tion of such occurrences by the police acting as agents for the Coroner. The information so collected can assist the recognition of critical factors in some fatalities and thereby make it possible to devise strategies to avoid their repetition or to mitigate their consequences. Without the resource of case documentation prepared for the Coroners it would not be possible to undertake surveys such as this.

Divemasters and those who are responsible for others may find it helpful to consider the recent as well as the total experience of those in their case. They may also remember the importance of keeping an effective watch on the surface where divers may appear and require assistance. In two instances an unconscious diver was not initially noticed. In another an alert divemaster noted the unusual quietness of a diver and immediately investigated. Had the diver not suffered an inevitably fatal CAGE, his action would have been life saving.

The dangers of carbon monoxide to hookah users are well known and these three deaths underline the serious consequences which may follow the intake of exhaust fumes into the compressor. While this gas itself is odourless it is possible that a refusal to dive when the air has any odour could be a wise safety move. It is regrettable that the investigation of the double tragedy revealed that there has been no improvement apparent in the application of diving safety regulations to the pearl diving industry over several decades. The District Medical Officers at Thursday Island and Broome have commented on the situation on occasion without apparent effect. Possibly matters will change with the increased attention to the diving industry by the various Workplace Health and Safety Officers. Thoughtfully applied, such attention would be of real long term benefit to many commercial divers.

Conclusions

The dangers of post-hyperventilation blackout are again confirmed. The only way to prevent the victim drowning would be by a change in attitude on the part of such divers and the use of surface observers of them during their dives. Such an attitude change is unlikely.

Scuba divers are reminded of the importance of checking their equipment and not tolerating demand valves which let in water or regulators which are hard to breathe from. They should be profligate with their air, ascending while having sufficient remaining air for any emergency. They should seek to never place themselves in a situation where a buddy breathing ascent is the only option as this can end fatally. The practising of such ascents is therefore not advisable. The importance of an efficient surface cover, of recent diving experience, and presence of a buddy nearby should one get into trouble are all desirable propositions.

The Coronial Investigation system is of great value and information derived from it is invaluable in improving our understanding of the critical factors in diving safety.

The importance of informed pathology investigation of diving-related deaths is again stressed.

Acknowledgements

This report would not be possible without the support of many people. In particular the on-going support of the Justice/Law/Attorney General's Department in every State, continues to be an essential element of this safety project.

MULTI-LEVEL RESTRICTIONS WITHIN THE US NAVY TABLES

Bruce Wienke and Dennis Graver

Abstract

Schemes for multi-level diving are employed in the commercial, scientific, and sport sectors. One approach employs back-to-back repetitive sequencing, assigning groups at the start of each multi-level dive segment based on the total bottom time (actual plus residual nitrogen) of the previous segment. At times, that method allows critical tensions, other than the controlling (repetitive) 120 minute compartment tension, to be exceeded upon surfacing. In the context of the US Navy tables, such a circumstance is suspect. But by tightening the exposure window and accounting for ascent and descent rates, such a multi-level technique can be made consistent with the permissible tension formulation of the US Navy tables. In studying this multi-level technique, we can draw a line (envelope) across the Repetitive Group Table, separating dives violating at least one critical tension at some point in the multi-level sequence from those not violating any critical tensions. Ascent and descent rates of 60 feet (18 m)/min are assumed, and the envelope also maintains tissue tensions below critical values throughout the multi-level dive. Some 16 million multi-level dives were analyzed on a CRAY supercomputer, permitting construction of the dive envelope. The standard US Navy sets of tissue half-lives and critical tensions were employed. The envelope moves non-stop time limits back a group or more in the US Navy tables, restricting the back-to-back repetitive method in the same measure. Restrictions are straightforward and simple for possible wet testing.

Introduction

To evaluate multi-level diving adequately within any set of tables, it is necessary to account for ascent and descent rates. While ascent and descent rates have small effect on in-gassing and out-gassing in slow tissue compartments, ascent and descent rates affect fast tissue compartments to a greater degree. Nitrogen build-up and elimination is measured in hypothetical compartments, whose half-lives denote time to double or halve existing levels of nitrogen.[1-15] Build-up and elimination of nitrogen is computed with well-known tissue equations (exponential rate expressions) and limit points, called critical tensions, are assigned to each compartment to control diving activity and exposure time. In multi-level diving, computed tissue tensions in any and all compartments must be maintained below their critical values. This is a more stringent constraint than just flooring the 120 minute compartment tension, the approach used in the US Navy Tables for repetitive diving.[3]

In the US Navy tables, from which many tables with reduced non-stop time limits derive, there are six compartments with 5, 10, 20, 40, 80 and 120 minute half-lives. These limit diving through limiting tensions (M-values) of 104, 88, 72, 58, 52, and 51 feet of seawater (fsw), respectively. The 5 and 10 minute compartments are fast, the 80 and 120 minute compartments are slow, and the others are often between, depending on exposure profile. Dive exposure times, depths, ascent and descent rates, affecting slow and fast compartments in a complicated manner, are virtually infinite in number, suggesting the need for both a high speed computer and meaningful representation of the results. A CRAY supercomputer addresses the first concern, while US Navy Tables provide a simple vehicle for representation of results.[16]

Controlling tissue zones

In performing multi-level analyses of the US Navy tables and derivative, tables, considering maximum allowable exposure time and minimal incremental change, it is possible to define (minimal) zones where each tissue compartment controls exposures. These incremental zones are the depths at which the 5, 10, 20, 40, 80 and 120 minute compartments control an exposure by virtue of 104, 88, 72, 58, 52 and 51 feet of seawater (fsw) critical tensions. In terms of multiples of 10 fsw, these multi-level zones are:

1	100 - 130 fsw	30-39 m	(5 minute compartment)
2	80 - 100 fsw	24-30 m	(10 minute compartment)
3	60 - 80 fsw	18-24 m	(20 minute compartment)
4	50 - 60 fsw	15-18 m	(40 minute compartment)
5	40- 50 fsw	12-15 m	(80 minute compartment)
6	0 - 40 fsw	0-12 m	(120 minute compartment)

Calculations show that is is possible to stay in each zone as long as the computed tissue tension does not exceed the critical tension for the controlling compartment, nor in all other slower compartments. Permissible times in subsequent zones are quite constant when the initial exposure (first level) is carried out to the reduced non-stop time limit for the deepest point in the zone. For the calculations, ascent and descent rates were taken at 60 ft (18 m)/minute. Bottom time for the the first level was measured from the start of the descent. Bottom times, after that, were actual times spent at that level, that is, ascent times are treated as extra exposure time and so the calculations are conservative.

TABLE 1

MULTI-LEVEL DIVE ENVELOPES WHICH NEVER VIOLATE USN M VALUES

1 100-130 fsw (30-39 m) for 8 minutes, 80-100 fsw (24-30 m) for 12 minutes, 60-80 fsw (18-24 m) for 5 minutes, 50-60 fsw (15-18 m) for 5 minutes, 40-50 fsw (12-15 m) for 10 minutes and 0-40 fsw (0-12 m) for 20 minutes

2 80-100 fsw (24-30 m) for 22 minutes, 60-80 fsw (18-24 m) for 5 minutes, 50-60 fsw (15-18 m) for 5 minutes, 40-50 fsw (12-15 m) for 10 minutes and 0-40 fsw (0-12 m) for 20 minutes

3 60-80 fsw (18-24 m) for 35 minutes, 50-60 fsw (15-18 m) for 5 minutes, 40-50 fsw (12-15 m) for 10 minutes and 0-40 fsw (0-12 m) for 20 minutes

4 50-60 fsw (15-18 m) for 55 minutes, 40-50 fsw (12-15 m) for 10 minutes and 0-40 fsw (0-12 m) for 20 minutes

5 40-50 fsw (12-15 m) for 80 minutes and 0-40 fsw (0-12 m) for 20 minutes

Zonal time limits

Maximum times in the different depth groups (the envelopes) of possible multi-level dives within the US Navy Tables, which never violate the fixed critical tensions (104, 88, 72, 58, 52 and 51 fsw) at any point during the dive or upon surfacing are summarized in Table 1. The times depend upon the depth of the first part of the dive.

Within these zonal times, the diver may hypothetically directly ascend to the surface, since tissue tensions in all compartments are always below critical values.

Some 16 million dives were analyzed on a CRAY supercomputer, in just a few minutes of actual run time. These multi-level constraints are coarse (based on worse case estimates in the whole zone), and therefore very conservative. Translated to the US Navy Tables, a line (envelope) can be drawn across the Repetitive Group Table (Figure 1), in the same manner described by Graver, separating permissible multi-level dives (no critical tensions exceeded) from non-permissible multi-level dives (one or more critical tensions exceeded).

Observations

From the above set of zonal constraints, and Figure 1, a few obvious facts emerge:

1 The deeper the initial depth, the shorter the total multi-level dive time

2 Maximum permissible multi-level dive times (total) vary between 100 and 60 minutes, depending on initial depths

3 Minimum permissible multi-level increments vary from 30 fsw to 10 fsw (9-3 m) as the depth decreases from 130 fsw to 40 fsw (39-12 m)

4 Multi-level US Navy Table dives falling within the envelope, and satisfying the above set of restrictions, never exceed critical-values, below or at the surface, in any compartments

5 Such an envelope is amenable to wet testing, given the simplicity of its structure

6 Supercomputers are great for complicated calculations.

Depth		Repetitive group designations									
m	ft	C	D	E	F	G	H	I	J	K	L
12	40	25	30	40	50	70	80	100	110	130	150
15	50	15	25	30	40	50	60	70	80	90	100
18	60	15	20	25	30	40	50	55	60		
21	70	10	15	20	30	35	40	45	50		
23	80	10	15	20	25	30	35	40			
27	90	10	12	15	20	25	30				
30	100	7	10	15	20	22	25				
33	110	5	10	13	15	20					
36	120	5	10	12	15						
39	130	5	8	10							

Figure 1. Part of the USN Repetitive Group Table with a line (the envelope) separating permissible multi-level dives, to the left of the line, from non-permissible dives.

Additionally, as an offshoot of calculations, some interesting features of the US Navy tables can be gleaned from a comparison of tissue tensions (Tables 2 and 3) computed at the reduced and US Navy non-stop time limits, again using 60 ft (18 m)/minute as the ascent rate.

1 The bottom and surfacing tension at reduced non-stop time limits never exceed the critical tensions when factoring the ascent/descent rate into calculations, just as with the multi-level calculations.

2 The bottom tensions at US Navy non-stop time limits exceed the critical tensions for a number of compartments, with the fastest compartments the worst cases when factoring the ascent/descent rate into calculations.

3 The surfacing tensions at US Navy non-stop time limits seldom exceed the critical tensions when the ascent/descent rate is included into the calculations, except in the 20, 40, and 80 minute compartments.

4 Ascent rates are crucial to using the US Navy Tables for bounce diving within the critical tension limits.

5 60 ft (18 m)/minute ascent rate off-gases fast compartments (5, 10 minutes) and in-gasses slow compartments (80, 120 minutes) with the faster compartments affected the most for bounce exposures.

Tables 2 and 3, where the units are in fsw nitrogen partial pressures (0.79 ambient pressure), will verify this.

Summary

This analysis shows that a multi-level diving technique can be made consistent with the critical tension formulation of the US Navy tables. A restrictive envelope, accounting for ascent and descent rates, can be drawn across the Repetitive Group Table to separate permissible from non-permissible multi-level dives. This should not surprise anyone using multi-level dive computers, since multi-level dive computers perform the same exercise on the fly underwater. The above is relatively simple, a set of profiles suggested for wet testing and extension of the US Navy tables.

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half-life (*min*)	depth (*fsw*)	USN limit (*min*)	tension (*fsw*)	reduced limit (*min*)	tension (*fsw*)	*M*-value (*fsw*)
5	130	10	93.1	8	86.0	104.
	120	15	99.0	12	93.6	
	110	20	98.4	15	93.5	
	100	25	94.7	22	93.4	
10	130	10	73.9	8	66.7	88.
	120	15	83.4	12	76.1	
	110	20	87.3	15	78.9	
	100	25	87.6	22	84.5	
	90	30	85.2	25	81.7	
	80	40	82.7	35	81.1	
20	130	10	55.1	8	50.0	72.
	120	15	63.2	12	57.2	
	110	20	68.2	15	60.2	
	100	25	70.6	22	67.0	
	90	30	70.9	25	66.2	
	80	40	72.4	35	69.5	
	70	50	70.7	45	68.9	
	60	60	66.8	55	65.7	
40	130	10	42.1	8	39.1	58.
	120	15	47.4	12	43.6	
	110	20	51.1	15	45.6	
	100	25	53.4	22	50.6	
	90	30	54.5	25	50.7	
	80	40	57.3	35	54.5	
	70	50	57.8	45	55.7	
	60	60	56.4	55	54.9	
	50	100	58.4	80	55.5	
80	130	10	34.5	8	32.9	52.
	120	15	37.5	12	35.4	
	110	20	39.8	15	36.6	
	100	25	41.3	22	39.7	
	90	30	42.2	25	39.8	
	80	40	44.5	35	42.5	
	70	50	45.4	45	43.8	
	60	60	45.2	55	44.0	
	50	100	48.9	80	45.7	
	40	200	52.1	130	47.4	
120	130	10	31.8	8	30.7	51.
	120	15	33.9	12	32.4	
	110	20	35.5	15	33.2	
	100	25	36.6	22	35.5	
	90	30	37.3	25	35.7	
	80	40	39.1	35	37.6	
	70	50	39.7	45	38.7	
	60	60	39.9	55	38.9	
	50	100	43.4	80	40.7	
	40	200	47.7	130	42.7	

Table 2. Comparative surfacing tensions for USN and reduced no-decompression time limits, employing 60 *fsw/min* ascent and descent rates for all excursions. Bottom time is measured from beginning of descent to start of ascent.

half-life (*min*)	depth (*fsw*)	USN limit (*min*)	tension (*fsw*)	reduced limit (*min*)	tension (*fsw*)	*M*-value (*fsw*)
5	130	10	98.6	8	88.9	104.
	120	15	107.6	12	100.0	
	110	20	106.7	15	100.5	
	100	25	102.3	22	100.8	
10	130	10	73.3	8	65.0	88.
	120	15	84.9	12	76.5	
	110	20	89.8	15	80.1	
	100	25	90.2	22	86.8	
	90	30	87.8	25	83.9	
	80	40	82.7	35	81.1	
20	130	10	53.3	8	47.9	72.
	120	15	62.5	12	56.1	
	110	20	68.1	15	59.6	
	100	25	70.9	22	67.1	
	90	30	71.4	25	66.5	
	80	40	73.1	35	70.0	
	70	50	71.4	45	69.5	
	60	60	67.4	55	66.3	
40	130	10	40.8	8	37.6	58.
	120	15	46.5	12	42.5	
	110	20	50.5	15	44.9	
	100	25	53.1	22	50.3	
	90	30	54.3	25	50.5	
	80	40	57.3	35	54.4	
	70	50	57.9	45	55.8	
	60	60	56.6	55	55.0	
	50	100	58.5	80	55.6	
80	130	10	33.7	8	32.0	52.
	120	15	36.9	12	34.7	
	110	20	39.3	15	36.0	
	100	25	41.0	22	39.3	
	90	30	42.0	25	39.5	
	80	40	44.3	35	42.3	
	70	50	45.3	45	43.7	
	60	60	45.2	55	43.9	
	50	100	48.9	80	45.7	
	40	200	52.1	130	47.4	
120	130	10	31.2	8	30.1	51.
	120	15	33.4	12	31.9	
	110	20	35.1	15	32.9	
	100	25	36.4	22	35.2	
	90	30	37.1	25	35.4	
	80	40	38.9	35	37.4	
	70	50	39.8	45	38.6	
	60	60	39.9	55	38.9	
	50	100	43.3	80	40.6	
	40	200	47.7	130	42.7	

Table 3. Comparative bottom tensions for USN and reduced no-decompression time limits, employing 60 *fsw/min* ascent and descent rates for all excursions. Bottom time is measured from beginning of descent to start of ascent.

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DEEP DIVING AND SOME EQUIPMENT LIMITATIONS

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Background

Reports of recreational diving fatalities in Australia[1] involved an analysis of the diving profile, observations of the witnesses, equipment assessment by a regulatory body, and a specialised autopsy. If the cause was not evident from the investigations, a re-enactment of the incident was often employed.

In re-enactment trials, the divers own equipment is reassembled and used, and the profile repeated by a diver of approximately the same stature, but hopefully without the same result. These techniques led to a number of breakthroughs in determining the causes of diving accidents in the Royal Australian Navy, as far back as 1967.[2]

One of the situations which has led to re-enacting dive profiles has been the observation that there is sometimes difficulty in obtaining sufficient air, either for breathing at moderate rates, or for inflating the buoyancy compensator (BC), at depths in excess of 30 m (100 feet). This is noted especially when the diver is getting "low on air".

Inadequate air supply situations have been highlighted as a significant cause of death in diving accident reviews.[1,3,4] Other workers have postulated the difficulty in obtaining adequate air through the regulator as a factor in diving accidents[5-7], and some explanations have been forthcoming.

Some of the factors which produce a limitation in the non-exhausted air supply, either to the diver, to the BC or to the alternative air supply line (octopus regulator), are obvious. These include a failure to fully open the cylinder valve, resistance or failure of the J valve (when used), and equipment malfunction problems causing regulator resistance. Laboratory investigations have demonstrated increased regulator resistance at, or near, reserve air levels, usually considered to be 35-50 bar.[6,8]

At the suggestion of one of us and while investigating a diving fatality, Wong[5] performed a series of experiments in 1988. These showed that in some circumstances, it is impossible to obtain adequate ventilation (especially under exercise conditions), while using the power inflator of the BC, once a reserve air level had been reached in the cylinder.

These problems led to a decision to observe what happens with a diver exercising (equivalent to moderately heavy breathing), at a significant depth, with the air supply on or near reserve, when using typical scuba diving equip-