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## A BUBBLE MODEL FOR REPETITIVE DIVING

Bruce Wienke

**Abstract**

Within the critical phase hypothesis in a bubble model, we have shown that reduced tissue tensions are necessary for multi-level and multi-day diving (multi-diving). Deep repetitive and shallower multi-day exposures are affected directly by the model. Within nucleation theory deeper-than-first dives are also affected. Sets of multi-diving fractions, accounting for micronuclei excitation and regeneration, reduced bubble elimination in repetitive diving and coupled effects on tissue tension, are discussed. Multi-diving fractions are simple multiplicative factors reducing permissible tissue tensions used in tables and decompression meters. These factors restrict repetitive diving over short time spans, deeper-than-previous and continuous multi-day diving, compared to standard algorithms using a fixed slow compartment. Within the model, fast compartments, controlling deeper exposures, are affected the most, and slower compartments, controlling shallower exposures, are least affected.

### Introduction

Validation of decompression schedules is central to diving and testing of no-stop and saturation schedules, with requisite analysis,[1-10] has progressed. Repetitive, multi-level, deeper-spike, and multi-day diving cannot claim the same validation, though some programs are breaking new ground. Application of present models in these latter cases has apparently produced slightly higher bends statistics that in the former ones, as reported in DAN newsletters,[7] and discussed at workshops,[5,6] and technical forums. Perceived problems associated with multi-diving might be addressed by reducing critical tissue tensions, particularly as they drive bubble excitation and growth beyond permissible levels in bubble models.[11-18]

Accordingly a model, called the reduced gradient bubble model[18] (RGBM), has been developed which reduces permissible tissue tensions in repetitive diving. The need for this reduction arises from the lessened degree of bubble elimination over short repetitive intervals, compared to long surface intervals, and the need to reduce bubble inflation rate through smaller driving gradients. Deep repetitive and spike exposures feel the greatest effects of gradient reduction, but shallower multi-day activities are also affected. Single daily (bounce) dives have long surface intervals to eliminate bubbles within the critical phase hypothesis, while repetitive diving must contend with shorter intervals, and thus reduced time for bubble elimination. Theoretically, a reduction in the bubble inflation driving force, namely, the tissue tension, holds the inflation rate down. The concern is bubble growth driven by dissolved gas, and a certain limiting volume for all bubbles, called the critical volume, before symptoms develop.

Within the RGBM three reduction factors, addressing bubble regeneration, deeper-than-previous excitation of nuclei, and shorter repetitive time spans for bubble elimination, are discussed and applied to some marginal exposures. First, we consider two repetitive dives to 36 m (120 fsw) for 10 minutes with a 2 hour surface interval, repeated for three days. Three repetitive dives to 36 m (120 fsw) for 10 minutes with 2 hour surface intervals, on one day, is known to cause bends in roughly three out of four cases, according to Leitch and Barnard,[19] so the exercise is not academic. As a second application, the hazardous repetitive profile reported by Edmonds,[5] three repetitive dives to 44.5 m (147 fsw) for 5 minutes, with 1 hour surface intervals, is also treated. Meter predictions of no-stop limits are contrasted with predictions of the RGBM, and the reductions in time limits are quantified. A brief description of some theory, then the applica-

tion, follows.

**Gas Dynamics**

Inert gas exchange is driven by the local gradient, the difference between the arterial blood tension and the instantaneous tissue tension. Such behaviour is modeled in time by mathematical classes of exponential response functions, bounded by arterial blood and initial tissue tensions. These multi-tissue functions are well known in Haldane applications, tracking both dissolved gas build-up and elimination symmetrically. Compartments with 1, 2, 3, 5, 10, 20, 40, 80, 120, 240, 480 and 720 minute half-lives are a realistic spectrum, according to inert gas washout experiments, and are independent of pressure. Haldane models limit exposures by requiring that the tissue tensions never exceed the critical tensions, fitted to any set of no-stop limits for example.

Bubbles, which are unstable, might grow from stable, micron size, gas nuclei which resist collapse due to elastic skins[16] of surface-activated molecules (surfactants), or possibly reduction in surface tension[10] at tissue interfaces. If families of these micronuclei persist, they vary in size, surfactant content, tissue location, effective surface tension on excitation to growth, and number density. Large pressures (somewhere near 10 ATA) are necessary to crush them. Micronuclei are probably small enough to pass through the pulmonary filters, yet dense enough not to float to the surfaces of their environments, with which they are in both hydrostatic (pressure) and diffusion (gas flow) equilibrium. Compression-decompression is thought to excite them into growth. Ordinarily, bubble skins are permeable to gas, but can become impermeable when subjected to large compressions (10 ATA). Such a model of skin behaviour, called the varying-permeability model (VPM), was proposed by Yount[11] and co-workers.[14-17]

Rudimentary discussions of nucleation and diving can be traced to Walder.[8] By tracking changes in bubble nucleus radius, that are caused by increasing or decreasing pressure, the VPM has additionally correlated quantitative descriptions of bubble-counting experiments carried out in supersaturated gel.[16,17] The model has also been used to trace levels of incidence of DCS in animal species such as shrimp, salmon, rats, and humans. Microscopic evidence has been gathered, suggesting spherical gas nuclei do exist and possess physical properties consistent with earlier assumptions. For example, bubble nucleus radii are of the order of 1 micron or less, and their number density in bio-media decreases exponentially with increasing radius, characteristic of systems of VPM nuclei in equilibrium with their surroundings at the same temperature.[15] Preformed nuclei have also been seen in serum and egg albumin. Spontaneous bubble formation in supersaturated tissues and blood, assuming characteristic fluid tensile strengths, seems less probable as a mechanism than growth from bubble nuclei.

A critical radius separates growing from contracting bubbles in the VPM and RGBM, and only depends on the depth of the dive. Bubble seeds smaller than the critical radius do not grow upon decompression. For bounce exposures, the critical bubble radius can be related to the permissible tissue tension and the absolute pressure, as well as the critical gradient, that is, the difference between the tissue tension and ambient pressure. Denoting the critical tissue tension as $M$, the absolute pressure as $P$, and the gradient as $G$, Figure 1 plots $G$ as a function of excitation radius, $r$, for the 2, 10, 40, 120 and 720 minute tissues, with bounce gradient, $G_0$, extracted from Figure 1 at $r$-$r_0$=0.8 microns. The critical surfacing gradient, $G_0$ allows direct surface ascent, and is our concern here. Compartment values are

**TABLE 1**

**MULTI-DIVING FRACTIONS (DIVES 120/10, 0/120, 120/10 DAILY FOR THREE DAYS)**

| t (min) | $G_0$ (fsw) | $\xi_1$ | $\xi_2$ | $\xi_3$ | $\xi_4$ | $\xi_5$ | $\xi_6$ |
|---|---|---|---|---|---|---|---|
| 1 | 195 | 1.00 | .95 | .95 | .88 | .86 | .80 |
| 2 | 151 | 1.00 | .95 | .93 | .88 | .86 | .81 |
| 5 | 95 | 1.00 | .95 | .93 | .88 | .86 | .81 |
| 10 | 66 | 1.00 | .95 | .93 | .89 | .86 | .82 |
| 20 | 47 | 1.00 | .95 | .93 | .89 | .86 | .82 |
| 40 | 36 | 1.00 | .96 | .93 | .89 | .86 | .82 |
| 80 | 27 | 1.00 | .96 | .93 | .89 | .86 | .82 |
| 120 | 24 | 1.00 | .96 | .93 | .90 | .86 | .82 |
| 240 | 23 | 1.00 | .96 | .93 | .90 | .86 | .84 |
| 480 | 22 | 1.00 | .98 | .93 | .91 | .86 | .85 |
| 720 | 21 | 1.00 | 1.00 | .93 | .93 | .86 | .86 |

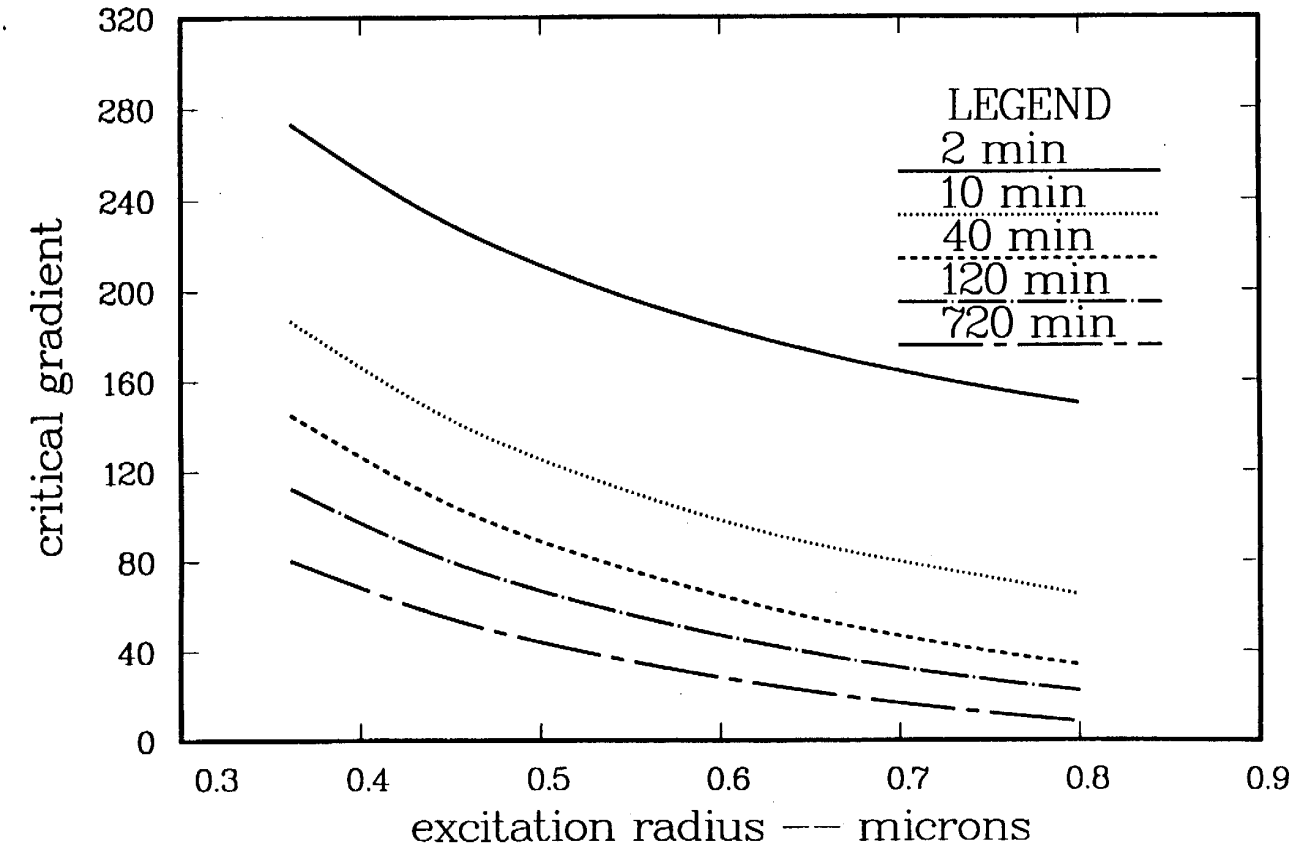


**FIGURE 1. CRITICAL GRADIENTS.**

listed in Table 1. The corresponding no-stop time limits, *t*, satisfy the approximate relationship, $dt^{1/2}$=400 fsw $min^{1/2}$, for *d* the depth of the bounce dive.

The rate at which gas expands in tissue depends upon the product of the excess bubble number and the supersaturation gradient defined above. The critical volume hypothesis requires that the time sum of the product of the two must always remain less than some limit point, called the critical phase volume. Implicit here is the assumption that free gas is continuously leaving the body, and that the permissible bubble excess represents the difference between the actual bubble number and the fixed amount safely eliminated by the body. Employing this phase hypothesis and constraint, Yount and Hoffman,[14] correlated data for bounce and saturation exposures. Repetitive exposures were not, however, included in that analysis.

In extending the model to repetitive exposures, we find that the phase hypothesis imparts distinct limits to diving activity, and that a set of repetitive criteria can be defined for multi-diving. These repetitive criteria act as a constraint on multi-diving, holding down bubble growth rates over repetitive surface intervals. Reduction in growth rate is effected by reducing permissible tissue tension through a set of bubble multipliers, $\xi$ (always less than or equal to one), defined at the outset of each dive segment. These factors multiply the bounce set, $G_0$, in Table 1 and impart shorter no-stop repetitive time limits, a penalty in effect, decreasing with $\xi$. The reduced critical gradients are related simply to the bounce set.

**Multi-diving fractions**

In untethered scuba diving, we must conservatively estimate fractions instantaneously, but based on previous dive history over intervals of 24 hours or more. Such estimates can be easily performed with a computer using multipliers that insure that bubble inflation rates over repetitive exposures are below those permitted by bounce exposures. As surface time intervals decrease, multi-fractions should get smaller, and staging approach saturation limits as repetitive frequency increases. As surface time intervals increase, multi-fractions should get larger, and staging approach bounce limits as surface intervals increases. In between, their behaviour depends on total elapsed time, total surface interval, tissue compartment, and profile. Before turning to specifics, a check-list of the properties of the fractions, correlating with diving practice, is also worthwhile:

1 $\xi$ equals one for a bounce dive, remaining less than one for repetitive dives within some time interval;
2 $\xi$ decreases monotonically with increasing exposure time;

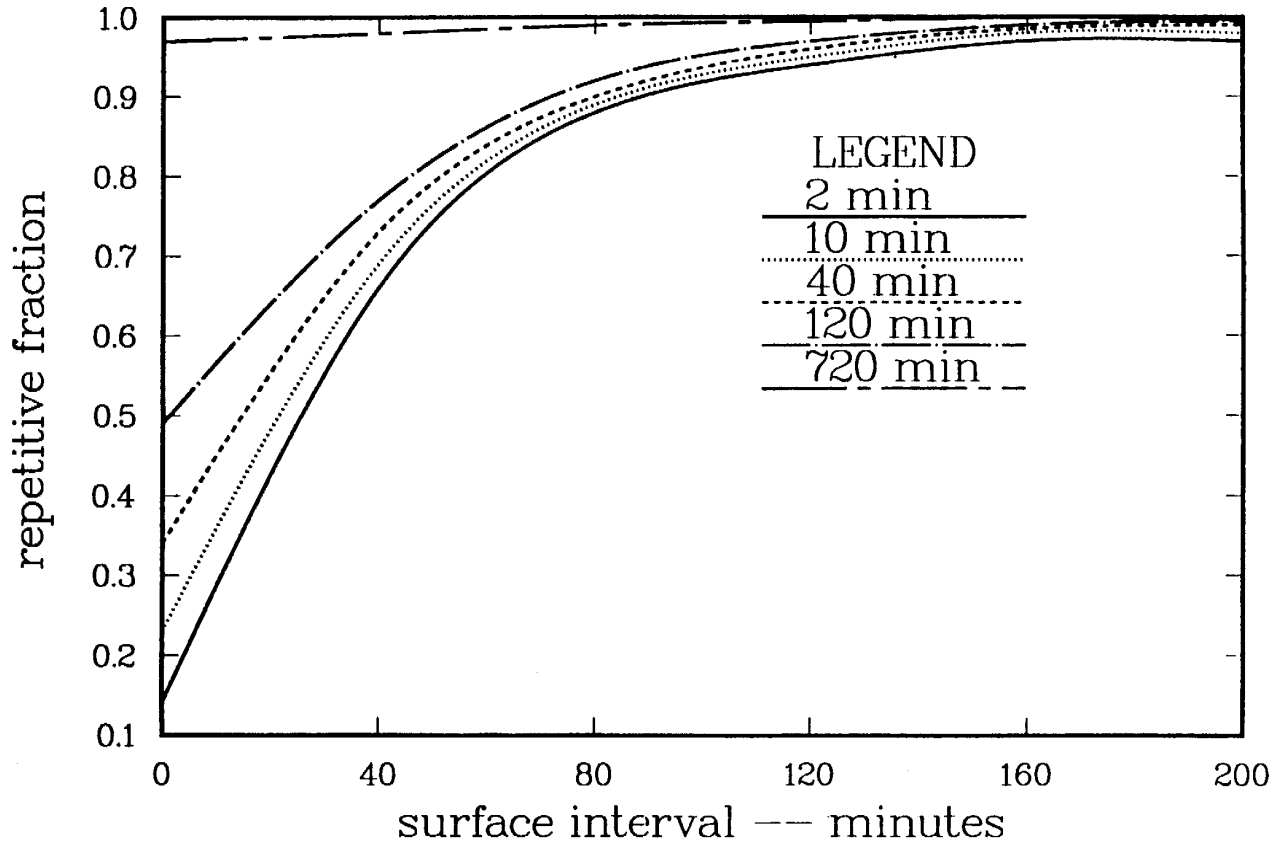


**FIGURE 2. REPETITIVE REDUCTION FACTORS**

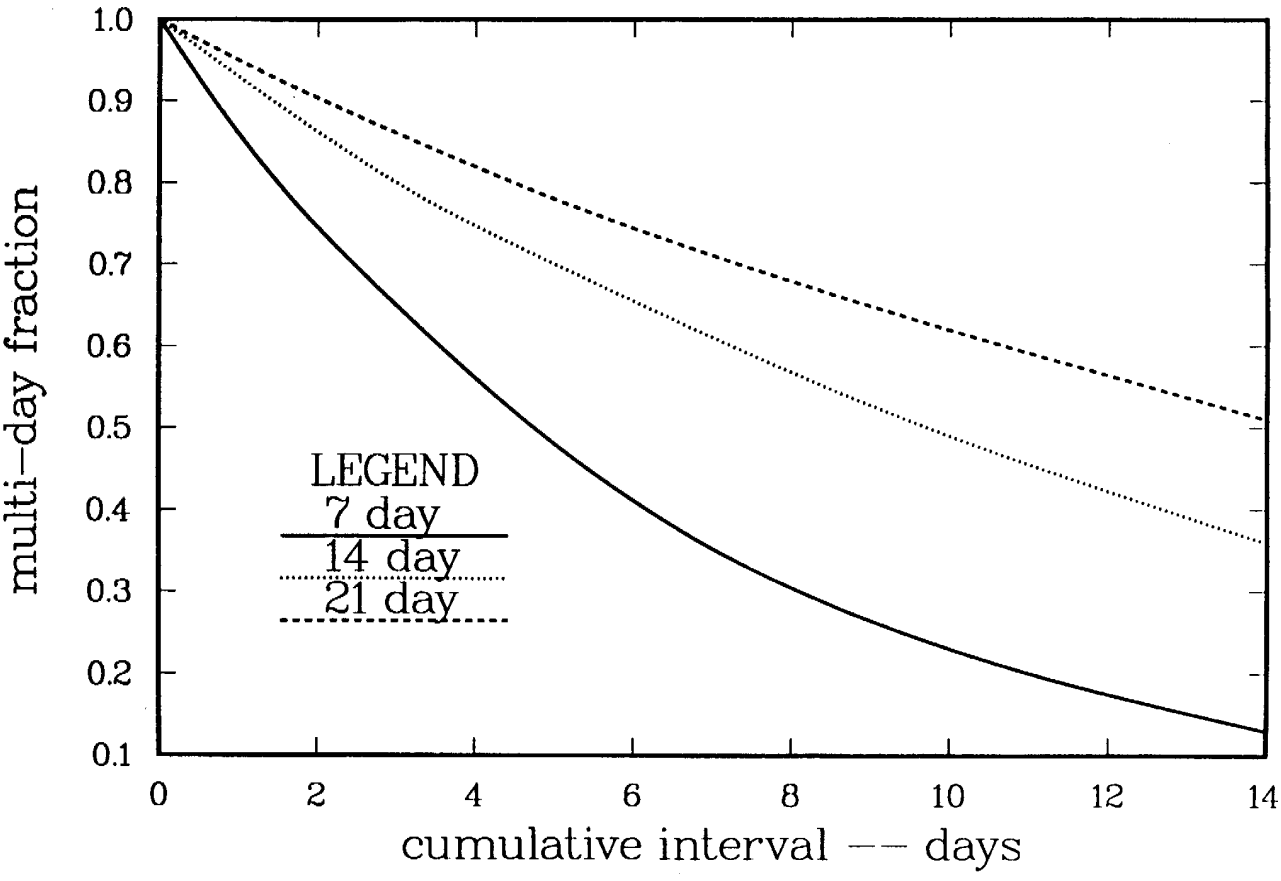


**FIGURE 3. MULTI-DAY REDUCTION FACTORS**

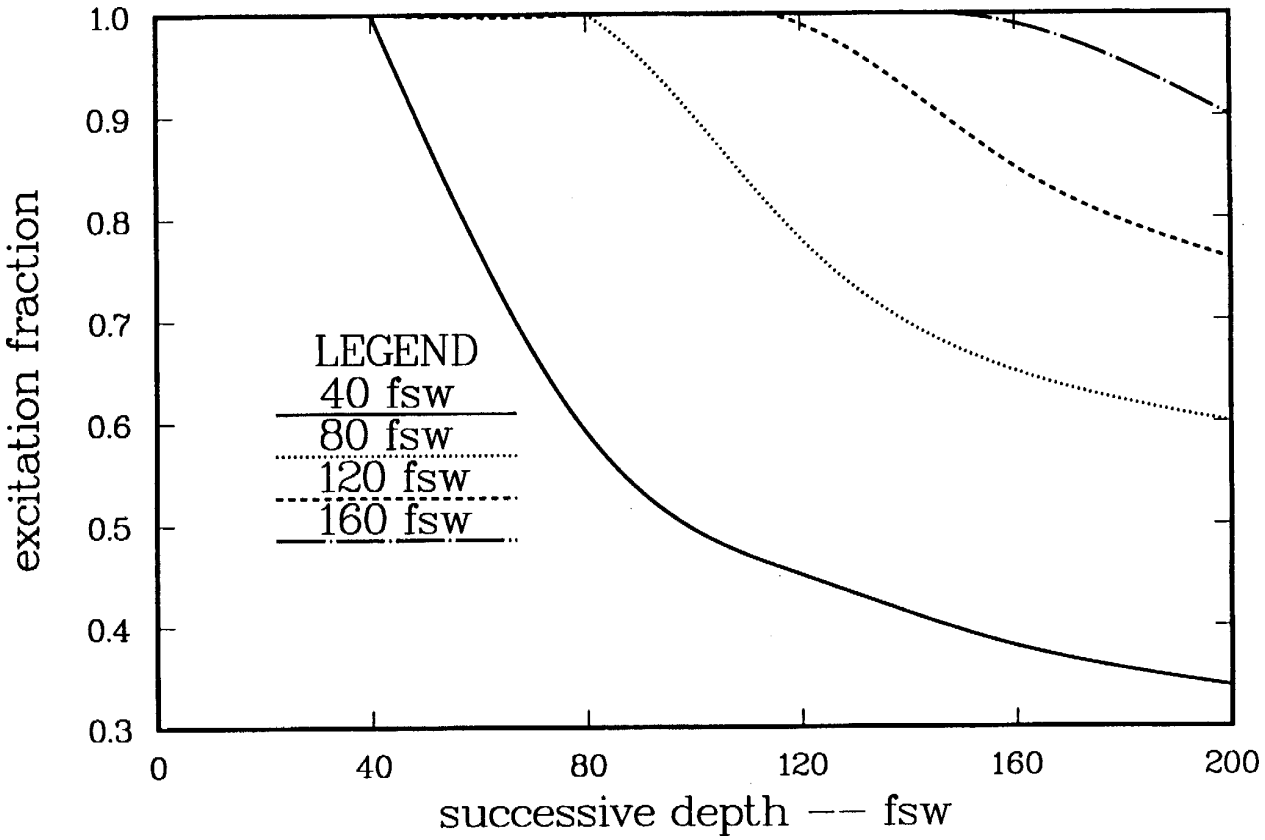


**FIGURE 4. EXCITATION REDUCTION FACTORS**

3 $\xi$ increases monotonically with increasing surface interval time;
4 $\xi$ affects faster tissue compartments the most;
5 $\xi$ decreases with depth of the dive;
6 $\xi$ affects deeper-than-previous dives the most;
7 x changes with every dive, but only within any dive when a greater depth is reached;
8 $\xi$ decreases with micronuclei regeneration;
9 $\xi$ time constants controlling x are linked to bubble growth rate and micronuclear regeneration time scales;
10 $\xi$ excitation of additional micronuclei increases with successively deeper depth.

In considering micronuclear regeneration through natural processes,[15] the permissible bubble excesses must be reduced over time. Assuming a slow exponential production rate over days, a regeneration reduction fraction is taken to be the ratio of present bubble production over initial bubble production. Since regeneration rates span days, the regeneration fraction affects multi-day diving. The penalty (reduction in permitted gradient) for consecutive multi-day diving increases with frequency.

Successively deeper exposures excite additional micronuclei on each excursion. While this is not good procedure even within a single dive (multi-level), it is well known to be hazardous in repetitive exposures. Deeper-than-previous dives might excite new pools of smaller micronuclei into growth, occurring on top of the growth of larger mirconuclei from previous dives. If bubble elimination between dives is not efficient, and earlier bubbles are approaching critical number and size, the next deeper-than-previous dive could excite enough additional bubbles to exceed the phase limit point. Diving within the crush limits of (shallower than) the first dive is always prudent. To treat the ill-advised case of deeper-than-previous consecutive exposures, an excitation reduction fraction is defined to be the minimum value of the ratio of the permissible bubble excesses on consecutive dives to depth. The penalty for repetitive dives deeper-that-previous increases with relative depth difference between the dives.

Repetitive exposures may not allow bubble elimination to go to completion. Accordingly, repetitive gradients need be reduced to compensate for shorter periods of bubble elimination, by a phase reduction fraction linked to the bubble expansion rate. The expansion rate is a function of instantaneous tissue tension, ambient pressure, bubble surface tension pressure, tissue diffusivity, effective phase concentration and tissue solubility. Throughout the course of any dive, it would be possible, but tedious, to track the expansion rate. So, we quantified the assumption that the expansion rate decays exponentially over characteristic surface time, on the order of an hour. The gradient reduction fraction is then the difference between maximum and present bubble radial growth rate, normalized to the maximum rate.

Consistent with Doppler detected bubble reduction[9] following a safety stop at shallow depth, the repetitive fraction restricts multi-dives over time intervals of tens of minutes, and relaxes to one in a few hours. Early upon surfacing, the growth rate is large, the reduction factor small and, therefore, the penalty is large.

Putting these factors together, a multi-diving fraction, $\xi$, can be defined at the start of each segment and deepest point of dive, as the product of regeneration, phase growth, and deeper excitation fractions. Consistent with recent workshops, reports and flying-after-diving, factors might relax to one following any 24 hour surface interval of non-diving. Tissue tensions and bubble excesses would tend to equilibrate with ambient pressure on those time scales. In simple application, penalties for multi-diving then result in systematic reductions in no-stop time limits, depending on previous depths, times and repetitive frequency.

**Diving application**

For illustration, repetitive, multi-day and excitation fractions, $\eta^{phase}$, and $\eta^{regen}$, and $\eta^{excite}$, are drawn in Figures 2 to 4 for representative time scales and bubble parameters. Figure 2 depicts $\eta^{phase}$ in 40 minute surface intervals. Multi-day factors, $\eta^{regen}$, are drawn for 7, 14 and 21 days of diving in Figure 3. Excitation factors, $\eta^{excite}$, are shown in Figure 4 at sea level. The repetitive factors relax to one after about 2 hours, while the multi-day factors continue to decrease with increasing activity, though at very slow rate. The excitation factors induce the greatest reductions in permissible gradients, when the depth of the present exposure exceeds previous maximum depth.

As first application of the model, consider two repetitive dives a day, 36 m (120 fsw) for 10 minutes, separated by a 2 hour surface interval, over three consecutive days. This profile, extended to three repetitive dives a day, has produced bends in three out of four cases on the first day,[19] so it is pertinent. Employing the critical gradients, $G_0$, the exponential (Haldane) tissue equations, and the multi-fractions from Figures 2 to 4, we can apply the RGBM to the multi-day, repetitive sequence. The model reduces the permissible gradients in each tissue compartment, on each segment of the six dives, as shown in Table 1, which lists $\xi$ at the start of each repetitive and multi-day segment.

Reductions in gradients approach 20% in the fast compartments and 15% in the slower ones, on the last dive. On the first day, reductions in the fast compartments are near 5% on the second dive, and near 10% on the second dive of the day. Smaller reductions, by a few percent, are seen in the slow compartments. Exposures in the 36 m (120 fsw) range are controlled by the 10 minute compartment, with 11 minutes the non-stop limit on the first dive (x=1) from Figure 2. On dives 2 to 5, no-stop time limits obviously decrease monotonically steadily within those same limits. Heavy multi-day, repetitive diving is obviously penalized the most in this approach. If deeper-than-previous exposures are attempted, additional restrictions are also imposed.

Table 2 contrasts various decompression meter predictions for the non-stop limits at each segment of the same multi-day profile with the RGBM (bottom row). Effective application of x in the RGBM results in a decreasing sequence of non-stop time limits. No-stop time limits were obtained from chamber tests of the meters for the exposures quoted.

A somewhat deeper repetitive profile, three 44.5 m (147 fsw) exposures for 5 minutes each with 1 hour surface intervals, is also hazardous according to Edmonds.[5] Decompression meter performance is contrasted with the RGBM in

**TABLE 2**

**NON-STOP TIME LIMIT COMPARISON FOR A THREE DAY (HAZARDOUS) REPETITIVE SCHEDULE (120/10, 0/120, 120/10)**

| | Day 1 | | Day 2 | | Day 3 | |
|---|---|---|---|---|---|---|
| Meter | Dive 1 (minutes) | Dive 2 (minutes) | Dive 1 (minutes) | Dive 2 (minutes) | Dive 1 (minutes) | Dive 2 (minutes) |
| Orca Delphi | 10 | 10 | 10 | 20 | 10 | 10 |
| Ocra Skinny Dipper | 10 | 10 | 10 | 20 | 10 | 10 |
| Beuchat Aladin | 8 | 8 | 8 | 8 | 8 | 8 |
| Sunnto/SeaQuest SME-MEL | 10 | 10 | 10 | 10 | 10 | 10 |
| Dacor MicroBrain ProPlus | 8 | 8 | 8 | 8 | 8 | 8 |
| Sherwood Source | 12 | 9 | 12 | 9 | 12 | 9 |
| ScubaPro Dive Tronic | 6 | 6 | 6 | 6 | 6 | 6 |
| RGBM | 11 | 10 | 8 | 7 | 6 | 6 |

**TABLE 3**

**NON-STOP TIME LIMIT COMPARISON FOR SINGLE DAY (HAZARDOUS) REPETITIVE DIVE SCHEDULE (147/5, 0/60, 147/5, 0/60,147/5)**

| Dive computer | Dive 1 (minutes) | Dive 2 (minutes) | Dive 3 (minutes) |
|---|---|---|---|
| Orca Delphi | 6 | 6 | 6 |
| Orca Skinny Dipper | 6 | 6 | 6 |
| Beauchat Aladin | 5 | 5 | 5 |
| Sunnto/SeaQuest SME-ML | 6 | 6 | 6 |
| Dacor MicroBrain ProPlus | 8 | 8 | 8 |
| Sherwood Source | 6 | 5 | 5 |
| ScubaPro DiveTronic | 4 | 4 | 4 |
| RGBM | 7 | 6 | 5 |

Table 3, using of no-stop limits. The times were again determined from bench tests of the meters.

Note the systematic reductions in the no-stop limits for repetitive diving within the RGBM. The numbers have been rounded off of course, but depend on the surface intervals. Meters offer varying limits, but each offers the same limit for each repetitive segment.

Repetitive, deeper-than-previous, multi-day, and multi-level diving present problems for Haldane based models which might be lessened in effect by a systematic reduction in critical gradients, or tensions, consistent with bubble mechanics and the phase volume limit. In the RGBM, reductions are based on possible excitation and regeneration of micronuclei and bubble inflation rates, and not just dissolved gas build up per se. As can be seen the RGBM imposes sensible constraints on multi-day, repetitive and deeper-than-first diving activity.

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