Predictions from a mathematical model of decompression compared to Doppler scores

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ABSTRACT

This paper describes an attempt to calibrate a mathematical model that predicts the extent of bubble formation in both the tissue and blood of subjects experiencing decompression from a hyperbaric exposure. The model combines an inert gas dynamics model for uptake and elimination of inert anesthetic gases with a simple model of bubble dynamics in perfused tissues. The calibration has been carried out using the model prediction for volume of free gas (bubbles) as μl/ml in central venous blood and relating this to Doppler scores recorded at the end of hyperbaric exposures.

More than 1,000 Doppler scores have been compared with the model predictions. Discriminant analysis has been used to determine the cut-points between scores below a certain level and all scores at or above that level. This allows each prediction from the model to be equated to a particular pattern of bubble scores. The predictions from the model are thus given a context against the more familiar Doppler scores as a means of evaluating decompression stress.

It is thus possible to use the mathematical model to evaluate decompression stress of a hyperbaric exposure in terms of the predicted volume of gas that will form into bubbles and to convert that to a prediction of the most likely pattern of Doppler grades which would be recorded from a group of subjects experiencing that exposure. This model has been used in assisting regulators to set limits to the level decompression risk that should be considered acceptable and in assisting those working with decompression procedures to design effective modifications.

INTRODUCTION

This paper reports an attempt to calibrate a very simple physiological model of decompression by comparing the volume of free gas, which it predicts in the body at the end of a decompression, to the Doppler scores recorded following that same decompression. The literature on decompression theory is very large and increasingly complex. It is not unreasonable to question the relevance of complex theories that cannot be properly evaluated within the living human body. If a simple model can be used to rank hyperbaric exposures in terms of likely stress levels, the development of safer decompressions could be considerably simplified.

The success of a decompression from a hyperbaric exposure can be only very crudely determined: until relatively recently, by the occurrence or apparent absence of DCS; more recently, by ultrasonic methods to evaluate the amount of free gas (bubbles) in the body, most usually in the blood. Both approaches are bedeviled by the variability of human anatomy and physiology, both between individuals and within an individual. A cynic could liken the use of DCS as an indicator of decompression stress to an attempt to determine the number of units of alcohol consumed from the magnitude/duration of the ensuing hangover. Careful assessment of free gas formation by ultrasound would seem to indicate a more useful approach but, as anybody who has worked with either Doppler bubble scoring or ultrasonic scanning for bubbles will testify, attempts to wrestle the results into a clear pattern are frustrated by the great variability that is found both within subjects and between subjects, even though they have experienced identical hyperbaric exposures.

Physiological models of decompression have traditionally had a bad press. From Haldane in the early decades of the 20th century and intermittently throughout the century, physiological models failed to predict the incidence of DCS with any reasonable accuracy. The modelers attempted to improve the fit by adding compartments with longer and longer time constants, with no marked improvement.

This failure of physiological models of decompression was difficult to explain, as such models were known to have been reasonably successful in describing the uptake and distribution of another group of inert gases, volatile anesthetics [1]. The lower the fat solubility of the volatile agent, the closer the fit of the mathematical model [2].

The inert gases of interest in diving have extremely low solubilities compared to anesthetics, and therefore their fate in the body should be well simulated by a simple physiological model. However, anesthetic gases and vapors stay in solution in the body, whereas the main feature of decompression has to be that the inert gases may come out of solution and form a free gas phase, referred to as bubbles. This would seem to indicate that to be successful, a mathematical model used to predict the outcome from a decompression must include a section which simulates bubble formation and growth. The model that is the subject of this paper is a combination of a relatively simple eight-compartment gas dynamics model based on that of Mapleson [3] for inert anesthetic volatiles, and a relatively simple model of gas bubble formation and growth published by Van Liew and Burkard [4].

Once this combination is made, one of the reasons for the apparent failure of physiological models, despite the use of longer and longer time constants, becomes obvious. The formation of bubbles causes a delay in the removal of gas from the area in which the bubbles exist. The extent of the delay is characteristic not only of the decompression schedule but also of the type of tissue in which the bubbles have been formed [5]. The slower compartments added by the early modelers were added to both the uptake phase and the washout phase, whereas the slowing of gas movement due to bubbles happens only during the gas removal phase and only after bubbles have formed. As shown in Flook [5], the removal of gas from the body follows a three-phase log-linear-log path, the linear section indicating the presence of bubbles. The final exponential section is of very short duration, lasting only as long as it takes to wash out the small amount of inert gas after the bubbles have been resolved.

The refinement of adding a bubble dynamics model to a physiological gas dynamics model, together with the improved end-point of ultrasonic bubble scoring rather than DCS, increases the possibility that a physiological model can, in fact, be a useful tool to evaluate decompression stress.

For longer than a decade the author has been using the mathematical model based on the Mapleson and the Van Liew-Burkard models. The model has been used to calculate the volume of free gas likely to come out of solution in the tissues and in the central venous blood as a means of estimating decompression stress. Much of this work is written up in reports that are not freely available. However, several studies carried out for UK Health and Safety Executive are included in the HSE list of research reports and are therefore in the public domain [6,7,8].

Until recently the model has been used only to compare and to rank decompressions from hyperbaric exposures and has not been used to make predictions of bubble scores. Predictions of an outcome in absolute terms require proper calibration of the model, and this has become possible only recently. As part of a recent study for UK HSE, the author was given details of the Doppler results for a large number of hyperbaric exposures carried out at Defence Research and Development Canada (DRDC) Toronto (formerly DCIEM). Since the study was published by UK HSE [9], 40% more data has become available, and it is that larger study that is reported here. All hyperbaric exposures included here had nitrogen as the inert gas.

THE MODEL

The model has been described in detail in various reports and publications – for example in Jones *et al.* [9]. It treats the body as eight compartments, defined in terms of the time constant for inert gas movement, the time constant being derived from blood flow, tissue volume and gas solubility values [3]; thus all tissues with similar time constants are grouped into the same compartment, as described by Mapleson [3]. Apart from changes based on known physiology (such as changes in muscle blood flow during physical activity) and for which the physiology literature can provide guidance, all parameter and constant values have remained unchanged since the model was first assembled. It is a particular strength of this model that none of the parameter values required by the model derive from the diving or hyperbaric literature.

The section of the model that simulates the formation of bubbles during decompression requires additional parameter values. The surface tension value used for the gas-liquid interface is 0.005 kPa-cm [4]. The initial nucleus, from which bubbles form, has been taken as 2µm. The density of gas nuclei, and therefore of bubbles within the tissues, used throughout the work are:

- in fat – 8000/ml;
- in muscle – 500/ml; and
- all other tissue including blood – 100/ml.

The discussions relating to the selection of these parameter values and the experimental validation are given in the detailed discussion of the structure of the model provided in Appendix 2 of Jones *et al.* [9].

Simulation of a hyperbaric exposure

The pressure profile and the breathing gas profile of the actual hyperbaric exposure, from the start of compression to the start of decompression, are used to calculate the inert gas uptake in each compartment up to the moment at which decompression starts. The uptake of inert gas during this phase is exponential, with the appropriate time constant for each compartment.

From the start of decompression the equations describing bubble formation and growth [4] are solved for each time increment which, in the case of the work described here, is set at six seconds in order to give accurate results for even the fastest tissues. The pressure and breathing gas profiles throughout decompression are applied to the bubble dynamic equations for the duration of the decompression and for at least an hour beyond the end of decompression to track the initiation, growth and decay of bubbles in each compartment from the initial nucleus. This part of the calculation gives a profile of the volume of gas carried as bubbles per unit volume of tissue and venous blood draining the tissues of each compartment. The output from each of the eight sections of this calculation is in effect the volume of gas carried as bubbles in the venous blood draining that tissue. This is used to calculate a weighted mean of gas volume carried as bubbles, which is equivalent to central, mixed venous, free gas load. The weighting applied to the output from each compartment simply relates to the distribution of cardiac output between the eight compartments. The central venous free gas load is the value that can be compared to precordial Doppler bubble estimates.

For decompressions in which oxygen has been used as the breathing gas, the model has been refined to include, during periods of oxygen breathing, an element of vasoconstriction. It is impossible to find textbook figures for the degree of vasoconstriction that might occur in tissue as inspired oxygen levels increase. Indeed, according to Professor Lambertsen: "Because each organ, its many different tissue components and even minute units of a single tissue has different relations of blood flow and metabolism, oxygen pressure gradients vary considerably from one discrete locus to another" [10]. The best that can be done is to find an average value for the effect of oxygen on blood flow in the whole body. These figures have been derived from Whalen *et al.* [11], quoted in Lambertsen.

From the information given in Whalen *et al.* about changes in peripheral resistance, blood pressure and cardiac output as inspired oxygen levels increase, it has been possible to derive figures for the average reduction in blood flow. Table 1 *(below)* lists these in relation to inspired oxygen partial pressure.

TABLE 1

Reduction in blood flow due to hyper-oxygen vasoconstriction

Inspired oxygen partial pressure (bar)	Blood flow as % of normal
1	94
1.3	93
1.6	91.5
1.9	90
2	89.5
2.2	89
2.5	86.8
3.0	86

During oxygen breathing the blood flow to each tissue has been reduced by the appropriate amount. The reduction in blood flow has the effect, during decompression, of slowing down the removal of inert gas from the body.

DATA

The data used for the calibration of the model comprise 1,013 Doppler results for 83 different hyperbaric profiles with a depth range of 9-80 msw (90-800 kPa). Of the results, just over 94% were carried out under the controlled conditions in a hyperbaric chamber. The exposures included air dives with decompression stops, air dives with no decompression stops, air dives with oxygen during the decompression, Sur-D exposures with and without oxygen during the "in-water" part of the decompression and compressed-air decompressions with and without oxygen. The 5.9% that were not carried out in the chamber included a small number of subjects who had Doppler data recorded at the end of an operational compressed-air job and 47 open-water dives, each with a single subject.

TABLE 2

Two very different hyperbaric exposures with almost identical Doppler results

Exposure (msw/mins)	**Predicted gas** (µl/ml)	**Grade 0**	**Grade I**	**Grade II**	**Grade III**	**Grade IV**
36/50	2.52	12	2	4	6	0
72/40	7.69	10	1	4	6	0

The Doppler scores were recorded at the end of the hyperbaric exposure. The Doppler scoring used is the Kisman-Masurel method and was carried out according to the procedure recommended by DRDC Toronto. This is well described in Nishi *et al.* [12]. The great majority, 94%, of the Doppler evaluations was carried out by technicians from DRDC Toronto. The remainder were recorded by two technicians trained by DRDC in the procedure, and the recordings were sent to DRDC for evaluation. This ensures a constant quality for all the Doppler results.

As described in Nishi [12], in the pulmonary artery the degree of bubbling in the blood draining the body is determined by recording over the precordium; peripheral bubbles are determined from both right and left subclavian vein. At each site the evaluation is made twice, once with the subject still and again after movement designed to flush through to the probe any bubbles adhering to the blood vessel walls.

In this work, a single Doppler score has been selected from the results for each subject, the highest grade detected in the precordial region while the subject was at rest. The KM scoring system allows for 12 grades, with intermediate grades between 0, I, II, III and IV. The intermediate grades have been taken into the "central" grade. Thus, Grades III- and III+ have been included in Grade III. The Doppler score has been compared to the maximum value for venous free gas volume in the central venous blood, predicted by the model for that hyperbaric exposure.

RESULTS

The values for predicted free gas for each exposure are given in the Appendix alongside the frequency of occurrence of each Doppler score. For the hyperbaric exposures used in this study, the range for concentration of predicted free gas in the central venous blood is 0.67 to 7.69 µl/ml.

The open-water dives, having only a single subject for each, could not be entered in the table as individual dives. The depth range for these dives was 18 msw to 42 msw and duration from four minutes to 15 minutes; predicted free gas 0.67 to 2.15 µl/ml.

For the purpose of displaying all results in the Appendix to demonstrate the proportion of subjects who had each Doppler score, these in-water dives have been shown as a single exposure with the average predicted gas volume. This has been justified on the grounds that this small proportion of the total number of exposures in the study was a very close group in terms of depth, exposure time and predicted free gas volume. In the data analysis, these in-water dives were handled as individual dives for all except the binary logistic analysis, where they were handled as a single exposure as given in the Appendix.

The data have been analyzed using several statistical approaches. As with all studies involving Doppler evaluation, there is great variation in bubble grade between subjects experiencing an identical hyperbaric procedure. Conversely, as shown in Table 2 *(above)*, two very different exposures – one to twice the depth of the other and with three times the predicted free gas volume – have Doppler score distributions that are almost identical. This variability has to be dealt with in order to calibrate the model.

An analysis of variance was carried out to compare the variability of predicted gas volume in bubbles within the individual grades to the variability of predicted volume between grades. The ratio of the between-grades variance and the within-grades variance (F) is 11.72, with degrees of freedom of 4 and 1,010 respectively. This demonstrates that the variability for predicted gas volume between grades is significantly greater than the variability within each grade. From this we conclude that there is a difference between the predicted gas volume in bubbles for each Doppler grade of bubbles over and above the variability within each grade.

Doppler grades and average predicted gas volume

The average predicted gas volume in bubbles for each Doppler score is given in Table 3 *(facing page, top)*. The number of exposures with Grade IV is very small, and therefore both mean and variation carry a lower level of confidence than the other grades.

The coefficient of variation is around 50% except for Grade III. The results for this grade differ somewhat from the other grades in that 34% of the results came

TABLE 3

Average predicted gas level for each Doppler grade

Doppler score	Ave pred gas µl/ml	Number	Coefficient of variation %
Grade 0	3.87	624	51.4
Grade I	4.19	98	58.7
Grade II	4.83	110	47.0
Grade III	5.01	171	26.7
Grade IV	5.24	10	3.05

from just two trials with predicted gas 5.0 and 5.11 µl/ml. The large number of subjects in each of these two trials, together with the coincidence of the similar predicted free gas volume, has the effect of considerably reducing the coefficient of variation for Grade III.

The large variance means that the predicted free gas volume for each of the five bubble grades cannot be separated from each other with the use of simple statistics such as a comparison of means.

There has been speculation in the literature about the relationship between Doppler grades – *e.g.*, does Grade II represent half as much free gas as Grade IV and twice as much as Grade I? Figure 1 *(right)* shows the average predicted free gas for each grade against a vertical scale to display the relationship between the grades as defined by this study. The result used for Grade 0 in this figure is from a subset, described below, which gives a high level of confidence that there were no detectable bubbles in these subjects. The dashed lines are set at the average predicted gas volume for the grade. The lines alone give a false idea of certainty. The shaded area has been included in order to set the lines against the full range of predicted gas volumes found in the study.

The average value of predicted gas volume in bubbles for Grade I is 4.19. The 99% confidence limits for Grade 1 range from 0.09 to 8.29 µl/ml. This means that every hyperbaric exposure included in this study could have resulted in Grade I bubbles in a proportion of the subjects. Including the 99% limits for each grade on Figure 1 would effectively produce the range as shown by the shaded area.

Grade 0 subset

There is within the data an interesting subset. This comprises subjects who showed no detectable bubbles at any of the recording sites either at rest or following movement. The lack of detectable bubbles following movement is taken to indicate that there can be a very high level of confidence that there was not enough free gas in the body of these subjects to cause detectable bubbles. There were 141 subjects from 23 different hyperbaric exposures in this subset. The average predicted gas volume for these subjects is 3.39 µl/ml with variance 0.39 µl/ml. As might be expected, this is a much tighter group of results, the coefficient of variation being 11.5%.

FIGURE 1

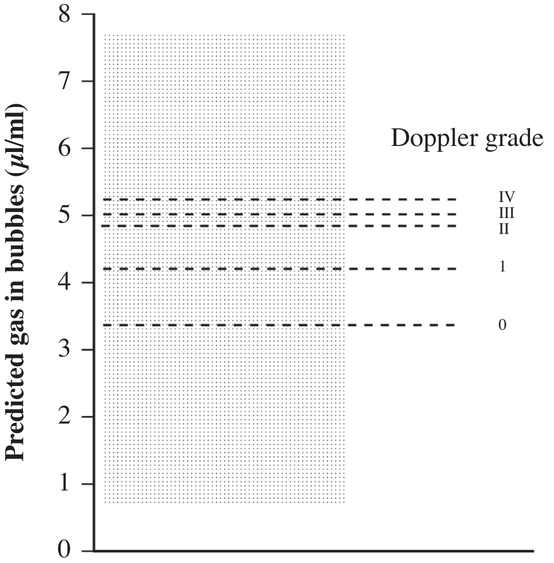

FIGURE 1 – The lines show the average predicted free gas value for each bubble grade. The range for the whole study is shown by the shaded rectangle.

Discriminant analysis of the data

We know from the analysis of variance that the variation in predicted free gas between the Doppler grades is greater than the variation within any one grade. This indicates that there is a difference between the predicted value of free gas for different grades. Though the difference cannot be detected by a comparison of means, it should be possible to make use of discriminant analysis to determine the risk of bubbles exceeding a particular grade for each hyperbaric exposure.

TABLE 4

Parameter values for division between grades

Doppler grades	Constant	St error	Regression coefficient	St error
=> I	-2.47	0.234	0.46	0.050
=> II	-3.22	0.268	0.52	0.056
=> III	-3.72	0.316	0.48	0.063
=> IV	-6.91	1.213	0.49	0.224

Binary logistic regression has been used to define the cut between grades. Table 4 *(above)* gives the value for the constant and regression coefficient for the lines separating grades. Thus, the first set of values defines the line separating Grade 0 from all higher grades; the second set defines the line separating all grades below II from those equal to or higher than II; the third set the cut between grades lower than III and Grades III or higher; and the fourth set the cut between Grade IV or higher and all lower grades.

The division between Grade IV and all lower grades deals with only 10 points on one side of the divide against 1,003 on the other. This explains the larger standard errors from that regression. The lines constructed from these results are shown in Figure 2 *(facing page)*.

Figure 3 *(facing page)* shows the line for the divide between Grade II or above and the lower grades. The data points used in the logistic regression are also shown. These are shown for each value of predicted free gas using the proportion of subjects with Grade 0 (■), Grade I (▲), with Grade II (▼) Grade III (*) and Grade IV (◆). There were several exposures for which all the subjects had Grade 0 bubbles as shown by the collection of ■ at proportion equal to 1. Likewise there were many instances of a particular grade not occurring in any subject; these are the symbols along the horizontal axis, proportion equal to zero.

Prediction of Doppler grades

The logistic regression equations have been used to calculate the risk (%) of having a particular Doppler grade or higher for a range of predicted gas volume values. These are shown in Table 5. The second column is of particular interest in that it gives the risk of there being any detectable bubbles. Thus, a hyperbaric exposure that the mathematical model predicts to give a free gas volume of 0.5 µl/ml has almost 10% risk of there being detectable bubbles and a 3% risk of there being some with Grade III; an exposure with a predicted gas volume of 5.0 µl/ml has almost 46% risk of there being detectable bubbles and a 21% risk of there being some with Grade III or higher.

DISCUSSION

The primary objective of this work was to evaluate the mathematical model as a means of estimating decompression stress in terms of bubble formation. There is a requirement for a mathematical model that, for example, will allow hyperbaric exposures to be ranked. Such a model could also be used to assist regulatory bodies in setting limits, based on an element of knowledge and understanding, within which proposed exposures should fall. Equally there is a need for a model to assist in design of new decompression procedures and which can be used to estimate the degree of improvement of any new exposures that are proposed.

The results do show that the model can be used to differentiate between hyperbaric exposures, though not with the precision one would wish. More than 1,000 exposures have been used in this study, and more than 60% (624) had no detectable bubbles. There is no doubt that a more even distribution of Doppler scores would have resulted in a more satisfactory outcome but, in fact, most operational hyperbaric exposures in humans, whether in the controlled conditions of a hyperbaric chamber or carried out in water, do result in no detectable bubbles [13]. The distribution of scores given here probably mirrors real life.

There are two questions that arise when using Doppler scores to evaluate decompression stress. The first concerns the threshold of detection – *i.e.*, how many bubbles, how much free gas, must be present for the bubbles to be detected. The second question relates to the relationship, if any, between Doppler grades. Does Grade II mean twice as much gas as Grade I, and Grade IV twice as much as Grade II? This study has shed some light on these questions but, as ever when working with quantification of decompression bubbles, it has not provided definitive answers.

The formation of free gas bubbles within the body is influenced by many factors, both physiological and anatomical. For example, small changes in local conditions such as blood flow, which Lambertsen recognized as influencing local oxygen gradients [10], also influence free gas formation. The local variations mean that any tissue effectively has a range of time constants. The time constant is critical in determining both inert

FIGURE 2

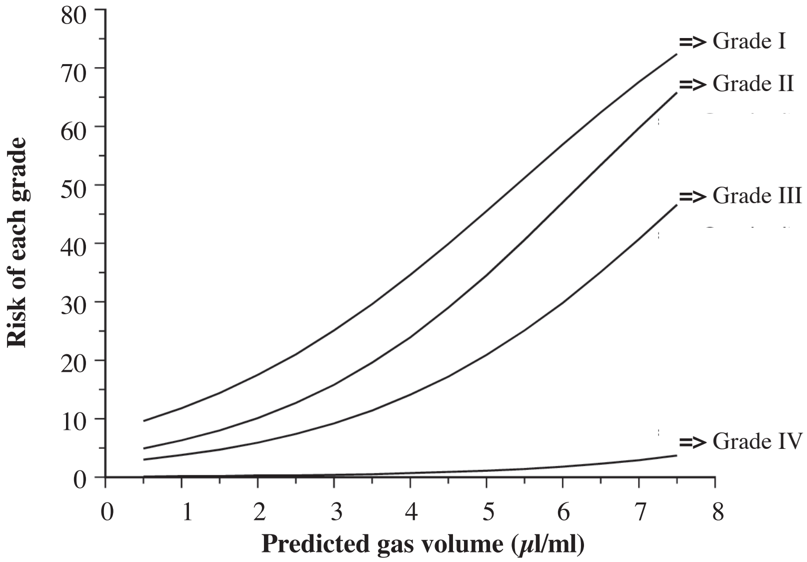

FIGURE 2 – The lines separating the Doppler grades, derived from the values in Table 4.

FIGURE 3

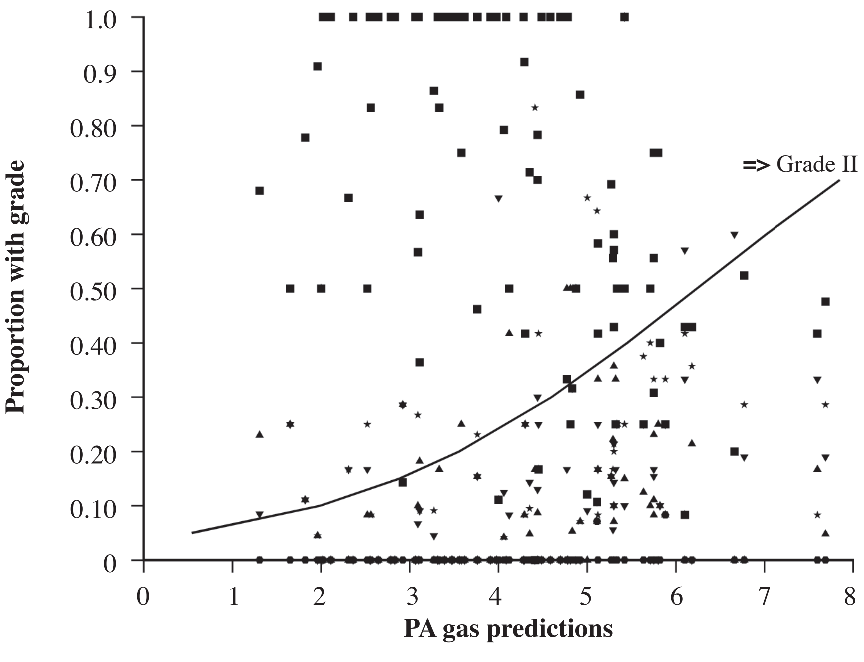

FIGURE 3 – The binary regression line showing the cut between bubble scores Grade II or higher and those Grade I and Grade 0. The points show the data expressed as proportion of total for that value of predicted gas (see text).

gas movement and free gas formation. Mathematical models can deal only with the average: average for each tissue type, average for each individual's gross anatomy. The mathematical model prediction itself carries a level of uncertainty that is impossible to quantify.

The detection of gas bubbles using Doppler depends not only on the presence of the gas but also on other factors such as the expertise of the Doppler technician and the anatomy of the subject. In this study we have reduced the effect of the technician by using only Doppler data derived from a single source. Anatomical differences between subjects can also have a considerable effect on Doppler detection.

Most Doppler technicians have had the experience of the occasional subject for whom it is very difficult to position the probe so that precordial bubbles are detectable. Detection is more difficult in subjects with a thicker layer of flesh underlying the probe. The model makes predictions for the "average man." Anatomical and physiological variability will mean that in fact there will be a range of free gas levels in subjects having the same decompression experience. The use of discriminant statistical analysis allows for all these factors and provides a means of drawing some kind of order from apparent chaos.

By making use of more than a thousand hyperbaric exposures, it has been possible to generate an estimate of risk in terms of the proportion of divers likely to exceed a threshold level of Doppler scores, as shown in Table 5 *(Page 194)*. However, no mathematical model can predict the bubble score for any individual. To do that would require a model that used parameter values measured in the individual under the conditions of the hyperbaric exposure.

TABLE 5

Predicted gas volume and associated risk for each bubble grade

Predicted gas volume µl/ml	*Percentage predicted to have:*			
	Detectable bubbles	**Grade II or higher**	**Grade III or higher**	**Grade IV or higher**
0.5	9.6	4.9	3.0	0.0
1.0	11.8	6.3	3.8	0.2
1.5	14.4	8.0	4.7	0.2
2.0	17.5	10.1	5.9	0.3
2.5	21.0	12.7	7.4	0.3
3.0	25.1	15.8	9.2	0.4
3.5	29.6	19.6	11.4	0.5
4.0	34.6	23.9	14.1	0.7
4.5	39.9	29.0	17.2	0.9
5.0	45.5	34.5	20.9	1.1
5.5	52.1	40.6	25.1	1.4
6.0	56.9	47.0	29.8	1.8
6.5	62.4	53.4	35.1	2.3
7.0	67.6	59.7	40.7	2.9
7.5	72.4	65.8	46.6	3.7
8.0	76.8	71.3	52.5	4.6

According to the information in Table 5, all of the exposures dealt with in this study could produce detectable bubbles in some subjects, even when only a small volume of free gas is predicted. For example, given a large enough number of subjects for each decompression, Grade I bubbles could be found in some subjects for all decompressions included here. For a predicted free gas concentration of 0.5 µl/ml, 4.7% could have Grade I, with a further 4.9% having higher grades, and just over 90% with no detectable bubbles. At the other end of the scale, predicted free gas volume of 8.0 µl/ml, 4.5% could have Grade I but, at this end of the range, that is against a background of over 71% with higher grades and only 24.7% with no detectable bubbles.

There is a small risk of Grade IV bubbles for decompressions predicted to give 1.0 µl/ml free gas, though in the data (see Appendix) the first level at which Grade IV was recorded was for a predicted gas level of 5 µl/ml. This is a clear demonstration that even with this analysis, we cannot make firm predictions of the degree of bubble formation. This has been demonstrated in this work in that the confidence limits for the average predicted gas volume equivalent to Grade III *(Table 3)*, are closer than for other grades because 58 subjects, in two exposures with similar levels of predicted gas, had Grade III bubbles.

Despite the high levels of uncertainty, the information in Table 5 makes it possible to set guidelines and test new procedures against them by use of the model. For example, if it is considered unacceptable for more than about 30% of divers to have Grade II bubbles or higher, then the limit can be set at a predicted gas volume of 4.5 µl/ml. In a situation where a higher risk is acceptable, say up to 50% of divers with Grade II or higher, the cut-off should be a predicted gas volume of around 6 µl/ml. Conversely, an exposure with a predicted gas volume of 1.0 µl/ml, likely to have 11.8% of divers with detectable bubbles, 3.8% with Grade III or higher, can be considered as a lower decompression stress than one with a predicted gas volume of 3.0 µl/ml, 25% having bubbles, 9.2% with Grade III or higher.

Table 5 can also be used in conjunction with the model to design new decompression profiles, to answer questions such as those relating to the efficacy of using deep stops and to offer informed contributions to debates such as those relating to the merits of decompression stops compared to no-stop linear ascent. It is obvious from the results that for a decompression profile to be considered an improvement in any worthwhile terms, the predicted gas level for the new profile would have to be considerably different from that for the original profile. There is little to be gained, nor would the improvement be measurable, by changing to a decompression profile that the model predicted to reduce free gas volume by, for example, 0.5 µl/ml. An improvement of 2 µl/ml or more would perhaps be worthwhile. This explains why in the past small "tweaks" to an existing profile rarely result in a significant change once the new profile is put into general use.

Threshold of detection

One of the questions that remains unanswered about Doppler bubble detection is: How much gas must there be in the free gas phase for the bubbles to be detected? In an ideal world, the relationship between predicted gas volume and lower limit of occurrence of Doppler Grade I would have zero detectable bubbles at a non-zero, positive value for the predicted gas. This would be the threshold of detection. The variation between individuals makes it impossible, even with 1,013 exposures, to put a reasonable value on the predicted gas volume that can be considered the threshold of detection. The subset of 141 divers in whom no bubbles were detected at any site, either after movement or at rest, formed a tighter group with a coefficient of variability of 11.5% for the mean predicted gas volume, which was 3.39 µl/ml. However, Table 5 shows that this level of predicted gas carries the risk of almost 30% having detectable bubbles. From this we can only conclude that the threshold of detection is unlikely to exceed a predicted volume of 3.39 µl/ml.

Conversely, Table 5 also indicates that 10% of subjects could have detectable bubbles when the predicted gas is as low as 0.5 µl/ml. Are these subjects who produce detectable bubbles at very low levels of free gas, or are they subjects who produce more free gas than predicted? We have no way to distinguish between these alternatives.

It is probably safe to conclude that there is a level of free gas that is too low for Doppler to detect; that there is a non-zero threshold for Doppler scoring. We have to conclude that decompression from a hyperbaric exposure may give no detectable bubbles but is most unlikely to give no bubbles. In practice, the threshold of detection is likely to be different for different individuals.

Relationship between Doppler grades

The other aspect of Doppler scores which has given rise to discussion over recent years is the relationship between grades and the volume of free gas present under the detector. From Figure 1 it would seem there is no obvious mathematical relationship; it is not linear, it is not exponential. There appears to be a narrow range of free gas concentrations covered by Grades II to IV. This might be significant when we consider that among organizations attempting to set an upper limit to acceptable level of bubbling, Grade III has been considered more acceptable than Grade II. The information displayed in Figure 1 would seem to suggest that there is not so great a difference between Grade II and Grade III and that to make a significant difference in risk selection of Grade I would be a better upper limit.

CONCLUSIONS

This study has demonstrated all too clearly the problems inherent in using bubble scores to estimate decompression risk. However, it has in effect set the model predictions into the context of Doppler scores. To this extent, it has shown that a physiological model of decompression can be useful to evaluate risk and to assist in reducing risk to divers. As with all mathematical models used to describe conditions in the body, it is not possible to predict for the individual. However, using the results of the analysis presented here, it is possible to predict likely bubble scores for groups of divers.

This work has highlighted the fact that the absence of detectable bubbles is most unlikely to indicate a bubble-free exposure and that subjects having Doppler Grade 0 should be more properly referred to as subjects with no detectable bubbles rather than non-bubblers. It has also demonstrated that it is unlikely that there is a simple relationship between the different bubble grades and volume of free gas.

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