REPORT USL 23-001

Reducing risk for upward excursions

REPORT

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UNIMED SCIENTIFIC LTD
123 Ashgrove Road West,
Aberdeen. AB16 5FA.

Telephone 44 (0)1224 680907
Fax 44 (0)1224 680908

AUTHORS

Valerie Flook

CLIENT	Well Ops UK Ltd
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SUMMARY

The work described in this report follows on from that reported in USL 22-015 2002. In that report recommendations were made to reduce the rate of ascent from downward excursions to 5 metres/minute and to delay the start of decompression until 6 hours after the last excursion. These changes will reduce bubble growth to below that for current practise. This report describes changes to procedures for upward excursions to ensure that the level of bubble formation during an upward excursion never exceeds that for the maximum allowed downward excursion for the particular saturation pressure.

The rate of ascent for upward excursions should be not more than 5 metres/minute. There should be a 12 hour hold at storage depth between downward and upward excursions. The maximum permitted upward excursion will then depend on both storage depth and the magnitude of the previous excursion and examples of these limits are shown in figure 2 in the report. With these limitations the maximum extent of bubble formation and growth due to the excursions will be the same whether a downward or upward excursion is done and will depend on saturation depth.

Return to storage pressure resolves the bubbles of upward excursions and therefore, following the 6 hour hold already recommended, the decompression should start bubble-free.

CONTENTS

1.0 INTRODUCTION

The work described in this report follows on from that described in USL 22-015 (Flook 2002) and deals specifically with the risk of excursions to a lower pressure than the storage pressure during saturation dives. In addition to the known link between decompression sickness (DCI) and number of depth changes during a saturation exposure (Jacobsen et al 1997), upward excursions carry a greater risk to the diver's safety because the decompression bubbles are present during the time he has to carry out his work.

It has been shown in animal studies that the presence of decompression bubbles causes pulmonary shunt which has the effect of reducing the levels of oxygen in arterial blood (Flook et al 1994). Increased inspired oxygen cannot reverse the effect of shunt and therefore divers might be expected to be tired and to perform tasks less efficiently and less safely during upward excursions.

The reduction in performance may be further compounded by the formation of bubbles in the central nervous system. The amount of bubble formation in this tissue depends critically on the rate of upward movement.

To some extent these problems are taken care of by regulations limiting the size of allowed upward excursions within 24, 48 or 72 hours of a downward excursion, the required time interval being greater the greater the storage depth. In effect this means that following a maximum downward excursion no upward excursion is allowed within the time limits. Following a downward excursion less than maximum, the allowed upward excursion within the time limit can be too small to be of any operational use.

These limits appear to have been set without any evaluation of the likely effect on risk. The purpose of the present work is to begin to define regulations for upward excursions taking account of the likely effect on risk.

1.1 SETTING ACCEPTABLE RISK LEVELS

The technique used is simulation of bubble formation using a mathematical model of decompression based on physiological and anatomical parameters. The model has been described in more detail in the earlier report. Output from the model is in the form of predictions of the volume of gas which will be carried as bubbles in each ml of tissue or blood. For the purposes of this work two locations have been considered; the bubbles which form in the brain and the bubbles which are carried in the central venous blood, this latter being an indication of whole body bubble load.

It is possible to make a link between the model prediction and likely bubble counts as recorded by precordial Doppler, and from there an approximate link to possible incidence of decompression sickness. However this is not the best way to use a mathematical model. The preferred way is to compare predictions for the new procedures with predictions for the old, accepted, procedures.

In the earlier work new procedures were suggested which would lower the bubble formation following downward excursions and during the subsequent decompression. A lower risk is a prediction of lower volume of gas in bubbles compared to the prediction for the current procedures. For the current work the acceptable level of bubble formation has been taken as equal to that for the new procedures for maximum downward excursions. At any saturation depth the level of bubble formation following a maximum downward excursion, using the new procedures, has been taken as the maximum allowed for an upward excursion.

The two main changes made in the earlier work were:

> that upward moves should be made at a rate not higher than 5 m/min. This reduced the formation of bubbles in the brain
>
> that decompression should not start until at least 6 hours after the end of the last excursion and that 1.5 bar oxygen should be breathed during the last hour of that hold. This reduced the whole body bubble load throughout the decompression.

These changes were adopted in the present work.

The current regulations require previous downward decompression to be taken into account for 24, 48, or 72 hours before the upward excursion. These time intervals do not fit with operational requirements in that a diver would be usually required to dive again 16 hours after the end of his previous shift. In some circumstances the rest time could be reduced to 12 hours. It therefore seemed worthwhile to look at ways in which upward excursions could be allowed on the next normal work shift following the downward excursion.

This report presents the level of bubble formation for upward excursions taken 12 hours after a previous downward excursion, expressing the bubble formation as a percentage of that which is predicted for the maximum downward excursion at that depth.

2.0 RESULTS

As mentioned in the previous section the level of bubbles taken as acceptable in this work was the gas volume predicted to be carried as bubbles per ml of central venous blood following the maximum allowed downward excursion when the return to the bell is carried out at a rate not exceeding 5m/min. Table 1 show these results, expressed as volume of gas in bubbles per ml of central venous blood, for the maximum allowed downward excursions from storage depths 30, 75, 100, 130 and 180 msw. The results are shown both as the maximum following return to the storage depth and the level reached after 12 hours at the storage depth.

Table 1
Gas in bubbles after downward excursion (ml/ml)

	17-30	25-75	29-100	33-130	38-180
Max	0.00046	0.00038	0.00036	0.00033	0.00029
at 12 hours	0	0.00005	0.00006	0.00007	0.00007

From these figures it is apparent that the greater gas load at the lower storage depth is cleared more quickly than a lesser gas load at higher storage depth. This appears to be due to the fact that the level of oxygen used during storage is a larger proportion of the total pressure for the lower storage depth than for the greater depths.

For each saturation depth the gas in bubbles after the 12 hour wait was calculated for the downward excursion. This value was used as the starting point for the upward excursion. For each depth, and for a range of downward excursions from that depth, a range of upward excursions were simulated so that graphs similar to those shown in figure 1 could be constructed.

Figure 1 shows the maximum central venous bubbles following the upward excursion, expressed as a percentage of the maximum predicted to result from the downward excursions given in Table 1, that is as a percentage of the numbers in the middle row of that table. The numbers against each line on the figure give the size of the downward excursion and the storage depth. The dotted line is the level at which the upward excursion bubbles are equal to those from the maximum downward excursion.

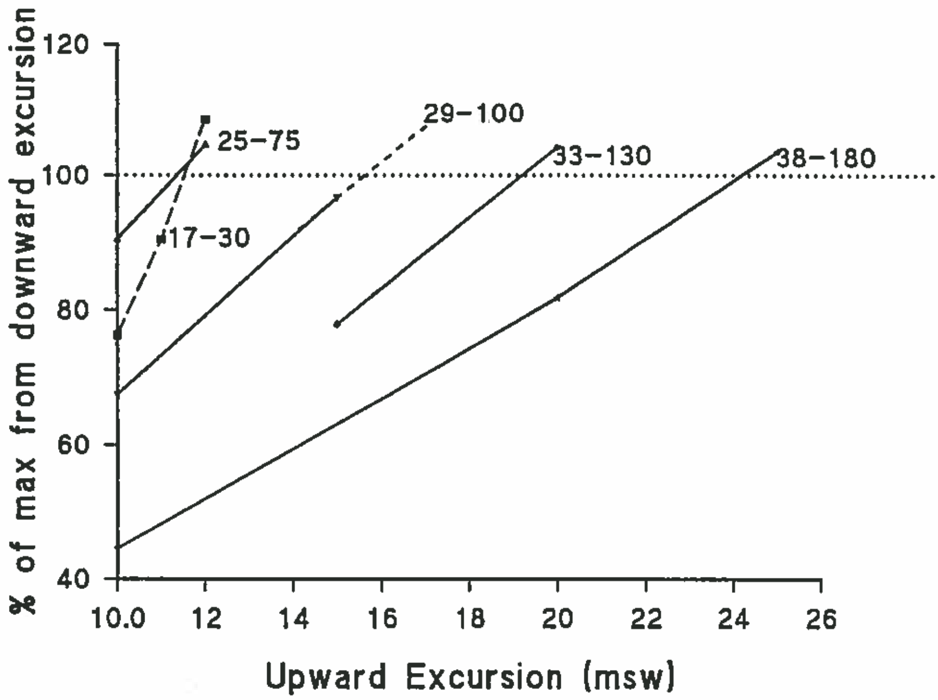

Figure 1 **Gas load on upward excursion as a percentage of the maximum gas load from the maximum downward excursion allowed for that depth.**

The line for the upward excursions from 30 msw is shown as a dashed line because, as shown in Table 1, the upward excursions will start with no bubbles anywhere in the body. In this situation the bubbles at the end of the upward excursion are dependent only on that excursion, there is no influence from the earlier excursion. This is manifest as a different slope to the line.

2.1 FOLLOWING MAXIMUM DOWNWARD EXCURSIONS

The results from simulations of upward excursions following maximum downward excursions are given in Table 2 expressed as % of the acceptable level, i.e. the middle row on Table 1.

Table 2
Upward excursion bubbles as % of maximum from downward excursion

	17-30	25-75	29-100	33-130	38-180
10msw	76.3	90.4	67.5		44.4
11msw	90.4				
12msw	108.6	104.5			
15msw			96.7	77.9	
20msw				104.2	81.8
25msw					103.5

From these results the maximum allowed upward excursions are as given in Table 3. The top row gives the size of the downward excursion and the storage depth.

Table 3
Upward excursion to same level of risk as maximum downward

	17-30	25-75	29-100	33-130	38-180
Upward	11.5	11.4	15.5	19	24

The practical consequence of the upward excursion starting bubble-free is apparent in that the allowed upward excursion from 30 msw is greater than that from 75 msw.

2.2 FOLLOWING SUB-MAXIMUM DOWNWARD EXCURSIONS

To determine upward excursions for the complete range of allowed downward excursions would require a large number of calculations. For the purpose of this work a limited number of combinations have been studied. For each storage depth 3 or 4 downward excursion depths were simulated. The effect of the 12 hours at storage depth was calculated. For each downward excursion a small range of upward excursions were simulated to allow interpolation to determine the upward excursion which produce the accepted upper limit of bubble production. The results for these calculations are shown in Figure 2.

The lines at the left side of Figure 2 relate to conditions in which all bubbles have disappeared before the end of the 12 hour hold and therefore the magnitude of the allowable upward excursion is independent of the earlier downward excursion and is only dependent on storage depth. The exact size of the downward excursion from which bubbles are gone by 12 hours has not been determined, which is why the lines on the left side of the figure have not been joined to those on the right. However each storage depth can be identified by the symbols on the lines.

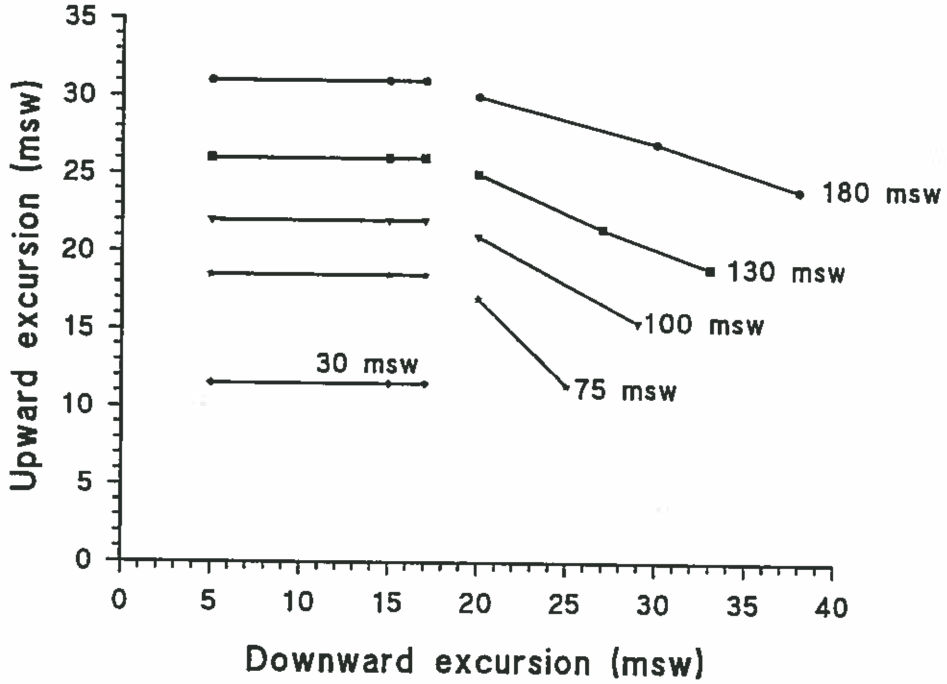

Figure 2 **Upward excursions which can be allowed 12 hours after a downward excursion**

2.3 BRAIN BUBBLES

The bubbles in the brain of the average diver will be resolved well within the 12 hours allowed between downward and upward excursions. Thus from the point of view of brain gas each upward excursion starts clean. The earlier work on downward excursions showed that by reducing pressure by no more than 5 metres per minute the amount of gas formed into bubbles in the brain tissue could be approximately halved and this rate has been used in all simulations for this report. As in the previous work the two types of brain tissue, gray and white matter, have been taken to be equal contributors to the overall gas load in the brain.

The volume of gas in bubbles per ml of brain tissue is given in Table 4, expressed as a percentage of that which would result from the maximum downward excursion for that storage depth. In other words the acceptable upper limit for brain bubbles has been set in the same way as that for central venous bubbles.

Table 4
Bubbles in brain as a percentage
of those following a maximum downward excursion

Downward	Upward	Brain bubbles
180		
38	24	44%
30	27	59%
20	30	74%
17,15,5	31	82%
130		
33	19	32%
27	21.5	61%
20	25	71%
17,15,5	26	77%
100		
29	15.5	20%
20	21	66%
17,15,5	22	81%
75		
25	11.4	16%
20	17	58%
17,15,5	18.5	74%
30		
17,15,5	11.5	81%

Thus all the allowed upward excursions are predicted to give less gas in bubbles in the brain than for the maximum allowed downward excursion and less than if the upward travel were at 18m/minute.

2.4 THE EFFECT OF DECOMPRESSION

In the earlier work is was shown that bubbles last long enough to still be present even after a wait of several hours. These bubbles grow during decompression and as a general rule the deeper the saturation, the longer the decompression, the more the gas bubbles grow. The longer the hold prior to decompression the less gas there is in bubbles to grow. If decompression is to incur no extra risk due to upward excursions then the gas bubbles present during the upward excursion must be resolved before the start of the decompression.

Figure 3 shows the fate of gas bubbles following an upward excursion of 40 msw above the storage depth of 180 msw and starting just 12 hours after a 38 msw downward excursion. Reference to figure 2 will show that this 40 msw upward excursion is greater than allowed so figure 3 refers to a bubble load higher than the accepted risk level. The bubbles are obviously compressed on return to storage depth thereafter there will not be enough inert gas to form bubbles prior to the start of decompression.

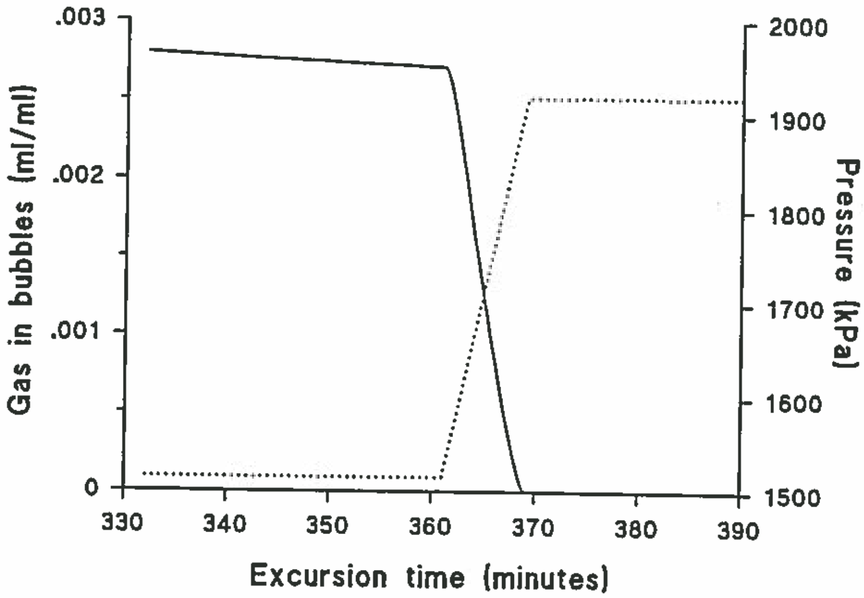

Figure 3 **Decay of bubbles after return to storage depth**

This demonstrates that for the average diver the 6 hour hold between end of last upward excursion and start of decompression should result in decompression beginning with no bubbles.

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