POTENTIAL FIFTY PERCENT REDUCTION IN SATURATION DIVING DECOMPRESSION TIME USING A COMBINATION OF INTERMITTENT RECOMPRESSION AND EXERCISE.

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INTRODUCTION

- Gas bubbles form and grow prior to onset of DCS symptoms (1). Conventional saturation decompression protocols use linear decompression rates that become progressively slower at shallower depths, consistent with gas bubble control vs. dissolved gas elimination kinetics. The use of faster ascent rates, to accelerate inert gas elimination, combined with short periods of recompression, to control gas bubble size, has previously been proposed as a more effective saturation decompression strategy (2). This theoretical advantage of intermittent recompression arises because the benefit of decreasing bubble size outweighs the penalty of inert gas uptake; gas bubbles decrease in size nearly instantly whereas the tissue inert gas tensions increase very slowly. These predictions, based on the Tissue Bubble Dynamics Model (TBDM) (3), are supported by recent experimental data in human (4) and animal (5) decompression trials.
- The NASA prebreathe reduction program demonstrated that exercise during O_2 prebreathe resulted in a 50% reduction (2 h vs. 4 h) in the saturation decompression time from 14.7 to 4.3 psi and a significant reduction in decompression sickness (DCS: 0% vs. 23.7%). Combining exercise with intermittent recompression, which controls gas phase growth and eliminates supersaturation before exercising, may enable even more efficient saturation decompression schedules than intermittent recompression alone.

METHODS

- The tissue bubble dynamics model (TBDM) was used in conjunction with a NASA exercise prebreathe model (NEPM) (6) that relates tissue inert gas exchange rate constants to exercise (mL O_2/kg/min) to develop schedules for decompression from saturation at depths from 45 feet sea water (FSW) to 400 FSW. These profiles were then compared with standard decompression profiles.
  - For the 45 FSW profile, the NASA exercise prebreathe protocol of 10 min at 75% VO_2 peak was used at 20 FSW on 100% O_2 followed by 60 min rest.
  - For the 400 FSW protocol, the same NASA exercise prebreathe protocol was performed with a breathing gas of 1.6 ATA ppO_2, followed by 24mins light exercise (5.8 mL O_2/kg/min) performed intermittently during the subsequent 110 min. A constraint of two such exercise sessions and two non-exercise intermittent recompressions (30 min, 1.6 ATA ppO_2) per 24 hrs was used.
- The models provide significant prediction ($p < 0.001$) and goodness of fit with 430 cases of DCS in 6437 laboratory dives for TBDM (Table 1) and with 22 cases of DCS in 159 altitude exposures for NEPM (Figure 1). The models have also been used operationally in over 25,000 dives (TBDM) and 40 spacewalks (NEPM).

Tissue Bubble Dynamics Model (TBDM) (3)

Bubble Growth Equation:

$$\frac{dR}{dt} = \frac{-\frac{\alpha D}{h(r,t)}\left[P_a - vt + \frac{2\gamma}{r} + \frac{4}{3}\pi r^3 M - P_{Total} - P_{metabolic}\right] + \frac{rv}{3}}{P_a - vt + \frac{4\gamma}{3r} + \frac{8}{3}\pi r^3 M}$$

r = Bubble Radius (cm)
t = Time (sec)
α = Gas Solubility ((mL gas)/(mL tissue))
D = Diffusion Coefficient (cm^2/sec)
h(r,t) = Bubble Film Thickness (cm)
P_a = Initial Ambient Pressure (dyne/cm^2)
v = Ascent/Descent Rate (dyne/cm^2·s)
γ = Surface Tension (dyne/cm)
M = Tissue Modulus of Deformability (dyne/cm^2·cm^3)
P_{Total} = Total Inert Gas Tissue Tension (dyne/cm^2)
$P_{metabolic}$ = Total Metabolic Gas Tissue Tension

Table 1. A statistical analysis of 6437 laboratory dives (430 DCS cases) compared predictions of the TBDM to Workman M-value and the Hempleman PrT index. TDBM predictions (Bubble Growth Index) yielded best log-Likelihood and Hosmer-Lemeshow Goodness-of-Fit Test (Table 1).

Data Set: In-Water Decompression on Air		Test for Improvement		Test for Goodness of Fit	
Index	Log-Likelihood	x^2	p-value	x^2	p-value/df
Null set	-529	n/a	n/a	n/a	n/a
Bubble Growth Index	**-498**	**62.8**	**<0.001**	**4.8**	**0.77/8**
Relative Super-saturation	-524	10.8	.001	19.4	0.08/12
Exposure Index	-505	47.9	<0.001	30.5	0.00/9

NASA Exercise Prebreathe Model (NEPM) (6)

The partial pressure for a specific inert gas that is reached in a designated tissue compartment after a specific time is calculated by the NEPM using the following equation:

$$P_t = P_0 + (P_a - P_0) \times (1 - e^{-k \cdot t})$$

where P_t = the inert gas partial pressure in the tissue after "t" minutes, P_0 = initial inert gas partial pressure in the compartment, P_a = inspired inert gas partial pressure. The following function defines the rate constant (k, min-1) in an exponential inert gas washout equation in terms of the normalized O_2 consumption, x (mL O_2/kg/min):

$$k = 1 / (e^{\lambda x} * C)$$

Logistic regression was used to fit the λ and C constants to DCS incidence in 159 altitude exposures with 22 cases of DCS (6) (Figure 1).

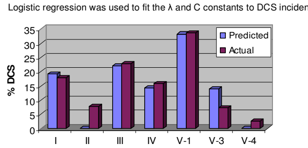

Fig. 1. Actual vs. NEPM-Predicted DCS incidence for 159 human altitude exposures during NASA prebreathe reduction protocol (6). Hosmer-Lemeshow p=0.70.

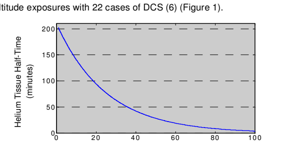

Fig. 2. Half-time variation with exercise level (mL O_2/kg/min) for a 210 minute half-time compartment as calculated by the NEPM (6).

RESULTS

Effect of Intermittent Recompression: 165 FSW Nitrox Sat

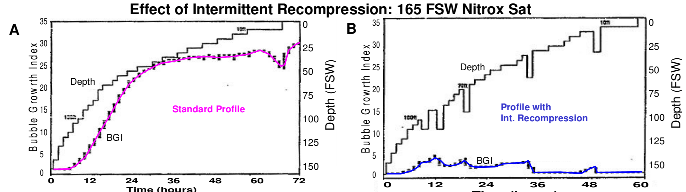

Fig. 3. A: 165 FSW saturation on Nitrox, decompressed to 45 FSW using an experimental staged protocol (ppO_2=0.5 ATA), then switched to air for remaining decompression. 50% DCS (n=10) observed with the 4000 minute protocol (7). Protocol modified to 7000 minutes (4.86 days) for operations.
B: Same decompression protocol as in A, but modified to include intermittent recompression (without exercise) achieves a faster ascent time (2.43 days) with lower decompression stress (Bubble Growth Index, or BGI), demonstrating the theoretical advantage of intermittent recompression.

Effect of Single Recompression: 45 FSW Air Sat

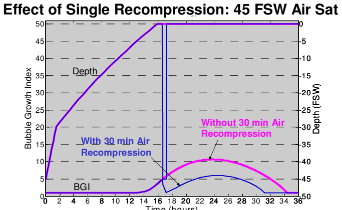

Fig. 4. Standard NOAA Aquarius Air Saturation Decompression from 45 FSW with, and without, a 30 min recompression on Air to 45 FSW. NOAA protocol includes a ~30 min recompression to 45 FSW after decompression to sea level in the habitat to allow divers to exit the habitat and swim to the surface. This procedure has the inadvertent effect of reducing decompression stress (BGI: 6.0 vs. 10.7).

Effect of IRECM: 45 FSW Air Sat

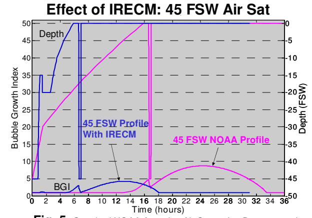

Fig. 5. Standard NOAA Aquarius Air Saturation Decompression from 45 FSW (15.9 hrs with 1 hr total O_2 breathing) vs. IRECM protocol from 45 FSW (5.9 hrs, 2 hrs total O_2 breathing). IRECM protocol yields 63% time saving and lower decompression stress (BGI: 4.2 vs. 8.7).

Effect of IRECM: 400 FSW Heliox Sat

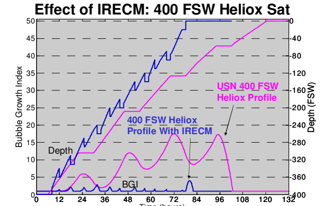

Fig. 6. Comparison of standard USN Heliox decompression from 400 FSW with decompression using IRECM, resulting in 37% reduction in decompression time and much lower decompression stresses (BGI of 4.0 vs. 17.5)

Effect of IRECM, -Controlling for O_2

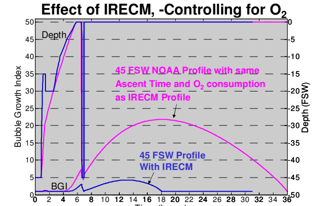

Fig. 7. 45FSW IRECM profile vs. 45FSW NOAA profile modified to match the same total decompression time and O_2 breathing time and depths as the IRECM protocol, showing that the benefit of IRECM is not attributable to additional O_2 breathing (BGI: 4.2 vs. 21.8).

- Exercise increases cardiac output, local blood flow and metabolites, effectively increasing tissue inert gas elimination rate constants. The beneficial effects of exercise in accelerating inert gas elimination are proportional to the gradient between the inspired inert gas partial pressure and the tissue tension of that inert gas species. Thus, the benefit of exercise increases as the inspired inert gas partial pressures are reduced, either through switching inert gas breathing mixtures or increasing inspired O_2 concentration. Other physiological considerations including O_2 toxicity and N_2 narcosis reduce the effectiveness of the exercise countermeasure at greater depths.
- The TBDM predictions are based on the assumption that the volume of gas in the bubble is small compared to the volume of gas in surrounding tissue. This assumption is supported by experimental evidence from human (4) and animal (5) decompression trials. If tissues were profusely nucleated, resulting in many small bubbles, then tissue tensions would reduce as the bubbles grow, with the effect of decreasing off-gassing gradients. In this case, the larger quantity of gas in the numerous small bubbles would simply redistribute into the tissue during the recompression, resulting in an equivalent decompression penalty and no decompression benefit. However, the empirical data detailed in Figures 8-10 suggest that this is not the case.

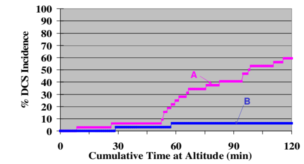

Fig. 8. The percentage of cumulative DCS onset incidence plotted vs. cumulative time at altitude for the two conditions: **A** (one 120-min altitude exposure with no ground-level preoxygenation), and **B** (four 30-min altitude exposures to the same simulated altitude, but with 1-h ground-level intervals breathing air; no prebreathing). *From Pilmanis et al. (4) by permission.*

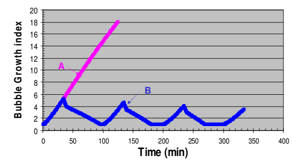

Fig. 9. The TBDM-calculated BGI for the two altitude decompression conditions described in Figure 8. The intermittent recompressions in profile B control bubble growth resulting in a maximum BGI of 5 in profile B compared with 18 in profile A. The benefits of intermittent recompression predicted by the TBDM are consistent with the observed DCS incidence in Figure 8.

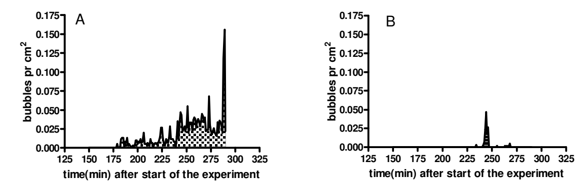

Fig. 10. Two groups of six pigs were compressed to 130 FSW with 90 minutes bottom time and were then decompressed following one of two decompression procedures with the same decompression time; either with a 5-min 12 FSW recompression at the end of the three last decompression stops (experimental group), or without such recompression (control group). The control profile was a modified USN profile for this exposure. The average number of venous gas bubbles measured in the pulmonary artery during the decompression is shown for the control group (A) and the experimental group (B). The results indicate significantly fewer bubbles in the experimental group than in the control group (p<.0001). *From Møllerløkken et al. (5) by permission.*

DISCUSSION

- The TBDM and NEPM models predict that the combination of intermittent recompression and exercise countermeasures (IRECM) can reduce saturation decompression time by up to 63% while lowering decompression stress. These predictions illustrate the potential advantages of IRECM, but have not been rigorously optimized.
- Intermittent recompression in the deeper phases of the decompression profile controls the bubble growth allowing much faster ascent rates in the shallow region than would otherwise be possible.
  - The model indicates that intermittent recompressions reduces decompression stress by limiting the bubble growth time and size, resulting in a higher bubble to tissue diffusion gradient due to the effects of surface tension (Laplace's Law).
- The NASA prebreathe reduction program has clearly demonstrated the benefit of exercise prior to decompression when tissues are not supersaturated (6). Use of intermittent recompression serves to both control gas phase and eliminate supersaturation providing the conditions under which exercise has been proven to reduce decompression stress.

CONCLUSIONS

- Experimental data and theoretical predictions suggest use of intermittent recompression and exercise countermeasures may significantly reduce saturation diving decompression stress and decompression time.
- Further research is needed to characterize and optimize this decompression method across a wider range of depths and operational assumptions.
- Prospective experimental trials conducted in laboratory conditions are required to validate these predictions.

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