUTEC, we have monitored six divers during decompression from a saturation exposure to 350 m s.w. by using both Doppler and ultrasonic imaging. One of these divers showed no evidence of bubble formation from either the ultrasonic imaging (the scan was from the lateral skin surface of the upper left thigh and from the medial skin surface of the upper right thigh) or the Doppler recording (from both femoral veins, the pulmonary artery and the carotid artery). The other five divers all showed evidence of a progressive accumulation of stationary bubbles, revealed by the ultrasonic imaging, throughout the last 5 d of the decompression (11 d total decompression time). Three of these five divers had a few bubbles in their femoral veins, revealed by the Doppler technique, throughout the last 5 d of the decompression. None of the divers had detectable bubbles in either the pulmonary artery or the carotid artery. Two overt cases of decompression sickness (knee pain) occurred, the first after 6 d of decompression and the second after 9 d of decompression. The second of these was predicted, from the ultrasonic imaging, on the basis that a substantial accumulation of stationary bubbles had occurred and was seen to be increasing. The first instance of symptoms was not predicted, although at the time of appearance of the symptoms, ultrasonic imaging revealed that a large amount of stationary gas was present. It was felt that the symptoms were not predicted owing to the timing of the ultrasound monitoring sessions (in the middle of each day's decompression), and that if we had monitored this diver either at the end of the previous day's decompression or before the decompression was resumed on the next day, then the build-up of the stationary bubbles would have been detected. The Doppler techniques did not reveal any bubbles in the pulmonary artery (the conventional pre-cordial monitoring position), and, therefore, no prediction of symptoms was made. Although some bubbles were detected in the femoral vein, these did not correlate with the appearance of symptoms. (Brubakk *et al.* 1983).

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T. R. Hennessy (*AMTE Physiological Laboratory, Gosport, U.K.*). Changes in the e.c.g. of small animals such as the rat indicate the presence of large quantities of intravascular gas, probably in the heart, and, after such gross decompressions, one can simply view the whole animal as a single equilibrated tissue! Small animal experiments may not be helpful in interpreting decompression sickness in a larger animal, such as the goat, which should be viewed in a multi-tissue sense on provacative decompressions. So it is important to be able to use the 64 element array transducer on goats as well as on milder decompressions with humans. Unfortunately there are severe difficulties to be overcome in preventing transducer–tissue movement artifacts and in finding a suitable and flat enough site for the transducer.

Dr Davies has had some success in observing the appearance of a gas phase on human decompressions, and subsequent regression on recompression. However, as with all other forms of ultrasonic detection, not all of these cases have progressed to a decompression incident. In particular, on one of the slides presented, a dive is described as ending in a therapy. This is rather misleading because the incident referred to was in fact a sore finger and the therapy was done purely as a precautionary measure! There were also a few cases of skin itch, which frequently occur on perfectly safe chamber dives. A realistic assessment of mild human decompression trials must await comparative studies with the same transducer on more provocative large animal experiments.

S. Daniels. The e.c.g. changes observed in the guinea pig, while undoubtably reflecting a severe case of decompression sickness, can nevertheless be seen to vary in severity in proportion to the severity of the decompression, and do not inevitably lead to death, the usual criterion of decompression sickness in small animals. Decompressions from less than 20 m s.w., with the guinea pig, have revealed that bubble formation is selective, initially appearing intravascularly. It would be erroneous to assume that under these conditions the guinea pig would be any different to man, and could not therefore be regarded as a single equilibrated tissue. I agree that as the ultrasonic pulse–echo technique is improved, experiments on larger animals will be necessary, but the information to be derived is likely to be more important for the association of the extent and location of bubble formation to signs of decompression sickness than for the understanding of the factors underlying bubble formation. Indeed, it must be stressed that the animal experiments are designed to answer fundamental questions about the reasons for bubble formation and are not expected to show how, in man, the extent of bubble formation is related to the appearance of decompression sickness. The recent work by Dr Davies with the integrating pulse–echo ultrasound technique has used human subjects and has shown that it is possible, in man, to predict the occurrence of decompression sickness. The role envisaged for large animal experiments would be the study of decompressions, which are known to give rise to symptoms, and as such cannot be done with men. Experiments with goats have shown that the technique can be successfully used.

The description of any recompression as 'therapy' is purely operational. The well known difficulties of diagnosis meant that we accepted the clinical judgement, at the time, that a recompression was advisable as a therapy. We accept that some of the recompressions we have termed therapeutic were in fact precautionary. Our main interest, however, was whether or not the recompression reduced the echo count, as indeed was demonstrated, and could therefore be taken to indicate the presence of gas bubbles. It is certainly true that, before the hypothesis that stationary bubbles precede symptoms of decompression sickness can be established, we need to study more than the four cases presented, in which overt symptoms of decompression sickness occurred.

Studies of nucleation relevant to decompression sickness†

A. Evans (*Decompression Sickness Research Laboratory, The University, Newcastle upon Tyne, U.K.*). Although there can now be little doubt that bubbles of separated gas play a major role in the aetiology of decompression sickness, the origin of these bubbles remains obscure. It is well known that the bubbles in most systems of practical importance arise from pre-existing gas nuclei, and in their absence a liquid may be stressed right up to the limit for homogeneous nucleation. In 1969 we demonstrated that if a living creature (the common shrimp) was subjected to extreme hydrostatic pressure to dissolve any gas nuclei, it became much less prone to internal bubbles at subsequent decompression (Evans & Walder 1969).

In early attempts to identify a possibly origin for acute or chronic nuclei, various additions were made to supersaturated air–in–water solutions, which had been stabilized in the same way (Evans & Walder 1974). No great progress was made, though it was shown that the 'thermal spikes' associated with spontaneous nuclear fission of atoms of uranium–238 did allow bubbles to arise under minimal stress (Walder & Evans 1974; Evans 1978).

† Organizer's footnote. The question of nucleation arose in discussion, but time did not allow proper treatment. The following two discussion papers have therefore been added, based on material prepared before the meeting.

Considerable advances became possible by the introduction of a radically different experimental system. A modification of the Berthelot tube, formed into a helix to allow the internal pressure state to be determined (Evans 1979), was used to induce mechanical tension in a wide variety of pure liquids, solutions, animal tissues (including live nematodes) and solids of possible relevance to decompression sickness (Evans 1981). It had been hoped that it would be possible to identify failure of adhesion at some interface as a source of bubbles under minimal stress, though once again no evidence for this manifestation of passive heterogeneous nucleation *in vivo* could be demonstrated.

TABLE D1. DISTRIBUTION OF BREAKING TEMPERATURES

breaking temperature range/°C	estimated mid-range tension/bar	number of runs in chamber	number of runs at Howdon
31 and over	under 9.5	8	6
30.8–30.99	10.4	15	8
30.6–30.79	12.1	16	7
30.4–30.59	13.9	17	14
30.2–30.39	15.7	17	8
30.0–30.19	17.4	26	16
29.8–29.99	19.2	25	14
29.6–29.79	20.9	22	28
29.4–29.59	22.7	8	22
29.2–29.39	24.5	20	31
29.0–29.19	26.2	13	46
28.8–28.99	28.0	6	15
up to 28.79	over 29.0	2	7
	totals	195	222
Approximate thickness of cover (metres of water equivalent)		0.4	46

However, consideration of the results obtained from some hundreds of runs in tension with 'control' tubes (containing only water) and the results with solutions of uranium salts led to the suggetion (Evans 1981) that active heterogeneous nucleation, owing to interactions by high energy cossmic rays with atomic nuclei within the specimen, could be important not only in the Berthelot tube but also, by inference, *in vivo* during decompression. It was also suggested that the most convenient way to assess this hypothesis would be to determine the effect of taking the experiment underground (Evans 1981).

We have recently been able to do this with a large Berthelot helix (designated 1S) containing 21.1 g ethanol, and operating under precise microprocessor control to give on each run a tension increasing gradually (at the rate of 1.5 bar/min) until the dilated liquid column is disrupted by nucleation. Results are reported for the observed breaking temperatures in table D1; a low value indicates high internal stress attained in the alcohol after a long waiting time in tension before rupture.

Runs were made in both of the steel compression chambers in the Decompression Sickness Research Laboratory in Newcastle, which are at ground level, to simulate the environment in which men are normally decompressed, and on two visits to the Howdon lower plant room of the Tyne Pedestrian Tunnel (Paton & Walder 1954), which has vertical cover of about 22 m of wet sand and rock. Since there was no significant difference between the results from the two chambers, they have been aggregated to give 195 results at ground level; similarly the two Howdon series have been combined to give a total of 222 underground results.

It is evident that, as was found for previous long series of runs with the Berthelot tube (Evans 1981), the limiting tension was far from consistent, and covered a wide range in both locations. However, it is also clear that on a higher proportion of the runs in the tunnel the liquid remained in tension for long enough to reach the low breaking temperature, especially to less than 29.2 °C. For this distribution χ^2 is found to be 48.1, with 12 d.f., so that $P < 0.0005$; there is a very significant association between breaking temperature and place.

This is entirely consistent with random premature nucleation, which gives higher breaking temperatures, within the chambers at ground level by 'cosmic rays', for it is known that the flux of all cosmic high energy particles and rays is greatly attenuated underground. So it would appear that serious consideration should be given to the possible role of cosmic nucleation in the origin of the bubbles seen at decompression. Further experiments, both with ethanol and with more physiologically appropriate liquids are now in progress.

I am much in debt to the staff of the Tyne Tunnel, especially Mr K. Evans and Mr J. Weatherall, for facilitating the underground experiment; to Professor G. D. Rochester, F.R.S., for advice concerning cosmic rays, and to the U.S. Office of Naval Research for financial support.

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K. C. Eastaugh (*Department of Pharmacology, University of Oxford, U.K.*). At the beginning of this meeting, Dr Smith referred to the question of homogeneous or heterogeneous nucleation underlying the separation of gas in decompression sickness. The fact that pre-exposure to pressure both *in vivo* and *in vitro* diminishes gas separation, provides evidence for the presence of micronuclei that create such heterogeneity (Evans & Walder 1969; Yount & Straun 1976; Vann *et al.* 1980). We have been studying the susceptibility of micronuclei to hydrostatic pressure, by using the common shrimp, *Crangon crangon*. This species, used by Evans & Walder (1969), is very suitable as an experimental animal because it can withstand high pressures, and being translucent allows direct microscopic observation of gas bubble formation *in vivo*. The effect of various magnitudes and durations of hydrostatic pressure on nucleation, and the subsequent regeneration of nuclei, have been studied.

The shrimps were pretreated in a constant volume bomb in which the pressure was increased hydrostatically to the required level. They were then exposed to sub-atmospheric instantaneous decompressions from atmospheric pressure to 0.1 bar in a perspex decompression cell, and the bubbles appearing in each shrimp were counted during the first 15 min after decompression. Only bubbles that formed and remained were counted; bubbles forming in the gut were rapidly eructated, and were treated as external, as were bubbles in the gills and those forming

underneath the carapace. The cephalothorax was more prone to bubble formation than was the abdomen.

Under these conditions, and using 20 shrimps in each exposure, the control mean bubble count per shrimp was 3.6 ± 0.8 (s.e.) There was a notable variation between animals. The distribution-free Wilcoxon test for two samples was used for assessing significance of results ($P < 0.05$), and only results significant by this test are reported.

For a pretreatment lasting 10 s, pressures of 50, 100 and 200 bar reduced bubble formation to 50, 58 and 33% of control, respectively. Pretreatment for 2 min, with the same pressures, led to reductions to 47, 28 and 14% of control. For an exposure of 10 min at these pressures, the reductions were to 30, 8.2 and 8.2%; and even a pressure of 25 bar now produced a significant reduction, to 19%. The sensitivity to pressure of the nuclei mediating gas separation is therefore also time-dependent; given time, pressures lower than those usually envisaged have proved to be effective.

In experiments on regeneration, shrimps were pretreated at 200 bar for 2 min, a procedure sufficient to reduce bubble formation to 14% of control, and were then left for various time intervals before the test decompression. The results showed that the micronuclei appeared to be regenerated *in vivo* with a half-time of 8–10 h. The regeneration was complete in 16–24 h. The mechanism for this regeneration is at present unknown; experiments on the possible role of locomotor activity are in progress.

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