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GRAPHICAL ANALYSIS: DECOMPRESSION TABLES AND DIVE-OUTCOME DATA

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19. ABSTRACT. We use a graphical approach to compare prescriptions for ascent given by various air decompression tables with outcomes of experimental dives compiled in the U.S. Navy Decompression Database. For a given dive depth, we plot times at decompression stops plus time to travel from depth to the surface (TDT) on the Y-axis and bottom time on the X-axis. The analysis dramatizes the large differences among alternative decompression instructions: tables from different sources require markedly different TDTs. For the same depth/bottom-time combinations, the TDTs for USN57 (the current U.S. Navy Standard Air table) are about one-third as long as those for VVal-18 (a table developed for the U. S. Navy). Many profiles that resulted in decompression sickness (DCS) have longer TDTs than those of the USN57 table; thus, divers developed DCS despite spending more time at stops than the table requires. To a lesser extent, the same is true for the table used by the Canadian forces. A few DCS cases occurred in profiles having longer TDTs than those of the VVal-18 table or a table prepared at the University of Pennsylvania. A table developed at Duke University enables divers to avoid DCS by avoiding long bottom times. The NMRI '98 table (generated by a U.S. Navy probabilistic model, evaluated for 2.2% risk) has far longer TDTs than almost all the experimental dives that resulted in DCS cases, and in many cases the TDTs are more than twice as long as those for VVal-18.

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FOREWORD

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INTRODUCTION

Figure 1 shows decompression instructions from five different decompression tables. The Y-axis is total decompression time (TDT), defined as the sum of times at decompression stops plus the time it takes the diver to ascend from the bottom to the surface. The TDT is plotted against bottom time, defined as the elapsed time between leaving the surface and leaving the bottom depth. Figure 1 illustrates a problem that we hope to clarify: the tables depicted in the figure vary widely in the amounts of time they prescribe at decompression stops for a particular dive. For example, the U.S. Navy Standard Air Table (labeled "USN") prescribes a 176 min TDT for an 80 min dive to 150 fswg, whereas the VVal-18 table (labeled "VVal") prescribes 612 min. Except at the left side of the graph, the Naval Medical Research Institute's "NMRI '98" table prescribes TDTs two or more times longer than VVal-18.

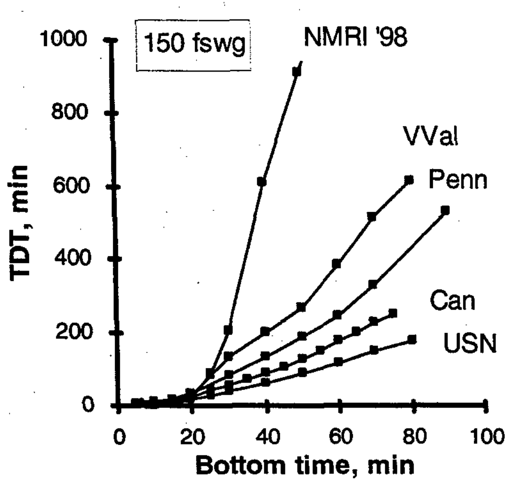

Figure 1. Illustration of differences between five decompression tables (see text for descriptions of the tables); the example is for dives to 150 fswg. Nodes show TDTs (total time at decompression stops plus travel time) at specific bottom times. For long bottom times, the NMRI '98 table requires TDTs that are much longer than TDTs for the other tables.

Our approach is to reflect the kind of table traces depicted in Figure 1 against dive-outcome data [whether or not subjects contracted decompression sickness (DCS) on particular experimental dive profiles]. In addition to providing perspective on the differences between tables, the analysis will also bear on earlier contentions[1–3] that the U.S. Navy Standard Air Table[4] provides too little time at decompression stops for long, deep dives.

DECOMPRESSION MODELS

"Deterministic" decompression models are generated from a theory and then compared with the available dive-outcome data by eye. With tables generated from deterministic models, a diver is expected to avoid DCS if he follows the table's instructions as to depth, bottom time, TDT, and ascent rate. In contrast, tables generated from "probabilistic" models are produced by statistical techniques that fit dive-outcome data to an algorithm.[5] Probabilistic models recognize DCS as a chance phenomenon, so instead of being rated as safe or unsafe, any specific dive profile can be accompanied by an estimate of the probability that DCS will occur. For practical use, tables are produced from probabilistic models by generating dive profiles that have a specific probability of DCS (*Pdcs*).

We consider decompression tables for air-breathing divers derived from six decompression models:

- The current U.S. Navy Standard Air Decompression Table[4] (designated "USN," sometimes called "USN57") was generated from a deterministic model and has been used with few changes since 1957.

- The Canadian Forces Air Decompression Table[6,7] (designated "Can") was generated from a deterministic model and has been used since 1986.

- The table that is designated "Penn was generated from a deterministic model at the University of Pennsylvania and has been used commercially.[8,9]

- The table that is designated "VVal" was generated at Duke University from a deterministic model known as the "VVal-18 Algorithm." [3,10,11]

- The table that is designated "NMRI '98" was generated from a probabilistic model known as "NMRI '98 Model 2" [12] – we use a table generated from the model at a target risk of 2.2%; stop time was optimized in simulated real time using non-conditional probability.

- The table that is designated "Duke" was generated at Duke University from a probabilistic bubble-volume model known as "BVM-3" [13] – we use a table generated for a target risk of 2%; stop time was optimized in simulated real time using conditional probability.

In the sources we use, three of the tables mandate an ascent rate of 60 feet of seawater (fsw) per minute (Canada, Penn, and VVal-18), and three mandate a rate of 30 fsw/min (USN57, NMRI '98, and Duke). Originally the USN57 Standard Air Decompression Table mandated an ascent rate of 60 fsw/min, but in 1993 the rate was changed to 30 fsw/min, with no changes made in any of the table entries.

METHODS

DIVE-OUTCOME DATA

In 1997 the Naval Sea Systems Command gave the Navy Experimental Diving Unit the task of developing a new set of integrated air and nitrogen-oxygen decompression schedules.[16,17] The first step in this task was to make a worldwide survey of existing air and nitrogen-oxygen decompression procedures.[18]

The second step is the objective of this report: to compare table traces with the observed DCS incidence in experimental dive trials. The binomial confidence intervals for chance phenomena such as DCS dictate that uncertainty about the "true" incidence for groups of subjects diminishes as the number of subjects increases. The high cost of dive trials precludes large numbers of dives, so the confidence intervals tend to be large. To obtain groups of subjects large enough to yield meaningful confidence intervals for DCS incidence, we reconfigured information and combined profiles from the U.S. Navy Decompression Database[14,15] to generate what we call a "Compendium." Our manipulations of the data mean that our Compendium is not a simple subset of the original information. Our Compendium is limited to dives in which the breathing gas was air.

The U.S. Navy Decompression Database is a compilation of carefully executed experimental dives. An entry in the Database gives details of the depth/time profile of a group of subjects who dived together; depths and times are recorded throughout the dive. Separate entries are allocated to divers who developed full-blown or marginal DCS and to those who did not. Such detail is essential for probabilistic modeling,[5,12] in which all aspects of the dive profile are considered. However, the way the details are compiled makes it impossible to envision the data as a whole: no summaries show the number of divers tested and the number of DCS cases observed for particular dive profiles.

The total decompression time (TDT) is a major feature of our analysis. For example, for a 50-minute dive to 100 fswg, the U.S. Navy Standard Air Table mandates a 2-minute stop at 20 feet of seawater, gauge (fswg; 1 fsw = 3.063 kPa; 33.08 fswg = 2 atm absolute), and a 24-minute stop at 10 fswg. Ascent rate is 30 fsw/min. The TDT is therefore 26 min + 3.33 min = 29 min 20 s. We speculate that except for depth and bottom time, TDT is the most influential variable in preventing DCS. There may be some leeway in the particular pattern of times at stops: Survanshi and coworkers state that with certain probabilistic models, many different stop-time combinations having the same TDT result in the same probability of DCS.[19]

THE COMPENDIUM

Table 1 lists the18 files in the U.S. Navy Decompression Database that contributed single-level, nonrepetitive air-breathing dives for our analysis. Each of the 18 files is based on a particular published report and is reviewed in a summary Navy report.[14] The entries in the source files provide information about 1–86 persons who followed a particular dive profile. Using the entry heading as a guide, we carefully studied the details of the time and depth profiles of each entry. The heading contains the name of the data file, the depth of the dive, the bottom time, the TDT, the number of divers on the specified profile, and the outcome — i.e., no DCS, definite DCS, or marginal DCS. Marginal cases can be defined as transient complaints that are not severe or persistent enough to require treatment. For our purposes, we assigned marginal cases to the status of "no DCS," because they do not disrupt operations and do not appear to be associated with long-term health consequences.

TABLE 1. DATASET FOR PRODUCTION OF THE COMPENDIUM: DETAILS OF SOURCE FILES

	Source file	File date	Entries	Person -dives	Cases Obs	% Obs
1	DC4D	10/9/97	209	657	16	2.4%
2	DC4W	12/21/93	108	187	4	2.1%
3	EDU1157	9/23/97	27	46	15	32.6%
4	EDU1351NL	12/3/96	43	143	2	1.4%
5	EDU159AVL	9/30/97	3	6	4	66.7%
6	EDU545	11/20/97	42	94	18	19.1%
7	EDU557	5/29/97	81	371	13	3.5%
8	EDU849LT2	5/5/97	74	141	26	18.4%
9	EDU849S2	6/27/97	34	52	13	25.0%
10	EDU885A	12/20/93	82	483	30	6.2%
11	EDUAS45	1/15/98	10	14	3	21.4%
12	NMR97NOD	8/19/97	9	103	3	2.9%
13	NMRNSW	1/29/91	28	48	5	10.4%
14	NSM6HR	12/20/93	14	36	3	8.3%
15	PASA	5/26/92	26	72	5	6.9%
16	RNPL52BL	7/20/95	23	177	1	0.6%
17	RNPL57L	7/21/95	50	50	9	18.0%
18	RNPLX50	9/19/97	10	39	4	10.3%
	Totals		873	2,719	174	

We deleted profiles having more than one distinct bottom depth or an indistinct series of bottom depths. When the recorded information in a profile indicated that the heading was inaccurate or that there was a small deviation from a square-wave exposure to depth, we made appropriate corrections so that the depth, bottom time, and TDT pattern corresponded approximately to square-wave behavior. Delays at the beginning and end of the dives necessitated by far the most corrections; datafiles DC4D, DC4W, and EDU885A needed the most corrections.

1) We took the bottom time to be the difference between the time when the divers left a depth of 3 fswg or shallower and the time when the divers left the bottom depth.
2) We took the TDT to be the difference between the time when the divers left the bottom depth and the time when they reached a depth of 3 fswg or shallower. We verified that the pattern of decompression stops in the test dives were generally in line with Navy practice: the stops began at depths relatively shallow in comparison to the bottom depth, and stop times lengthened at successive stops.
3) All profiles of EDU885A needed correction for lags at 7 fswg at the beginning of the dives, with the average correction of -2.54 min $\pm$ 1.34 min (SD).
4) We adjusted for irregularities in depth so that the area under a graph of depth vs. bottom time was approximately equal to that under an uncorrected graph:
   - When the summary heading did not account for a delay near the final bottom depth, we decreased the bottom depth by an appropriate amount.
   - When the summary heading did not account for a slow descent to depth, we shortened bottom time and/or decreased bottom depth.
   - When the summary heading did not account for small variations in bottom depth, we took average depth.

The EDU159AVL file (Table 1, row 5) contains information on 11 person-dives to 34, 36, and 38 fswg; we changed the information from that in the U.S. Navy Decompression Database file, EDU159A, following our rereading of the original documentation of the dives.[20]

We next eliminated dives with bottom times longer than 720 min, depths shallower than 40 fswg, and depths greater than 195 fswg. These eliminations restricted the dataset to the range of USN57.

For the Compendium, we judiciously combined entries having the same, or very similar, depths, bottom times, and TDTs. To do so, we first rounded depths to the nearest 10 fswg (divide the recorded depth by 10, use the EXCEL spreadsheet function "Round" to round to the nearest digit, and multiply by 10).

We rounded bottom time to the nearest 5 min (divide the recorded bottom time by 5, round to the nearest digit, and multiply by 5). If the last digit in the number to be rounded is 5, Excel's Round function makes the rounded number 10: for example, 45 fswg becomes 50 fswg, and 92.5 min becomes 95 min.

We next sorted the information by increasing depth, sorted within depth by increasing bottom time, sorted within bottom time by increasing TDT, and then combined like entries to make a row in the Compendium. These like entries are often identical profiles in which all divers have the same depth, bottom time, and total decompression time, but sometimes we combined dives having a small range of TDTs to increase the numbers of person-dives in the row.

After exploring other possibilities, we settled on a standard graph to display both the dive-outcome data and the prescriptions given by a decompression table: as in Figure 1, bottom time is on the X-axis, and TDT is on the Y-axis. A separate graph for each depth is necessary. We were unable to devise a convenient graphing technique that accounts for both TDT and pattern of times and depths at decompression stops. We used the Excel spreadsheet program with Microsoft Windows to prepare the graphs.

RESULTS

Table 2 is a summary of the Compendium. In 163 of its 240 rows of profiles, no subjects contracted DCS; in 77 rows, one or more subjects suffered DCS. For 39 rows, we have 95% confidence that the true incidence is greater than 2% (single-tail exact binomial), and for 19 rows the true incidence is greater than 5%. Table 3 gives details of the profiles that have high incidence, according to the binomial theory.

The entire Compendium is reproduced in the Appendix; a row in the Compendium gives a data point on the graphs in the RESULTS section. Some rows show ranges of TDT; when there was a range, data points on the graphs show average TDT. The ">2%" and ">5%" symbols in the right-hand column signify that incidence is 2% or greater, or 5% or greater, according to the binomial theorem.

DIVE-OUTCOME DATA VS. THE USN57 TABLE

Figure 2 shows DCS cases for dives having various bottom times, all at the same depth of 150 fswg. Circles represent a row in the Compendium for a dive profile that did not cause DCS (range of person-dives per circle, 1 to 72). A triangle represents a row in the Compendium for a dive profile that caused one or more cases of DCS. Black triangles represent DCS cases for which we can say with 95% confidence that the DCS incidence is greater than 5%. Gray triangles represent DCS cases for which we can say with 95% confidence that the

TABLE 2. SUMMARY OF THE COMPENDIUM OF DIVE-OUTCOME DATA (± = SD)	
Depth	40 to 190 fswg, average = 120 ± 42 fswg
Bottom time	5 to 720 min, average = 73 ± 116 min
TDT	1 to 1,445 min, average = 71 ± 162 min
Number of rows	240
Rows with no DCS	163
Rows with DCS	77
Rows with DCS incidence greater than 2%	39
Rows with DCS incidence greater than 5%	19
Person-dives per row	1 to 107, average 12 ± 1.5
DCS cases per row	0 to 21, average 0.7 ± 1.8
Incidence of DCS (100 x cases/person-dives) per row	0 to 100%, average 7% ± 16%
Person-dives in rows having DCS cases but no confidence that DCS incidence is greater than 2%	627, with 44 DCS cases
Person-dives in rows having 95% confidence that DCS incidence is greater than 2%	573, with 130 DCS cases
Person-dives in rows having 95% confidence that DCS incidence is greater than 5%	305, with 89 DCS cases

DCS incidence is greater than 2% but cannot say it is 5% or greater. Because the black and gray triangles are based on relatively few person-dives, the true risk of DCS may be substantially greater than 5% and 2%, respectively.

We made the white triangles smaller than the other triangles: for them, it cannot be said with statistical confidence that DCS incidence exceeds 2%; isolated cases of DCS could occur by chance in relatively safe dives. White triangles that are based on only a few person-dives may actually represent high risks, but white triangles that are based on profiles having a large number of person-dives may represent a risk less than 2%. If many white triangles occur close to each other, risk in the region may be appreciable.

TABLE 3. PROFILES WITH INCIDENCE ABOVE 5% OR ABOVE 2% ACCORDING TO THE BINOMIAL THEORY

Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS
True incidence is 5% or greater					
40	720	1–2	91	21	23%
60	180	72	10	3	30%
60	180	111	10	4	40%
100	30	4	22	4	18%
100	55	4	18	5	28%
100	85	61	26	9	35%
120	50	57	6	3	50%
130	55	76–80	21	4	19%
140	240	353	2	2	100%
140	240	421	4	2	50%
140	240	440	2	2	100%
140	240	489	2	2	100%
140	240	517	6	2	33%
140	360	700	6	2	33%
150	30	6	32	8	25%
150	35	6	15	7	47%
150	45	73–89	5	2	40%
150	60	260–290	20	5	25%
160	25	18–19	7	2	29%
True incidence is 2% or greater, but cannot be said to be 5% or greater					
40	360	1–2	39	3	8%
100	60	112–113	27	3	11%
100	100	82–86	14	2	14%
100	720	723	2	1	50%
100	720	1,445	2	1	50%
110	90	88–93	12	2	17%
120	20	9–10	8	2	25%
120	50	36-38	12	2	17%
120	70	213	10	2	20%
120	80	267	10	2	20%
130	50	47–54	18	2	11%
140	40	64–65	21	3	14%
140	80	135–138	10	2	20%
150	26	6	10	2	20%
150	30	46–50	12	2	17%
150	40	81-85	25	3	12%
150	45	57	2	1	50%
150	45	65	2	1	50%
170	10	18–23	22	3	14%
190	40	238	10	2	20%

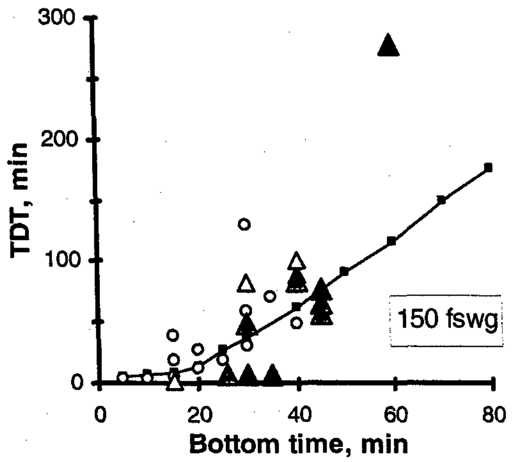

FIGURE 2. Plot of TDT vs. bottom time for dives at a depth of 150 fswg. Trace = instructions according to the U.S. Navy Standard Air Decompression Table; nodes on the trace = TDT/bottom-time entries from the Table. For explanations of circles and triangles, see text.

Nodes on the table trace in Figure 2 show TDTs prescribed by USN57 for given bottom times, all at a depth of 150 fswg. The TDTs increase as bottom time increases, because long dives require more stops and longer stops. For example, the table prescribes 62 min of TDT when bottom time is 40 min.

Because of the probabilistic nature of DCS, circles and triangles often fall in the same region on the graph. For a profile that causes DCS in a small percentage of the subjects, we can expect many trials that have no DCS, unless the subject groups are large. Also, we can expect a gradient of the symbols. Black triangles should predominate where decompression stops are inadequate near the zero TDT axis. Gray triangles should tend to have higher TDTs than black triangles. At high TDTs, we can expect a mixture of white triangles and circles. At very high TDTs, we can expect circles only, an expectation indicating that time at decompression stops is more than enough to prevent DCS. Unfortunately, the number of dive trials is insufficient to show such a gradient pattern. Note that the presence of a circle or the absence of a triangle does not mean that a region has *Pdcs* less than 2%; it means only that there is no information to the contrary.

It is difficult to display the inherent danger of a particular dive profile; one DCS case in 100 dives is far different from 10 cases in 10 dives. We can say with statistical confidence that the black triangles represent incidence greater than 5% of DCS and gray triangles represent incidence greater than 2%, but the confidence intervals for the true incidence are large. For example, the gray triangle at 40 fswg in Figure 2 is for 3 cases among 25 person-dives; the two-tailed 95% confidence interval for the true incidence is 3% to 28%, so although the observed incidence is 12%, the dive could actually be either reasonably safe or very dangerous.

For circles, 58 person-dives with no DCS cases are required to say with 95% confidence that incidence is below 5%, and 148 dives with no cases to say that incidence is below 2% (one-tailed binomial distribution). For circles on the graphs, the average number of person-dives is 9.3 ± 8.4 (SD) with maximum of

72, so we cannot say with 95% confidence that any of the circles have a probability of DCS less than 2%.

In Figure 2 the triangles fall both above and below the USN57 trace. The five triangles below the trace in Figure 2 show DCS cases that are expected, according to the table, because the divers did not spend the prescribed times at decompression stops. For example, consider the three black triangles near bottom times of 25 and 35 min: USN57 prescribes about 35 minutes at decompression stops, but the divers actually spent little or no time at stops.

Six triangles in Figure 2 are above the trace, an indication that USN57 prescribes insufficient time at decompression stops: that is, the divers completed the prescribed time, or more, at decompression stops, but they developed DCS nevertheless. Adding time at decompression stops would make the trace steeper and thereby reduce the number of unpredicted cases. The highest black triangle is particularly worrisome: TDT would have to be twice that prescribed by USN57 to avoid the high DCS incidence signified by the black triangle.

OTHER TABLES

Figure 3 adds traces for five other tables to the information presented in Figure 2. From the positions of the triangles in Figure 3, it is reasonable to infer that the VVal-18 algorithm furnishes adequate decompression times. We might conclude that NMRI '98 mandates excessive, inefficient decompression times, but this conclusion is not certain: neither triangles nor circles are to the left of bottom time = 50 min and above TDT = 150 min. That is, no decompression trials are in the region of high TDTs, where the NMRI '98 trace lies. The Duke table rises toward high TDTs but stops at shorter bottom times than the other tables.

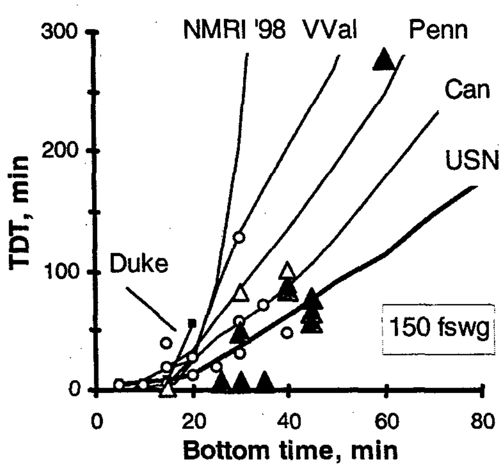

FIGURE 3. Same information as in Figure 2, plus traces for five additional tables. In this figure and those that follow, nodes for the table entries are omitted from the traces, except for the trace for the Duke table.

The trace for the Canadian table in Figure 3 is higher than the USN57 trace; it falls above gray triangles at 30 and 40 min, whereas USN57 falls below them. The trace for the Penn table is between the VVal-18 and Canadian traces.

Figure 4 presents graphs similar to those of Figure 3 for depths from 40 to 190 fswg, inclusive. Sixty of the 74 data points that represent DCS cases in our Compendium appear in one or another of the 16 panels of Figure 4; the 14 which do not appear are off

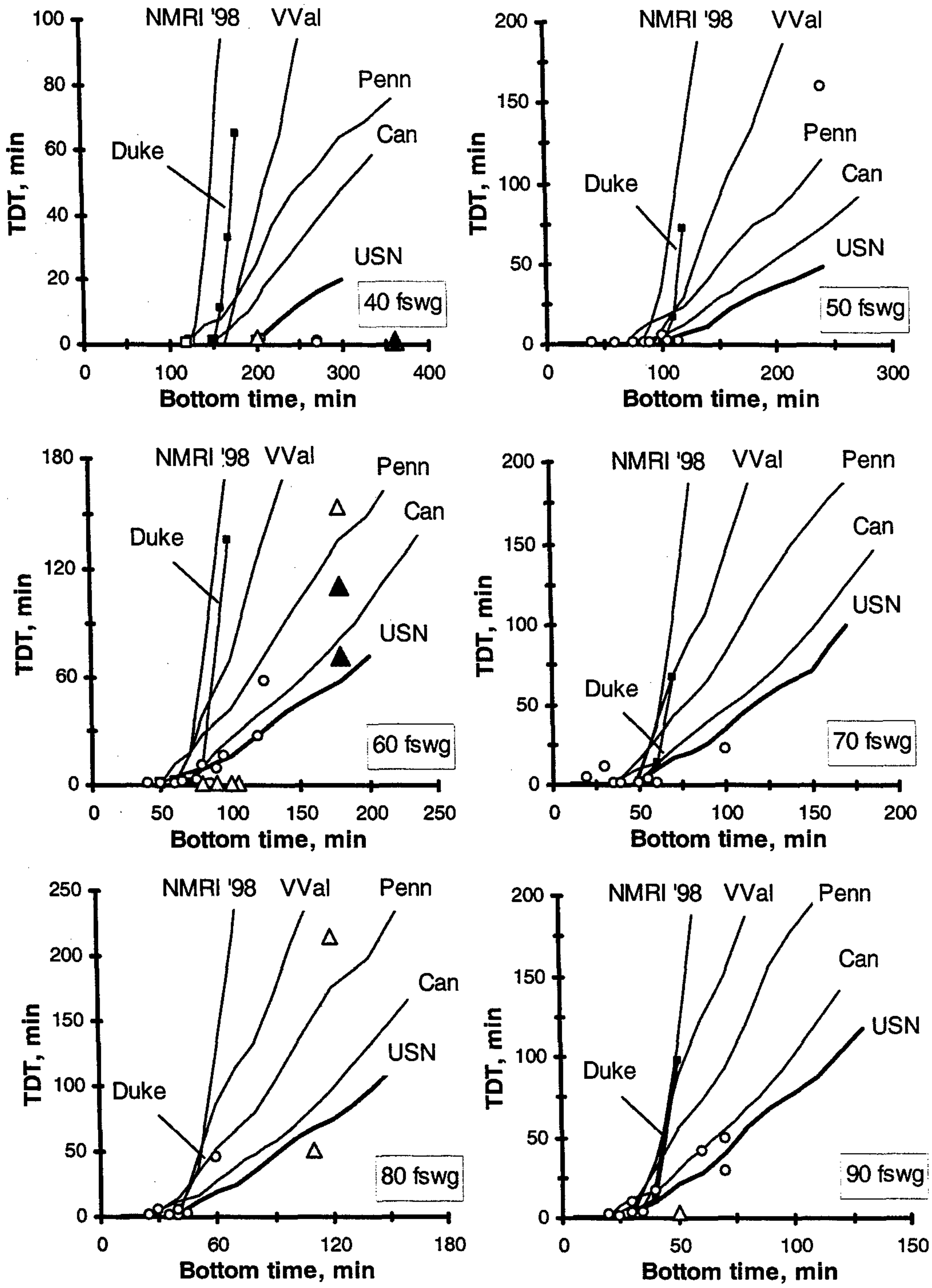

FIGURE 4, FIRST OF THREE GROUPS OF DEPTHS. Total decompression time vs. bottom time for each depth, showing dive-outcome data (symbols) and instructions for ascent for six tables. Circles represent dives that did not result in DCS; triangles represent dives in which one or more cases of DCS occurred. For white triangles, no statement about incidence is warranted; for gray triangles, it can be said with 95% confidence that incidence of DCS is greater than 2%; for black triangles, it can be said with 95% confidence that incidence of DCS is greater than 5%.

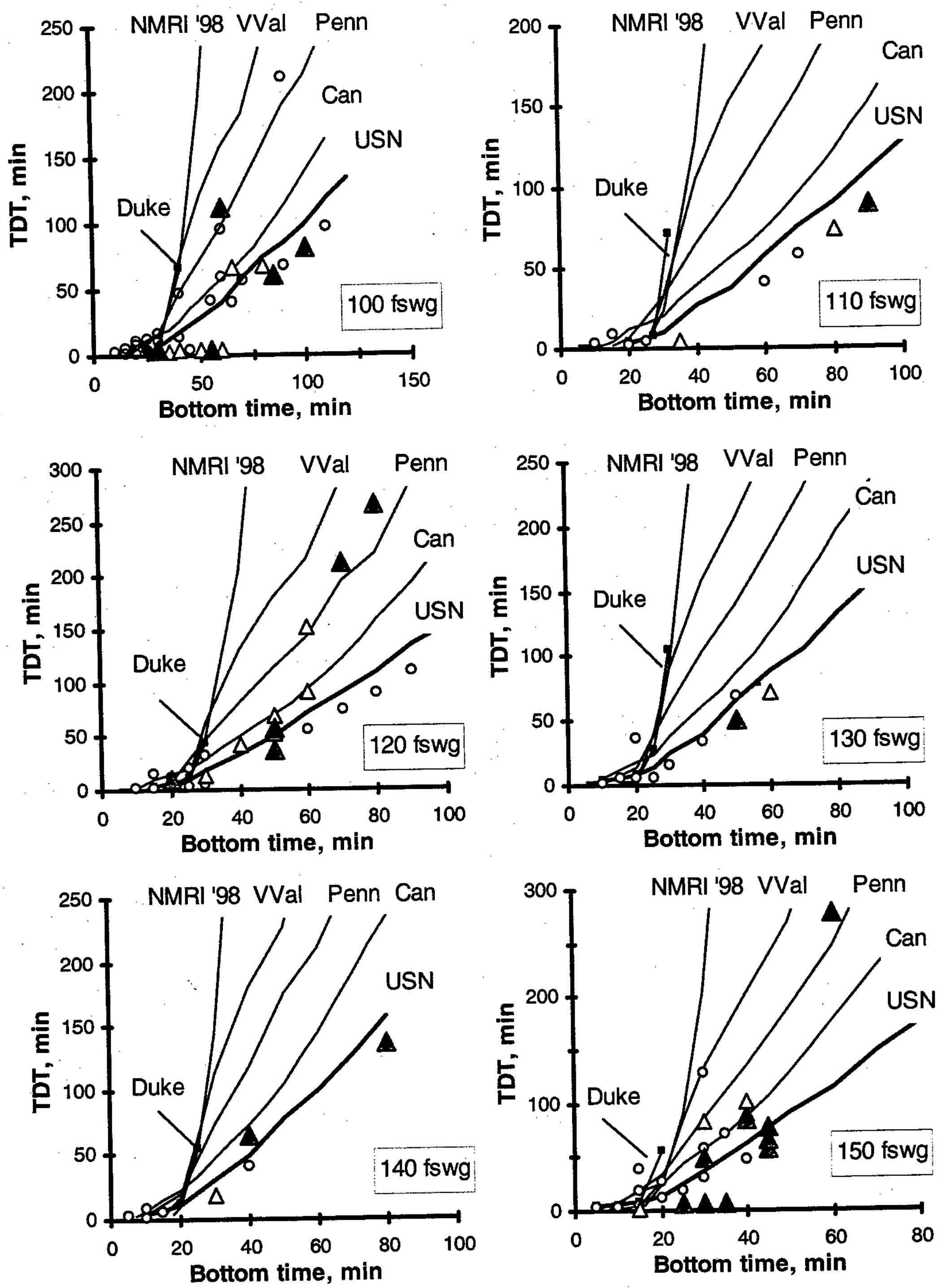

FIGURE 4, CONTINUED. Second group of depths.

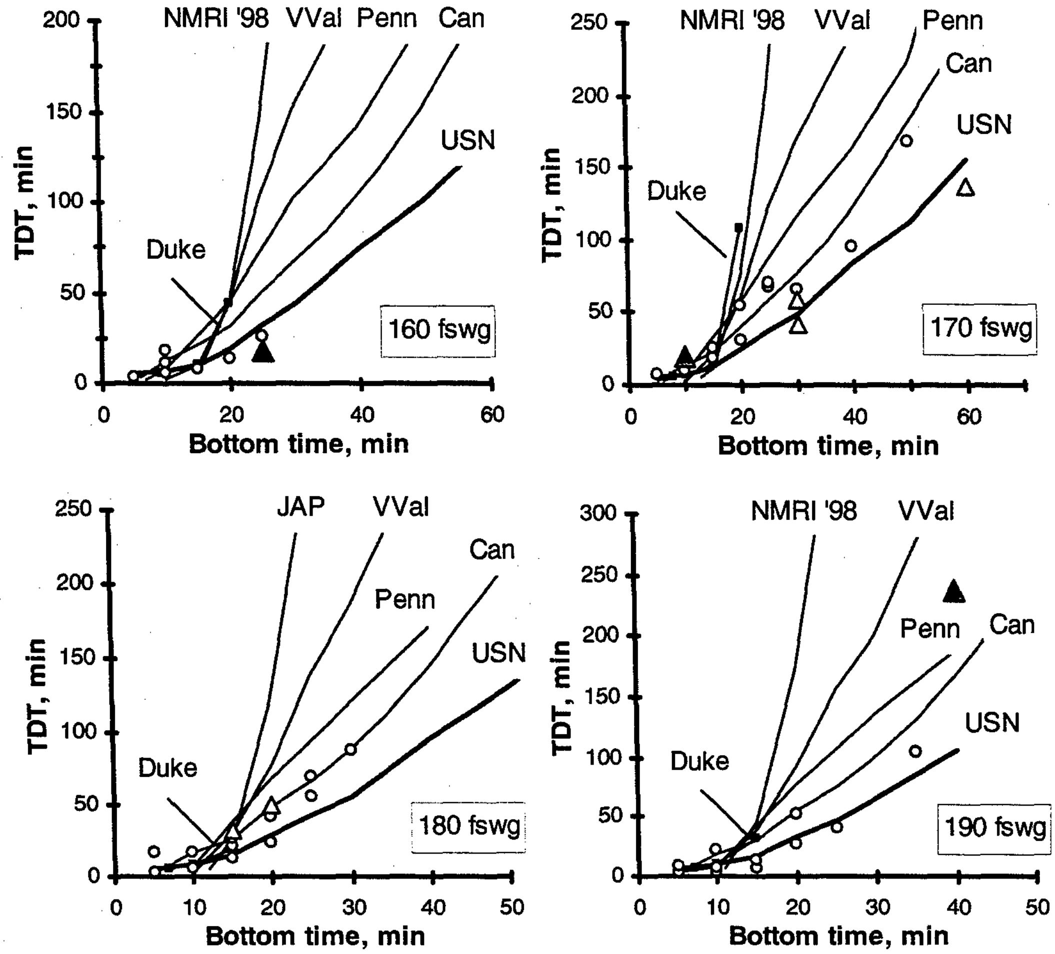

FIGURE 4, CONTINUED. Third group of depths.

scale at the right, at bottom times beyond our range of interest. Two of the depths (50 and 70 fswg in Figure 4) show no DCS cases at all, and cases for the rest of the depths are sparse.

In all the panels of Figure 4 that have appreciable numbers of dive-outcome points, the patterns are similar to the pattern in Figure 3. For example, consider dives at a depth of 100 fswg. Except at very low TDTs, no circles or triangles are near the NMRI '98 trace to indicate whether the TDTs are excessive. As in Figure 3, VVal-18 is above the triangles; the Penn table is below VVal-18; and the Canadian table is above USN57.

The black and gray triangles in Figure 4 indicate that some of the tables do not prescribe enough time at decompression stops:

- the USN57 table at 60, 100, 120, 140, 150, 170, and 190 fswg
- the Canadian table at 60, 100, 120, 150, 170, and 190 fswg
- the Penn table at 100, 120, 150, and 170 fswg

- the VVal-18 table at 170 fswg

Positions of the table traces relative to the triangles in Figure 4 invite contentions about the safety and efficacy of the six tables:

- The Canadian table is safer than USN57; its traces fall near the top of the regions that contain triangles, in contrast to traces for USN57, which fall lower down.

- The Penn table traces are safer than those of the Canadian table but the Penn table does not predict as many DCS cases as VVal-18.

- The VVal-18 model appears to be safe: it falls above all the triangles except for the gray triangle at 170 fswg with 10 min bottom time.

- Traces for the Duke table avoid long bottom times: they rise steeply at relatively short bottom times and then stop.

- Neither circles nor triangles appear near the tops of the graphs, where the NMRI '98 traces are far above those for the other tables; in these high-TDT regions, there are no dive trials in the U.S. Navy Decompression Database.[14,15]

- Although both the VVal-18 and NMRI '98 tables avoid DCS cases, the VVal-18 traces mandate less time at decompression stops than the NMRI traces.

SHORT DIVES

On the scale of Figure 4, the groups of table traces in each of the panels resemble fans. Figure 5, which enlarges the lower left corner for several of the Figure 4 graphs, illustrates how the traces cross each other when bottom time is short. The NMRI '98, Duke, and VVal-18 traces tend to lie together. Black and gray triangles lie above some of the table traces in all panels. In particular, a gray triangle lies above the USN57, Canadian, and Penn traces on the 100 fswg plot, and a gray triangle above all the traces on the 170 fswg plot.

No-stop dive profiles are the lowest points on the traces in Figures 4 and 5. For most military, commercial, and recreational diving, bottom times are short enough that decompression stops are not needed; we might expect no-stop dives to be established well enough that the different tables would agree.

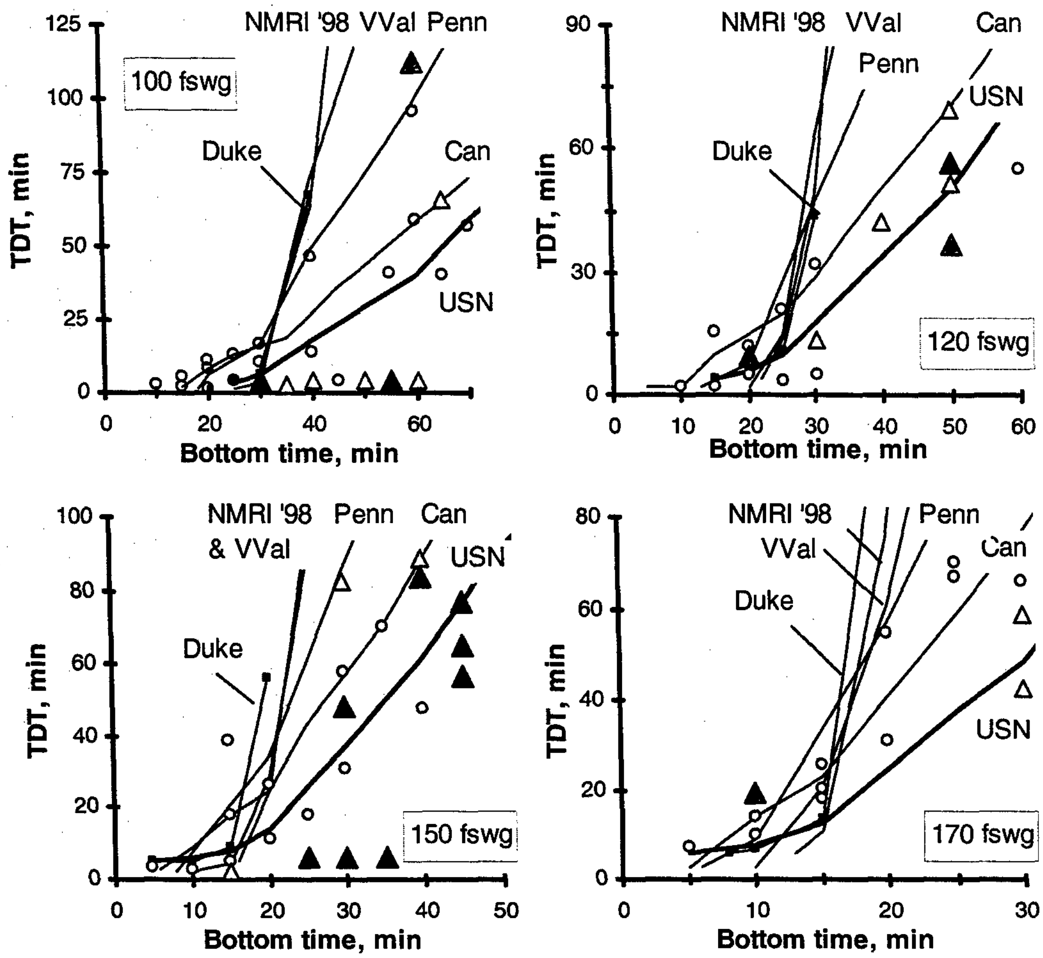

FIGURE 5. Enlarged scale to show dives having short bottom times and short TDTs for sample depths. Format is the same as in Figure 4.

Table 4 lists no-stop times for the decompression tables we study in this report. The allowed bottom times differ widely among the tables, with many of these times differing by factors of two or more: for example, times range from 120 to 200 min for 40 fswg, from 15 to 29 min for 100 fswg, and from 5 to 13 min for 170 fswg. The relative positions of the times shift with changes of depth. For example, the NMRI '98 table has the second-shortest bottom time for 40 fswg and the USN57 table has the longest, but for profiles deeper than 130 fswg, the NMRI '98 table has the longest bottom times, and USN57 is among the tables with the shortest bottom times.

Figure 6 shows the no-stop regions of four depths that have appreciable numbers of dive trials. Open squares in Figure 6 show no-stop points. For no-stop dives, the TDT is simply travel time, so vertical positions of the squares indicate differences in ascent rates at either 30 or 60 fsw/min. Dashed diagonal line segments that start from gray triangles are drawn by eye with slopes that approximate the average slope of the table traces in the region.

TABLE 4. NO-STOP BOTTOM TIMES FOR SIX DECOMPRESSION TABLES

Depth, fswg	Canada	Duke	NMRI '98	Penn	USN57	VVal-18
40	150	150	124	120	200	163
50	75	100	82	69	100	92
60	50	70	60	49	60	63
70	35	51	48	34	50	49
80	25	38	39	26	40	40
90	20	29	33	21	30	34
100	15	23	29	18	25	29
110	12	19	25	15	20	26
120	10	16	22	13	15	23
130	8	14	20	11	10	19
140	7	12	18	9	10	17
150	6	11	16	8	5	14
160	6	9	15	7	5	12
170	5	8	13	6	5	11
180	5	7	12	--	5	10
190	5	7	11	--	5	9

Comparison of the triangles and circles with the squares in Figure 6 invites contentions about the safety of no-stop instructions:

- In the 100 fswg panel, the position of the black triangle at 30 min bottom time, only 1 min from the positions of NMRI '98 and VVal-18 no-stop times at 29 min, suggests that no-stop bottom times at 100 fswg should be several minutes less than 29 min.

- In the120 fswg panel, the gray triangle at 20 min bottom time is above all the traces but that for Canada. The dashed projection suggests that bottom time should be 16 min or less. The two squares to the right of the dashed projection are for the NMRI '98 and VVal-18 models.

- In the 150 fswg panel, the gray triangle at 30 min bottom time is to the left of the USN57 trace. The dashed projection indicates that the no-stop bottom time should be 16 min or less. There are no squares to the right of the projection. The white triangle at 15 min bottom time represents one DCS case in 32 person-dives.

- In the 170 fswg panel, the gray triangle at 10 min bottom time with TDT of 19 min is to the left of all the traces. The dashed projection suggests that no-stop bottom time at 170 fswg should be around 5 min. On the graph, only two traces meet this criterion: those for Canada and USN57.

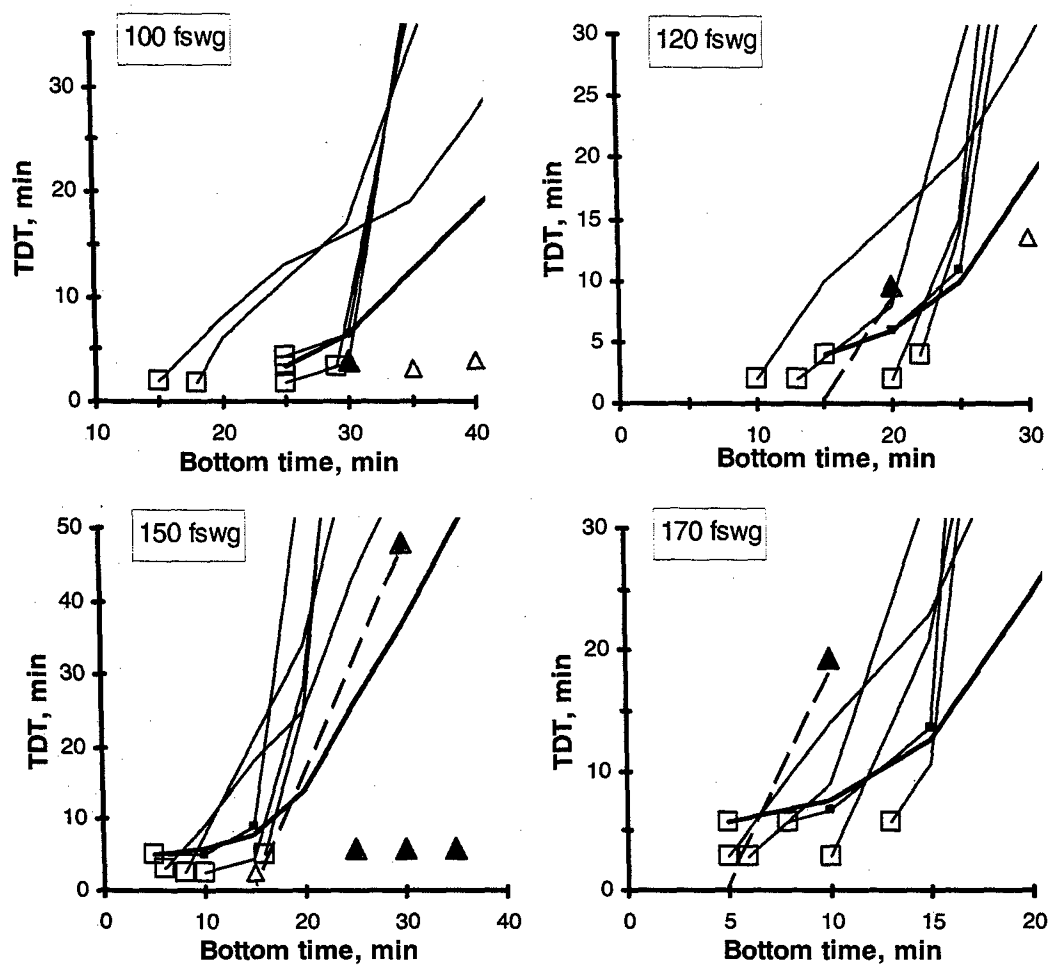

Figure 6. Illustration of no-stop times (squares) for several graphs presented in Figure 4: Squares can be matched with tables by using Table 4. Circles are omitted to reduce clutter. Dashed diagonal line segments in the 120, 150, and 170 fswg panels are drawn by eye.

DISCUSSION

Any graphical display of dive outcomes is only partially satisfying, because so many variables are important. At a minimum, dive depth, bottom time, total time at decompression stops, and incidence of DCS must be considered. Of course, the patterns of depths and times for decompression stops are also pertinent, along with other variables such as the type of dive (dry or in the water), the intensity of diver exercise, and the environmental temperature.

The tolerable risk for a given dive is a matter of policy and may vary with the circumstances. Recent discussions at Naval Sea Systems Command (NAVSEA) brought consensus that more than two cases of DCS per 100 dives in routine diving would hurt diver morale and slow operational tempo (personal communication, Murray CA; 2000). Accordingly, we give special attention to the data points for which we are 95% confident that the true DCS incidence is greater than 2%. Gray and black triangles above or to the left of a table trace on our graphs are strong evidence that TDTs prescribed by the table are insufficient.

Unlike decompression tables based on deterministic models, in which no risk is specified, tables based on probabilistic models can be generated for any desired level of DCS risk. In line with current NAVSEA policy, we chose a risk near 2% for the two probabilistic tables examined in this analysis. In the past, probabilistic modelers have made other risk choices: as great as 5% for decompression diving, and as great as 10% for exceptional exposure diving.[21]

Of the six tables we examined, USN57[4] is the oldest and has the shortest TDTs. Our analysis shows that many cases of DCS have occurred on experimental profiles with TDTs longer than those prescribed by USN57, and in many instances the TDTs of the experimental DCS cases and TDTs of USN57 differ substantially. These differences are strong evidence that the TDTs in USN57 should be lengthened or USN57 should be replaced.

Our conclusion about USN57 concurs with other warnings about it,[1–3] but this conclusion conflicts with the Naval Safety Center's operational experience.[22] From 1979 to 1996, the DCS rate for decompression diving using USN57 was 0.5% overall; only six profiles showed a rate higher than 2%. The confidence limits of all six do not allow a statement that the true incidence of DCS for those profiles is greater than 2%; the six profiles would appear as white triangles on our graphs. One of the six is off scale for our analysis, with a bottom time of 220 min and depth of 50 fswg. Depth, bottom time, and TDT for the other five are 100/60/40.3, 140/40/48.7, 150/25/26.0, 170/40/84.7, and 190/50/150.3.

Several differences between operational and experimental diving may account for these apparently divergent results. First, operational divers seldom follow USN57 exactly. In practice, delays in reaching the target depth are counted as bottom time; depths and bottom times are usually less than the maximum permitted by the table; and instead of the instructions for the actual dive, table instructions designed for a greater exposure are often used on an ad hoc basis — especially for dives perceived to be arduous or dangerous. Such changes can be shown to reduce the risk of DCS substantially.

Second, we do not account for the patterns of decompression stops, which may differ from USN57 practice in some of the experimental dives, even though we screened the data to see that the patterns of decompression stops in the test dives were generally in line with Navy practice.

Third, the carefully controlled dive trials in the U.S. Navy Decompression Database may not be good representations of actual operational dives. Some of the experimental dive trials were performed by immersed divers and some by divers in dry chambers, and levels of thermal stress and exercise for test dives may be greater or less than those levels for operational dives.

Finally, susceptibilities to DCS between the test divers and operational divers may differ because of acclimatization. Of all these factors, we judge dive profiles that are shorter and shallower than those prescribed by the table and acclimatization in operational diving to be most influential in keeping the observed DCS rate lower than our analysis predicts. To maintain the current safety record with USN57, it will be crucial to maintain the current pattern of diving and schedule jumping: if the pattern were made more aggressive, the inadequacies of USN57 would be quickly revealed.

Of the four deterministic decompression tables we examined (Canada, Penn, VVal-18, and USN57), only VVal-18 appears to avoid most of the DCS in the dataset. The Penn table is less successful than VVal-18, and the Canadian table is less successful than the Penn table but still substantially better than USN57. The VVal-18 table could be a candidate for replacing the current USN57 table.

The two tables based on probabilistic models differ from the four based on deterministic models in that they either prescribe longer TDTs (NMRI '98) or rise steeply toward long TDTs but avoid them by ending at short bottom times (Duke). The statistical technique for generating a probabilistic table uses the totality of the data points across depth to estimate risk of DCS.[3] The process is analogous to the familiar exercise of drawing a best-fit straight line through X-Y points: the points determine the position of the line. It is therefore surprising that the NMRI '98 model has such high TDTs when the graphs show no DCS cases in regions where its traces are located. The NMRI '98 model was built from a much larger dataset than we have used in our displays; it includes many different kinds of diving in addition to standard air dives. The difference in datasets may account in part for the high TDTs associated with 2% risk. In other work we have shown that including saturation dive data in calibrating a simple probabilistic model of air diving lengthens TDT substantially.[23] However, the precise source of the long TDTs in the NMRI '98 model remains unknown to us. To use either the NMRI '98 or Duke model in producing an air decompression schedule with realistic TDTs, one would have to increase the risk given by the model well beyond 2%. How the nominal risk given by a model will correspond to the actual risk for air dives is unknown.

CONCLUSIONS

1. The graphical analysis presented here provides a general basis for comparing decompression tables for single-level dives from any source. The graphs present a visual impression of the results of dive-outcome information and facilitate insight into the safety and efficacy of decompression tables produced from different assumptions.

2. The six tables we studied differ markedly.

3. The analysis provides quantitative background information for recommendations about decompression tables:

   - The USN57 table and, to a lesser extent, the Canadian table appear to specify insufficient amounts of time at decompression stops for dives of long duration.

   - The VVal-18 table and, to a lesser extent, the Penn table provide adequate time at decompression stops to avoid almost all the DCS cases in the Compendium.

   - The NMRI '98 probabilistic table seems to mandate excessive times at decompression stops, but the U.S. Navy Decompression Database[13,14] does not contain any dive trials in the high TDT regions to verify this contention.

   - Bottom times for deep no-stop dives appear to be dangerously long in some of the tables.

4. The VVal-18 algorithm should be further explored as the basis for a fully integrated air and nitrogen-oxygen table set.

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APPENDIX: DIVE-OUTCOME COMPENDIUM

SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
1	40	200	2	103	3	2.9%	
2	40	205	2	4	0	0.0%	
3	40	270	1	4	0	0.0%	
4	40	360	1–2	39	3	7.7%	>2%
5	40	480	1	3	0	0.0%	
6	40	720	1–2	91	21	23.1%	>5%
7	50	40	1	1	0	0.0%	
8	50	60	1	4	0	0.0%	
9	50	75	1	8	0	0.0%	
10	50	85	1	12	0	0.0%	
11	50	90	1	7	0	0.0%	
12	50	100	6	4	0	0.0%	
13	50	105	2	4	0	0.0%	
14	50	115	2	4	0	0.0%	
15	50	240	160	20	0	0.0%	
16	50	720	117	2	0	0.0%	
17	60	40	1	1	0	0.0%	
18	60	50	1	11	0	0.0%	
19	60	60	1	12	0	0.0%	
20	60	65	2	29	0	0.0%	
21	60	75	3	4	0	0.0%	
22	60	80	1–2	8	1	12.5%	
23	60	80	11	5	0	0.0%	
24	60	85	1	6	0	0.0%	
25	60	90	1	21	2	9.5%	
26	60	90	9	6	0	0.0%	
27	60	95	16	9	0	0.0%	
28	60	100	1	10	1	10.0%	
29	60	105	1	3	1	33.3%	
30	60	120	26–27	2	0	0.0%	
31	60	125	58–59	18	0	0.0%	
32	60	180	72	10	3	30.0%	>5%
33	60	180	111	10	4	40.0%	>5%
34	60	180	153–154	20	1	5.0%	
35	70	20	5	3	0	0.0%	
36	70	30	11	3	0	0.0%	
37	70	35	1	10	0	0.0%	
38	70	40	1	6	0	0.0%	
39	70	50	1	4	0	0.0%	
40	70	55	3	4	0	0.0%	
41	70	60	1	2	0	0.0%	

APPENDIX: DIVE-OUTCOME COMPENDIUM
SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
42	70	100	22	6	0	0.0%	
43	80	25	1–2	11	0	0.0%	
44	80	30	6	12	0	0.0%	
45	80	35	1	14	0	0.0%	
46	80	40	1–2	7	0	0.0%	
47	80	40	5	2	0	0.0%	
48	80	45	3	4	0	0.0%	
49	80	60	46	5	0	0.0%	
50	80	110	49–55	10	1	10.0%	
51	80	120	216	18	1	5.6%	
52	90	20	2	11	0	0.0%	
53	90	25	2	2	0	0.0%	
54	90	30	4	4	0	0.0%	
55	90	30	10	1	0	0.0%	
56	90	35	4	16	0	0.0%	
57	90	40	17	3	0	0.0%	
58	90	50	4	4	1	25.0%	
59	90	60	42	7	0	0.0%	
60	90	70	29	4	0	0.0%	
61	90	70	50	2	0	0.0%	
62	100	10	3	4	0	0.0%	
63	100	15	2–3	19	0	0.0%	
64	100	15	4–7	14	0	0.0%	
65	100	20	2	24	0	0.0%	
66	100	20	7–9	7	0	0.0%	
67	100	20	10–13	12	0	0.0%	
68	100	25	4	4	0	0.0%	
69	100	25	13	2	0	0.0%	
70	100	30	2	12	0	0.0%	
71	100	30	4	22	4	18.2%	>5%
72	100	30	10–11	3	0	0.0%	
73	100	30	14–18	8	0	0.0%	
74	100	35	3	13	1	7.7%	
75	100	40	2–4	32	1	3.1%	
76	100	40	14	8	0	0.0%	
77	100	40	47	5	0	0.0%	
78	100	45	4	8	0	0.0%	
79	100	50	4	12	1	8.3%	
80	100	55	4	18	5	27.8%	>5%
81	100	55	40–42	14	0	0.0%	
82	100	60	4	20	2	10.0%	

APPENDIX: DIVE-OUTCOME COMPENDIUM

SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
83	100	60	59–60	21	0	0.0%	
84	100	60	94–97	30	0	0.0%	
85	100	60	112–113	27	3	11.1%	>2%
86	100	65	40	9	0	0.0%	
87	100	65	59–70	11	1	9.1%	
88	100	70	57	2	0	0.0%	
89	100	80	69	9	1	11.1%	
90	100	85	61	26	9	34.6%	>5%
91	100	90	69	6	0	0.0%	
92	100	90	212	19	0	0.0%	
93	100	100	82–86	14	2	14.3%	>2%
94	100	110	98	2	0	0.0%	
95	100	360	725	4	1	25.0%	
96	100	540	725	2	0	0.0%	
97	100	540	1,085	2	0	0.0%	
98	100	720	723	2	1	50.0%	>2%
99	100	720	1,445	2	1	50.0%	>2%
100	110	10	2–3	17	0	0.0%	
101	110	15	6–12	19	0	0.0%	
102	110	20	2	4	0	0.0%	
103	110	25	5	8	0	0.0%	
104	110	35	5	4	1	25.0%	
105	110	60	41	4	0	0.0%	
106	110	70	58	6	0	0.0%	
107	110	80	74–79	12	1	8.3%	
108	110	90	88–93	12	2	16.7%	>2%
109	120	10	2	30	0	0.0%	
110	120	15	2	37	0	0.0%	
111	120	15	16	2	0	0.0%	
112	120	20	5	10	0	0.0%	
113	120	20	9–10	8	2	25.0%	>2%
114	120	20	12	6	0	0.0%	
115	120	25	3–4	19	0	0.0%	
116	120	25	9–24	12	0	0.0%	
117	120	30	5	3	0	0.0%	
118	120	30	13–14	7	1	14.3%	
119	120	30	31–32	12	0	0.0%	
120	120	40	41–43	12	1	8.3%	
121	120	50	36–38	12	2	16.7%	>2%
122	120	50	52	7	1	14.3%	
123	120	50	57	6	3	50.0%	>5%

APPENDIX: DIVE-OUTCOME COMPENDIUM

SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
124	120	50	68–71	19	2	10.5%	
125	120	60	55	6	0	0.0%	
126	120	60	90	20	1	5.0%	
127	120	60	149–153	29	1	3.4%	
128	120	70	74	6	0	0.0%	
129	120	70	213	10	2	20.0%	>2%
130	120	80	90	10	0	0.0%	
131	120	80	267	10	2	20.0%	>2%
132	120	90	110	2	0	0.0%	
133	130	10	2	14	0	0.0%	
134	130	15	5	8	0	0.0%	
135	130	20	6	1	0	0.0%	
136	130	20	36	3	0	0.0%	
137	130	25	5	4	0	0.0%	
138	130	30	13– 17	8	0	0.0%	
139	130	40	34	5	0	0.0%	
140	130	50	47–54	18	2	11.1%	>2%
141	130	50	69	10	0	0.0%	
142	130	55	76–80	21	4	19.0%	>5%
143	130	60	70–75	14	1	7.1%	
144	140	5	3	17	0	0.0%	
145	140	10	2	4	0	0.0%	
146	140	10	9	2	0	0.0%	
147	140	15	6	8	0	0.0%	
148	140	30	17–25	12	1	8.3%	
149	140	40	41	6	0	0.0%	
150	140	40	64–65	21	3	14.3%	>2%
151	140	80	135–138	10	2	20.0%	>2%
152	140	90	175	6	0	0.0%	
153	140	120	233	6	1	16.7%	
154	140	180	306	6	1	16.7%	
155	140	180	364	6	1	16.7%	
156	140	240	353	2	2	100.0%	>5%
157	140	240	421	4	2	50.0%	>5%
158	140	240	440	2	2	100.0%	>5%
159	140	240	489	2	2	100.0%	>5%
160	140	240	517	6	2	33.3%	>5%
161	140	360	700	6	2	33.3%	>5%
162	150	5	4	12	0	0.0%	
163	150	10	3	21	0	0.0%	
164	150	15	3	32	1	3.1%	
165	150	15	5	41	0	0.0%	

APPENDIX: DIVE-OUTCOME COMPENDIUM

SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
166	150	15	18	2	0	0.0%	
167	150	15	36–46	14	0	0.0%	
168	150	20	11	8	0	0.0%	
169	150	20	24–31	20	0	0.0%	
170	150	25	18	1	0	0.0%	
171	150	25	6	10	2	20.0%	>2%
172	150	30	6	32	8	25.0%	>5%
173	150	30	31	6	0	0.0%	
174	150	30	46–50	12	2	16.7%	>2%
175	150	30	58–59	9	0	0.0%	
176	150	30	77–83	20	1	5.0%	
177	150	30	127–131	20	0	0.0%	
178	150	35	6	15	7	46.7%	>5%
179	150	35	70	12	0	0.0%	
180	150	40	48	6	0	0.0%	
181	150	40	81–85	25	3	12.0%	>2%
182	150	40	89	28	1	3.6%	
183	150	40	98–104	31	1	3.2%	
184	150	45	57	2	1	50.0%	>2%
185	150	45	65	2	1	50.0%	>2%
186	150	45	73–89	5	2	40.0%	>5%
187	150	60	260–290	20	5	25.0%	>5%
188	160	5	3	10	0	0.0%	
189	160	10	4–7	12	0	0.0%	
190	160	10	10–12	8	0	0.0%	
191	160	10	15–19	18	0	0.0%	
192	160	15	8	6	0	0.0%	
193	160	20	14	6	0	0.0%	
194	160	25	18–19	7	2	28.6%	>5%
195	160	25	27	6	0	0.0%	
196	170	5	3	8	0	0.0%	
197	170	5	7	4	0	0.0%	
198	170	10	5–9	18	0	0.0%	
199	170	10	11–17	72	0	0.0%	
200	170	10	18–23	22	3	13.6%	>2%
201	170	15	10	6	0	0.0%	
202	170	15	17–22	15	0	0.0%	
203	170	15	25–26	18	0	0.0%	
204	170	20	18	6	0	0.0%	
205	170	20	55–57	5	0	0.0%	
206	170	25	31	6	0	0.0%	

APPENDIX: DIVE-OUTCOME COMPENDIUM
SINGLE-LEVEL, NON-REPETITIVE AIR DIVES

Row #	Depth, fswg	Bottom time, min	TDT, min	Person-dives	DCS cases	% DCS	Confidence
207	170	25	67	4	0	0.0%	
208	170	30	42	10	1	10.0%	
209	170	30	59	20	2	10.0%	
210	170	30	70	1	0	0.0%	
211	170	40	66	4	0	0.0%	
212	170	50	95	2	0	0.0%	
213	170	60	137	6	1	16.7%	
214	170	70	168	2	0	0.0%	
215	180	5	3	9	0	0.0%	
216	180	5	17	1	0	0.0%	
217	180	10	5	6	0	0.0%	
218	180	10	14–18	29	0	0.0%	
219	180	15	12	6	0	0.0%	
220	180	15	21	2	0	0.0%	
221	180	15	24–28	23	0	0.0%	
222	180	15	32–33	16	1	6.3%	
223	180	20	23	6	0	0.0%	
224	180	20	40–42	19	0	0.0%	
225	180	20	47–52	12	1	8.3%	
226	180	25	55–57	19	0	0.0%	
227	180	25	70	12	0	0.0%	
228	180	30	86–90	19	0	0.0%	
229	190	5	3	4	0	0.0%	
230	190	5	8	8	0	0.0%	
231	190	10	3	8	0	0.0%	
232	190	10	6–7	16	0	0.0%	
233	190	10	22	2	0	0.0%	
234	190	15	6	9	0	0.0%	
235	190	15	14	6	0	0.0%	
236	190	20	27	6	0	0.0%	
237	190	20	52	6	0	0.0%	
238	190	25	41	6	0	0.0%	
239	190	35	103–106	19	0	0.0%	
240	190	40	238	10	2	20.0%	>2%