TABLE OF CONTENTS

PADI

OVERVIEW

A special seminar on "Decompression in Depth", sponsored by PADI, was held on March 10, 1979 at Santa Ana College in Santa Ana, California. As was expected, the program was a sell-out, with approximately 110 participants who came from as far away as Florida and British Columbia, Canada.

The participants came to view a panel of highly qualified individuals who cleared up many myths and misconceptions associated with dive tables and decompression. These speakers were: Bruce E. Bassett, Ph.D., USAF School of Aerospace Medicine; Richard Bell, Ph.D., University of California at Davis; Andrew Pilmanis, M.D., USC Catalina Marine Science Center; Charles V. Brown, M.D., Medical Editor for *Skin Diver* magazine; Dennis Graver, PADI Director of Training; and Jon Hardy, Underwater Consultant.

Dr. Bassett began the lectures with his talk on the "Development of the Dive Tables", and then again, later in the program, spoke on "Altitude Diving Studies". We received very informative lectures from Dr. Bell on "Altitude Dive Tables", Dr. Brown on "The Physiology of Decompression Sickness", Dennis Graver on "The PADI Dive Tables" and Jon Hardy on "Decompression Meters".

The entire seminar was geared to be presented in terms that would be easily understandable to divers and Instructors alike. Complex theories were explained in simple terms and panel sessions were conducted to permit audience interaction. This was an excellent opportunity for all to increase their understanding of many complicated and misunderstood concepts. Question and answer periods were extremely well received and enjoyed by all.

Overall, the program was a terrific success for both the participants and for PADI. Much valuable information was gained and many new insights were made concerning decompression. Evaluation Questionnaires from attendees showed overwhelming pleasure with the entire program and the way in which it was conducted.

THEORY OF AIR DECOMPRESSION FOR SCUBA INSTRUCTORS

By Bruce E. Bassett

INTRODUCTION

It has been noted that in all levels of sport SCUBA training, instruction covering the use of the Air Decompression Tables gives rise to many questions which cannot be answered from the information generally available to SCUBA Instructors. As a result of this lack of available information, many misconceptions regarding "built-in bends incidence", additional "safety factors", non-standard dive profiles, use of decompression meters, flying after diving, diving at altitude, and repetitive dive procedures have developed.

This presentation outlines the history of the development of safe approaches to decompression based on the findings of the English physiologist, J. S. Haldane, and discusses the subsequent development of the U.S. Navy Standard Air Decompression Tables. Application of these tables to sport SCUBA diving, with emphasis on the theoretical effects of modifications to standard procedures and other problems peculiar to sport diving will be stressed. The goal then is to provide more background information on decompression theory to the SCUBA Instructor.

N_2 UPTAKE AND ELIMINATION

Haldane reasoned that if N_2 uptake and elimination could be calculated for exposures shorter than saturation, decompression schedules could be constructed so as not to exceed this critical ratio in any given tissue.

However, calculation of N_2 uptake and elimination is complicated by at least three variables:

1. **Pressure Gradient**
   As a tissue becomes saturated or desaturated, the pressure difference between the nitrogen pressure in tissues, blood, and lungs decreases. As the difference (gradient) decreases, the *rate* of uptake or elimination decreases.
2. **Fat**
   Nitrogen is five times more soluable in fat than in water. Thus tissues with a large proportion of fat will hold more nitrogen, like a reservoir, and, consequently, will take longer to fill or empty – that is, saturate or desaturate than a tissue with less fat. The proportion of fat in various tissues varies tremendously; hence, nitrogen uptake and elimination rates vary between different tissues.
3. **Blood Flow**
   The rate of blood flow, and thus the rate of nitrogen delivery or removal, also varies greatly between different body organs.

Summary of Factors

Considering just these three factors, and there are probably others, make the possible calculation of nitrogen uptake and elimination by the total body or any region very complex, if not impossible. Yet, such calculations must be made if the critical supersaturation ratio is not to be exceeded for any tissue upon decompression.

THE MATHEMATICAL MODEL

Based on saturation times for experimental goats, extrapolated to man, Haldane developed a mathematical model based on various theoretical "half time tissues". The range of "half times" he considered were from 5 minutes to 75 minutes. The rapid tissue considered was 50% saturated or desaturated in 5 minutes – and almost 99% in six times five or 30 minutes.

The slowest tissue attained 50% equilibrium in 75 minutes – and almost 99% in 450 minutes (or 7½ hours).

CALCULATION OF TABLES

Calculating the tissue N_2 tension on a given depth and time for the five theoretical tissues then allowed calculation of pressue reductions which would not exceed the critical 1.58/1 supersaturation ratio for any of these tissues. The selection of half times was presumed to be representative of all the various possible different tissue rates. These calculated decompressions were designed to fit the convenient stage or stepwise approach.

Based on this theory and model then, the depth of the first stop, or the maximum time of exposure before a stop is required, was always based on the tissue which attains the greatest N_2 pressure. According to the Haldane approach, this was always the fastest tissue, that is, the one with the shortest half times.

With these concepts, Haldane constructed schedules and tested them with divers. Within the limits of technology at that time and the depth/time limits for his schedules, the Haldane tables proved to be effective in preventing bends. They also gave a much better balance between useable bottom time and decompression time compared to the slow linear procedures in use prior to his studies.

U.S. NAVY AND THE HALDANE THEORY

Using the Haldane approach, but over a wider range of depths and exposure times, two modifications to Haldane's observations were found and used by the U.S. Navy.[2]

1. **Half Times**
   The U.S. Navy found that even slower half times had to be considered, beyond Haldane's 75 minute half-time tissue. The present standard air tables were calculated using half-times of 5, 10, 20, 40, 80, and 120 minutes.
2. **Supersaturation Ratios**
   These later U.S. Navy studies also indicated that the 1.58/1 Haldane ratio did not apply to all half-time tissues. The allowable ratio was found to be greater for the more rapid tissues. Only the slower tissues agreed with Haldane's ratio, which makes sense since his ratio was based on *saturation* exposures, that is, exposures which saturated the slowest tissue.

BUILDING THE NAVY TABLES

In summary, then, the U.S. Navy constructed their original tables based on Haldane's concepts, except they covered slower tissues and different ratios for different tissues. The ratios are referred to as "M" values in the U.S. Navy and were determined by testing calculated dives.

The procedure then was basically to calculate decompression schedules, and test them under as realisitic conditions as possible, with real divers at the Navy's Experimental Diving Unit. Essentially, a zero bends incidence was the target. Therefore, if a bend occurred, the schedule was recalculated. In this way, the different half-times and M-values were determined. After retesting the tables, they were then used by the diving Navy. With this larger number of divers, exposed to a wider variety of environmental, individual and stress factors, a zero bends incidence was not attained. Thus, the tables were recalculated, retested and published in 1959. These are the tables we call the "Standard Tables".

Bends Incidence

The total number of cases of bends encountered in U.S. Navy divers has been reported since at least 1945. However, up until 1970, the total number of dives made had not been reported, thus the incidence (number of bends/number of dives) using U.S. Navy tables was unknown. The lack of this statistic gave rise to all sort of "guestimates" regarding *built-in-bends incidence* in the tables. This has undoubtedly led to distrust, fear or disregard of the tables, plus arbitrary "safety factors" being promoted.

Let's set the record straight. In 1970 the U.S. Navy adopted a reporting system for both the number of cases *AND* the number of dives, which now gives a clearer picture of the tables' effectiveness in the prevention of bends.

For the period 1 July 1970 to 30 June 1971 in dives made by qualified divers under U.S. Naval supervision, the overall accident rate was 30 out of 30,039 dives. Twenty-five of these accidents were decompression sickness cases.

The statistics of most concern to you involve air exposures only, which involved 26,035 dives with twelve accidents, or 0.046% incidence. The incidence is less than this for open circuit SCUBA, and slightly higher for surface supplied dives, both lightweight and deep sea.

Expressed as a risk factor, total experience was 1 per 2, 173 exposures, and SCUBA gave 1 per 2,857 exposures. This may or may not be an "acceptable" risk depending on your point of view. It seems quite reasonable, however, compared to the wild "guestimates" of 10 to 10% that have been cited in various diving circles and publications.

In the 24 months from January 1972 through December 1973 there were 127,103 U.S. Navy dives made, accounting for 4,280 man-days under water. There were 35 cases of decompression sickness for an overall incidence of about 0.03%. The depth range from 100 to 200 feet, which represented 12%

of all dives made, involved 57% of the cases of decompression sickenss. Only 4,302 dives/year involved decompression dives and gave an incidence of 0.41%[3]. Based on these very low bend's incidence figures it is doubtful that we will see any revision in the standard air decompression tables in the near future.

DO THE TABLES REALLY APPLY TO SPORT DIVERS???

The answer can be yes, no, or maybe.

YES, if the same restriction and strict adherence to the rules and procedures contained in the U.S. Navy Diving Manual are followed *AND* you are within the range of age, height, weight, sex and physical fitness as the average U.S. Navy diver.

MAYBE, if you follow the rules but the individual factors (age, sex, etc.) are not within the limits.

NO, if you use the tables in ways they were not intended to be used, or if you ignore them, modify them without regard to their design, or if you extrapolate them to cover non-standard conditions.

ACCEPTABLE MODIFICATIONS

1. When working with the tables you can always safely use a greater than actual bottom time, greater than actual depth, higher repetitive group, and greater residual nitrogen time for calculating decompression. Time and Air are cheaper than bones and nervous tissue.
2. You can safely ascend to the surface on no-decompression dives at a slower rate than 60 feet per minute, if you include the ascent time as part of the bottom time, i.e., subtract it from allowable bottom time for a given schedule.
3. Rearranging the tables like the NU-WAY, Reuter or similar changes to simplify their use is safe.

DOUBTFUL MODIFICATIONS

Safety stops added to no-decompression dives or adding stops to scheduled stops, can under some circumstances, lead to difficulties in repetitive diving. The factor altered, related to the theory discussed, is the pressure gradient for elimination. The best procedure to add safety factors is to use a greater depth, bottom time, etc., and base the repetitive dive calculations on the *schedule used*.

PROBLEM AREAS RELATED TO THEORY

Multilevel Dives

Extrapolation of tables to cover multilevel dives is difficult to impossible. The only acceptable, although very conservative, approach is to consider the maximum depth for the total bottom time. Calculating exact tissue nitrogen tensions on multilevel dives can be performed, but not for the infinite number of combinations, and not during the dive itself.

Decompression Devices

Devices designed to solve the problems of multilevel diving and repetitive diving for the sport diver in principle would be the diver's ultimate safety device.

In my opinion, the ultimate device in terms of safety is not yet available. Technologically it should be possible to build a device which would give the same results as using the tables.

Two devices have been on the market, one for over 10 years and one only in the past few years. The older Decompression Meter will not provide the diver the same margin of safety as the standard air tables. Red Howard at Scripps Institution of Oceanography has performed extensive testing on this device and all divers who continue to use it should read his reports[4]. In terms of the theoretical basis for the decompression tables, relying on the meter will cause the critical supersaturation ratios for various half-times to be exceeded by a significant amount on deeper no-decompression dives and on repetitive dives and will omit the deeper stops on decompression dives.

The more recent device, the Decomputer, which has been recalled by the manufacturer, apparently for quality control problems, seems to be based on sounder theoretical grounds which should allow it to give readings closer to the tables for both single and repetitive dives. The device, in my opinion, is misnamed. It should be called a No-Decompression Limit Indicator for it was designed to function as just that. If it would perform that function and the limits would match those of the U.S. Navy Tables, sport divers would have the device they have needed for years. However, sport divers should *DEMAND* that *ANY* safety device of this type be tested by independent laboratories for function and quality control with test reports made public *BEFORE* such devices reach the market.

As stated previously, technologically a safe, reliable, device which would give reproducible results and which would give the same limits for single and repetitive no-decompression dives as the U.S. Navy tables, should be available. Divers should demand this, and no less, from equipment manufacturers. On the other hand, divers should not expect to attain such a critical piece of equipment at "dime-store" prices. What is the price tag of a spinal cord? Divers should expect such devices to be in the price range of any of their other life support/safety equipment – not in the range of nice-to-have accessories.

DIVING AT ALTITUDE

Diving at altitude presents problems with M-values, i.e., supersaturation ratios, since the absolute pressure at the surface and at any given depth is less than at sea level. While the P_{N_2} level reached at equal depth is less on a given exposure, ascent on the standard tables may exceed the critical ratio since the denominator is reduced.

The November 1970 issue of *Skin Diver* and the NAUI publication "Altitude Procedures for the Ocean Diver" contains tables and instructions for diving at altitudes up to 10,000 feet. My own calculations, sampling without referring to the table, verified that these tables do follow the same criteria as the standard tables and should provide the same degree of safety. I recommend these to any of you involved in altitude diving. However, while these tables appear to be conservative and safe, they have not been subjected to the rigorous manned validation tests required of decompression tables.

FLYING AFTER DIVING

Flying after diving is similar to diving at altitude. The limiting factor is the critical ratio, since the total pressure, the demoninator in the ratio, is reduced at altitude. Remember, excess supersaturation is the primary requirement for bubble formation.

Extensive tables could, but have not yet been, constructed to cover various dives, surface intervals and exposure altitudes. However, one study has been done which I feel is valid in terms of calculation, methods of testing and conclusions. Dr. Ed Beckman and Pete Edel working with J&J Divers in Pasadena, Texas, determined the safe interval between diving and flying in pressurized commercial aircraft, i.e., a maximum cabin altitude of 5,000 to 8,000 feet[5]. Their recommendations are as follows:

1. If you stay within the no-decompression limits of the tables (not the meter) for a 12-hour period, you can fly under the conditions specified after a minimum surface interval of 2 hours.
2. If decompression dives are performed, or should have been performed, in the 12-hour period, the surface interval must be 24 hours.

SUMMARY

I have discussed, with the intent of providing you more background to use in your teaching, the history of the developments of decompression procedures.

I hope I have dispelled some misconceptions and perhaps given you some further confidence in the tables. They may not be the ultimate, but statistically they are extremely safe, if followed rigorously.

Finally, I have discussed some of the problems areas we face as sport divers related to decompression, and hopefully, gave you some solutions and recommendations.

REFERENCES

[1] Boycott, A.E., Damant, G.C.C., and Haldane, J.S., *"The Prevention of Compressed-Air Illness."* J Hyg (Lond) (1908) 8:342-444.

[2] Workman, R.D. *"Calculation of Decompression Schedules for Nitrogen Oxygen and Hilium-Oxygen Dives."* Res Rept 6-65, U.S. Navy Experimental Diving Unit, Washington, D.C. (1965).

[3] Berghage, T.E., Rohrbaugh, P.A., Bachrach, A.J. and Armstrong, F.W., *"Navy Diving Summary Statistics"*, Proceedings of the Working Diver, 1976 Symposium, pages 285-303, 1976.

[4] Howard, R. and Schmitt, K. *"The Decompression Meter – Another Look"*, Proceedings of the 6th International Conference on Underwater Education, 1974.

[5] Edel, P.O., Carroll, J.J., Honaker, R.W., and Beckman, E.L. *"Interval at Sea Level Pressure Required to Prevent Decompression Sickness in Humans Who Fly in Commercial Aircraft After Diving."* Aerospace Med 40:1105-1110, 1969; U.S. Navy Med 57-13-19, 1971.

THE ULTIMATE DIVE TABLE CONFIGURATION

By Dennis Graver, Director of Training

At last there are dive tables designed for use by the recreational diver. PADI's new Dive Tables are intended to provide solutions to common problems with decompression tables, such as:

1. The table not being used for dive planning.
2. Confusion about adding and subtracting Residual Nitrogen Time.
3. Determining the Residual Nitrogen Time for repetitive dives shallower than 40 feet.
4. Figuring the minimum surface interval to make a no-decompression dive.

The new tables are extremely simple to learn, containing only the information needed for sport diving.

The design concept for the tables was simplicity. There are three tables, each leading to the next. Following is how the PADI Dive Tables are arranged.

Parts of the United States Navy No Decompression Limits and Repetitive Group Designation Table and the Standard Air Decompression Table have been combined and rearranged to form Table One of the PADI Dive Tables. Recreational dives are to be no-decompression dives and limited to depths of 130 feet or less. Table One is designed to keep divers within these limits by not providing information for dives to excessive depths and by emphasizing the no-decompression limits for each depth. In the event that a limit should inadvertently be exceeded, emergency decompression information is provided in a unique way. The length of time required at the ten-foot decompression stop is indicated in conjunction with the total Bottom Time for a dive. This integration of the Standard Decompression Table simplifies learning of the dive tables, because one table is eliminated and the same method of referring to Bottom Time is used for both no-decompression and emergency decompression situations.

The standard Navy Surface Interval Credit Table has been rearranged to form Table Two of the PADI Dive Tables. The requirement for a Group D designation when flying after a no-decompression dive has been included and is marked to call attention to the procedure.

Table Three of the PADI tables is adopted from the U.S. Navy Residual Nitrogen Time Table for Repetitive Air Dives and from the No-Decompression Limits and Repetitive Group Designation Table. The Residual Nitrogen Times are subtracted from the maximum no-decompression limits for a given depth, and adjusted no-decompression limits are shown below the Residual Nitrogen Time for each group designation at that depth. This simplifies the mathematics for repetitive dives as you will soon see.

Many divers have been taught to use the 40 foot depth to figure the Residual Nitrogen Time for a repetitive dive of *less than* 40 feet. In some instances, they are taught to use the 40 foot Residual Nitrogen Time and the exact or next greater depth actually dived. Another method commonly taught is to use the 40 foot Residual Nitrogen Time and the 40 foot depth on the No-Decompression Table, regardless of the actual depth of the shallow dive. There are problems associated with both methods, and neither is desirable. The preferred method is to obtain the Residual Nitrogen Time from the No-Decompression Table, add the actual Bottom Time to it, and use the actual depth of the dive. For example, a Group D diver going to 20 feet for 30 minutes would have an equivalent Residual Nitrogen Time of 100 minutes (see Table One or the USN No-Decompression Limits Table) plus an actual Bottom Time of 30 minutes for a total Bottom Time of 130 minutes at 20 feet, which would put the diver in Group E at the end of the dive. Figured using the previously described methods, the diver would incorrectly be designated as a Group D or Group G diver. PADI Dive Table Three has simplified the procedure by including the shallow depth Residual Nitrogen Times from the No-Decompression Limits Table, so only one procedure needs to be learned for repetitive dive calculations.

The New PADI Dive Tables are designed to be used in a continuous sequence, starting with Table One, going to Table Two, then to Table Three, and returning to Table One. The tables are printed on both sides, with each table leading to the next, so a person using them keeps turning the card over while following through the tables. A common problem for a person learning the dive tables is to become confused as to the next step after the Residual Nitrogen Time Table, but this is not the case with the PADI tables, which lead the user back to Table One. Using PADI's new tables is as simple as one, two, three.

Some typical table problems which usually require math are handled simply and effectively in the PADI tables with nothing more than simple addition. Both the planning of a no-decompression repetitive dive and the minimum surface interval for a no-decompression dive can be dealt with simply, quickly, and without math as follows.

To plan a no-decompression repetitive dive, simply refer to Table Three and the planned depth for your repetitive group designation; e.g., a Group G diver planning a dive to 50 feet. The actual Bottom Time of the dive is not to exceed the adjusted no-decompression limit shown in white numbers – in this case 44 minutes. A person desiring to dive longer than the limit specified has the options of planning the dive to a shallower depth or extending the surface interval to reduce Residual Nitrogen Time and increase the adjusted no-decompression limit. There is no math necessary.

To plan the minimum surface interval for a no-decompression dive, a diver plans the length of time desired for a dive to a planned depth and consults Table Three to determine which group at the planned depth will permit the dive to be made. As an example, suppose the Group G diver from the previous paragraph wanted to make a 20 to 30 minute dive to a depth of 70 feet. Referring to 70 feet on Table Three, we find that to have an adjusted no-decompression limit of at least 30 minutes, the diver would need to be in Group D. To determine how long it will take a Group G diver to attain a Group D designation, simply refer to Table Two and note the time, which is a minimum of two hours for this situation. Again, there is no math involved. In fact, the only math required for the use of the PADI tables is to add the actual Bottom Time to the Residual Nitrogen Time for determining the total Bottom Time for a dive. This is clearly indicated next to Table Three as a reminder.

Learning to use the decompression tables is easy with PADI's new tables, and students will retain the ability to use the tables much longer than when learning with other popular table configurations. The new tables are integrated into PADI's new scuba course. Support materials to aid in teaching the tables include a textbook, tables, study guide, quizzes, exams, tables, wall chart, and an Instructor's guide. The PADI tables, printed on plastic for use in diving activities during and after training, are included as part of the new PADI textbook. The student is introduced to the tables in text, work self study problems in the study guide, is taught further by the Instructor in the classroom, and evaluated with a quiz. This is followed by additional study guide work, another classroom session on the tables, and an exam. The tables are also used on training dives to develop proper habit during actual diving operations. This repetition in learning the tables increases the retention of knowledge in their use. By providing students with tables which can be used after training, divers will be more likely to have and consult the tables when diving.

The PADI Dive Tables, printed in three colors on durable waterproof material, are available from PADI Headquarters. The tables are four inches by eight and one-half inches and contain a small hole so they may be attached to an object to prevent loss. The tables are $4.95 when purchased separately, but are included at no extra cost when the new textbook (*PADI Diving Manual*) is purchased. Buy both and save. A two color wall chart is available for teaching the use of the PADI tables. The chart is 25 inches by 26 inches and priced at $5.95. The study guide, quizzes, exams, and Instructor guide for the new PADI scuba course are also available from PADI Headquarters. For additional information on the tables and other support materials for the new PADI course, request information from PADI, 2064 North Bush Street, Santa Ana, California 92706.

PADI's new Dive Tables are simplified, easy to use, and designed for sport divers. Order yours today.

USING THE U.S. NAVY DIVE TABLES FOR SPORT DIVING

By Dennis Graver, Director of Training

The various rearrangement of the U.S. Navy Tables for use by sport divers indicate problems associated with the use of the standard tables. Additionally, even the Navy tables and their accompanying instructions do not deal with situations commonly encountered by sport divers, such as repetitive dives to less than 40 feet, and varying depths during a dive.

In learning to use the tables more effectively for typical recreational diving, it is advisable to assure a firm foundation of knowledge on which to build some new concepts. Let's review the general use of the dive tables, learn an easy worksheet method to keep track of our dives, then dig into some sophisticated uses of the tables to make sport diving safer and more enjoyable.

Just to make sure we communicate, here are definitions and abbreviations of terms to be used in this chapter:

Bottom Time (BT): Elapsed time from beginning of descent until beginning of ascent.

No-Decompression Limits (NDL): The maximum time a diver can remain at a given depth and ascent directly to the surface without decompression being required.

Surface Interval (SI): Elapsed time between surfacing from a previous dive and the time of descent on the next dive.

Residual Nitrogen Time (RNT): Time in minutes a diver must consider already spent on the bottom when starting a repetitive dive.

Total Bottom Time (TBT): The sum of RNT and actual BT. This total must be used to determine a Repetitive Group Designation following all repetitive dives.

Now let's review the use of the standard tables to refresh your memory. Two divers want to make three dives to 70 feet in a single day. Their Bottom Time for the first dive is 30m (minutes).

1. What is their Repetitive Group after the first dive?
2. What is their Residual Nitrogen Time after a Surface Interval of one hour?
3. After a one hour Surface Interval, what is the maximum Bottom Time they can have at 70 feet without decompression?
4. What would the minimum Surface Interval be after the first dive which would allow the divers to spend at least 25m at 70 feet without decompression?

One hour after surfacing from the first dive, the diver descends again to 70 feet for 20m.

5. What is their Repetitive Group after the second dive?
6. In this Repetitive Group, what is the maximum Bottom Time for a third dive to 70 feet without decompression?

7. If the divers wanted to spend at least 20m at 70 feet without decompression on a third dive, what would their minimum Surface Interval have to be?

After waiting the minimum Surface Interval to permit a 20m no-decompression dive to 70 feet, the divers make a third dive to 70 feet for 18m.

8. What is their Repetitive Group designation after the third dive?
9. What would their Repetitive Group be if their Bottom Time had been 25m?
10. What would their Repetitive Group be if they had reached a depth of 75 feet on the third dive?

Answers

1. Group F
2. Group E
3. 24m
4. One hour, 30m
5. Group J
6. None
7. Two hours, 21m
8. Group I
9. Group K (after decompression)
10. Group K (after decompression)

How did you do? If you scored poorly, you need to review the fundamentals of the tables before proceeding. If you scored over 50%, however, polish your skills by solving this problem:

A dive to 60 feet for 30m is followed 50m later by another dive to 60 feet.

1. What is the maximum Bottom Time without decompression for the second dive?
2. With a Bottom Time of 21m on the second dive, what is the minimum Surface Interval required to allow another 20m dive to 60 feet without decompression.

Answers

1. 30m
2. One hour, 30m

If you can solve problems of this type correctly, you have a good understanding of the decompression tables and are ready for some advanced concepts.

THE "T" SYSTEM

Let me share a method for diagramming dives and keeping track of dive information that works very well in the actual diving situation. Work sheets are fine when available and the person using them is dry. But you need a system you can scratch out on a slate or piece of scrap paper when you're soaking wet. Here's a system developed by Jim Williams, a good friend of mine from San Diego. He calls it the "T-system", and I've modified it slightly A diagram of our first dive problem using the "T-system" would look like this:

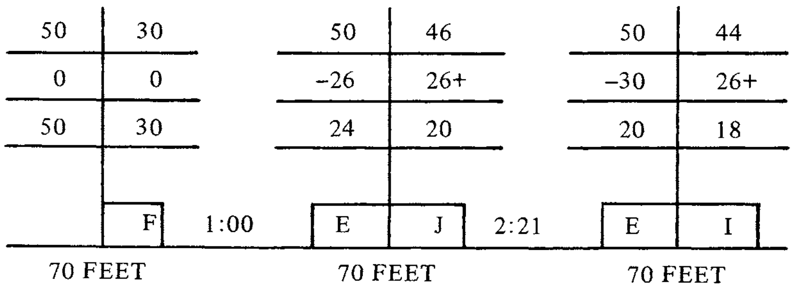


Figure A

The system works essentially as follows: On the left hand lines you work from top to bottom and subtract RNT (middle number); while on the right hand lines you work from bottom to top and add the RNT (middle number.) This provides an organized method to plan the dive to avoid decompression, and to determine the Total Bottom Time for the dive. Here's an explanation of each line:

The NDL for the depth is entered on the top left hand line for the dive. The RNT (if any) is placed on the line below and subtracted from the NDL to obtain the maximum allowable actual BT without decompression (the bottom left hand line). The actual BT is entered on the right hand bottom line, and the RNT (if any) is entered on the line above. These two figures are added together to obtain the TBT for the dive, which is entered on the top right hand line. The actual BT on the bottom right must not exceed the allowable BT figured on the bottom left, or the dive will require decompression. Entries for depth, Repetitive Group, and Surface Interval are obvious. This is a simple, easy method to keep track of diving activity.

Now you diagram the second review problem using the modified "T-system" and compare it with the following example:

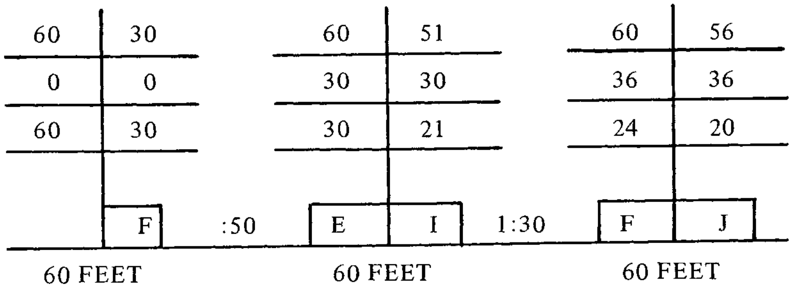


Figure B

SHALLOW DIVE TABLE TECHNIQUES

Using the "T-system", let me show you a disparity in the way the Navy tables are commonly used. The situation will be a dive to 70 feet for 30m, followed 10m later by a dive to 25 feet for 30m. Two solutions are presented – A and B.

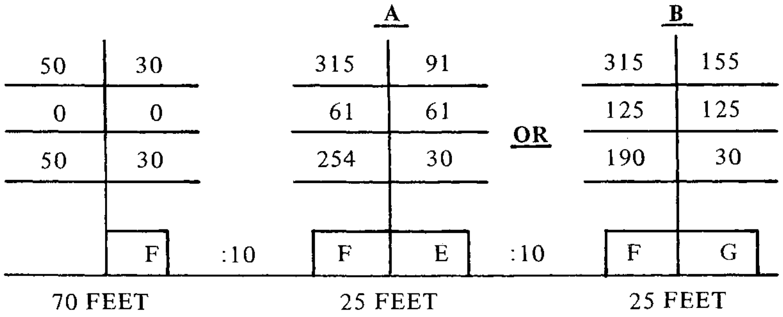


Figure C

Solution A is the method commonly used. The RNT for a Group F diver going to 25 feet is obtained from the Repetitive Dive Timetable 40 foot depth. This time is then added to the actual BT of 30m to obtain a Total BT of 91m, which classifies the diver in Group E. BUT . . .The diver attained Group E only 40m after surfacing from the first dive (and 30m of that time was spent underwater) when it would have taken 46m to attain Group E if the diver has remained at the surface after the first dive! This is not correct, as the diver should actually be taking on more nitrogen on the second dive, not getting rid of it.

Solution B shows the correct method to deal with the situation. Obtain the RNT for the 25 foot dive from the No-Decompression Limits and Group Designation Table. Ask yourself how long you would have to stay at 25 feet to be in Group F. The answer (125m) becomes your RNT, to which the BT (30m) is added. The TBT is, therefore, 155m, which puts you in Group G. That's more like it.

Now you work a similar problem for practice. A Group H diver makes a dive to 30 feet for 25m. What is the diver's Group designation following the dive?:

Answer

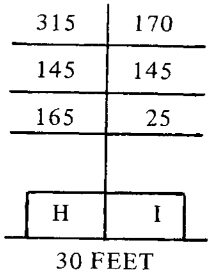


Figure D

MULTI-LEVEL PROCEDURE

OK. If you have followed the concepts thus far, you are ready for a more advanced one – using the Navy tables for multi-level diving. First let me explain the problem and the need for a multi-level procedure.

Sport divers typically dive at more than one depth during a dive, and if they follow the rule of the decompression tables of using the bottom time and the greatest depth attained to obtain a Group designation, are often severely penalized as if they had spent the entire dive at the greatest depth.

For example, a diver going to 100 feet for 10m and finishing the dive at 60 feet is faced with (a) limiting the TBT at 25m to avoid decompression, or (b) decompressing if more than 15m is spent at the 60 foot level, or (c) guessing that decompression will not be required since the dive was completed shallower than 100 feet. Additionally, what will the diver's Group designation be following the dive? Figure E shows a profile of the situation. Greater variances in depths or more levels of diving would further compound the problem.

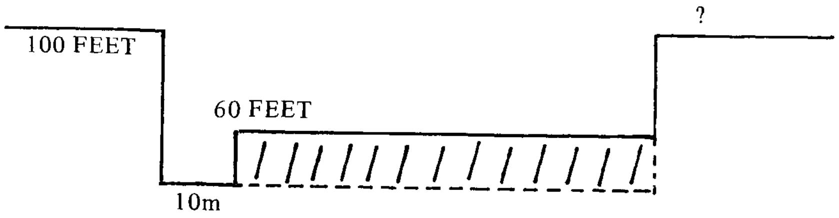


Figure E

The shaded area shows the penalty paid for multi-level diving following the stated procedures for using the tables.

The solution to this problem is to be charged for only the amount of time spent at a given depth. This can be done by determining the Group designation for the time spent at a depth, and only charging that amount of nitrogen uptake against ourselves. In the example (Figure E) we spent 10m at 100 feet, which would put us into Group D. The next step is to convert this into an equivalent amount of time spent at the new depth of 60 feet, and to then add any additional time at the new depth to this equivalent figure. To obtain Group D at 60 feet would require 20m BT, so when you reach 60 feet after 10m at 100 feet, your bottom time (equivalent) becomes 20m rather than 10m, and any additional BT at 60 feet is added to the 20m. It is simply finding an equivalent BT for that group at the new depth, and adding any additional BT to that figure.

Let's work a sample multi-level dive problem together: Here is the problem. The depths and times spent at each depth are indicated on the diagonal lines at the base of the "T-system". Two divers spent 15m at 100 feet, ascent to 50 feet for 25m, ascent to 30 feet for 5m, and then surface. What is the diver's Group designation following the dive?

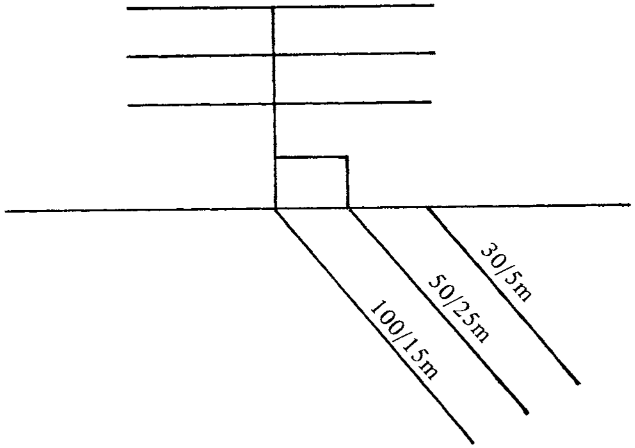


Figure F

Solution: 15m at 100 feet puts the divers into Group E. When the Group E divers ascend to 50 feet, it is equivalent to having spent 30m at 50 feet (see the No-Decompression Limits and Group Designation Table). After 25 additional minutes at 50 feet, for a TBT of 55m, the divers are in Group H. The divers now ascend to 30 feet, where the equivalent time required for a Group H designation is 145m. An additional 5m at 30 feet gives a TBT of 150m, so the divers surface as Group I divers . . . *with no decompression required.* (Note that if this diver were figured using the deepest depth and the total bottom time, (100 feet/50m), the divers would need to decompress for 2m at 20 feet, 24m at 10 feet, and would have a Group designation of L!).

This method of multi-level diving using the tables has been shown to be as safe as the tables themselves. You are not "pushing" the tables, or overextending your stay. You are only using the no-decompression limits in a way which is very practical for sport diving – a way of diving which is quite common.

There are a few rules for the use of the multi-level procedure, but these are quite simple and easy to remember.

1. The procedure is limited to no-decompression dives of 130 feet or less. (So what, as sport divers don't make decompression dives or dive below 130 feet)
2. The depths must become progressively shallower during the dive.
3. There are some situations approaching the limits of the tables (which you normally won't get close to) where the procedure is not valid. Thus, the following No-Decompression Limits are established for the multi-level procedure:

Depth (feet)	**Multi-Level Limits (minutes)**
40	170
50	70
60	55
70	45
80	30
90	25
100	20
110	15
120	15

An examination of the No-Decompression Limits table shows 91% of the table can still be used when using the multi-level procedure. All these limits mean is that if you are ascending to a new depth on a multi-level dive, your total bottom time at the new depth should not exceed the multi-level No-Decompression Limits.

Pretty neat procedure, isn't it? It allows you to safely increase bottom time on multi-level dives without having to decompress, and is really quite simple to use.

Now let me give you some tips on how to use the procedure in the actual diving situation. I've discovered you can use it easily with just a dive watch and some waterproof tables. Dive to the deepest planned depth first for the pre-detemined length of time (you need to plan your dives with your buddy, remember). As soon as you have ascended to the next level of your dive, note the Bottom Time, determine your Group designation for the deeper depth, figure your equivalent time to reach the same group at your new depth, and reset your watch bezel to indicate the equivalent time as the elapsed bottom time. For example, a diver spends 15m at 80 feet, then ascends to 40 feet.

Fifteen minutes at 80 feet puts the diver into Group D. The equivalent time at 40 feet to reach Group D is 30m, so the diver changes the watch setting from 15m to 30m. When the diver ascends at the end of the dive, the BT can then be read directly from the watch bezel.

Now you work a problem on multi-level diving to see if you understand the concept.

Two divers descend to 90 feet for 20m, then ascend to 60 feet for 20m before surfacing. What is their Group Designation following the dive?

The problem should be diagrammed like this:

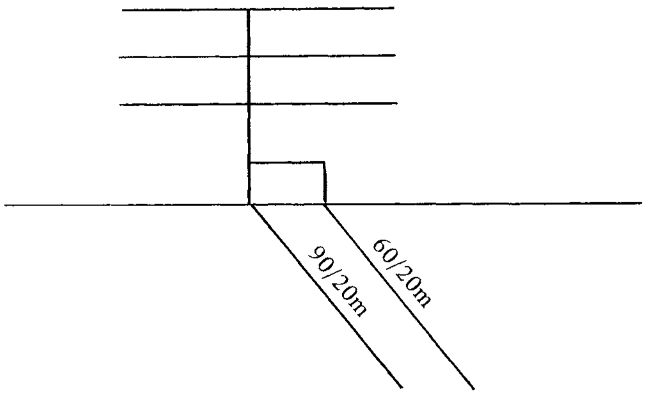


Figure G

Here's the answer: Ninety feet for 20m puts the divers in Group F, so when they ascend to 60 feet, the equivalent time to attain Group F at 60 feet is 30m. An additional 20m at 60 feet increases their BT to 50m, so their TBT is 50m at 60 feet, which puts them into Group H.

One last point on the multi-level procedure. I have used the technique numerous times with no problems, and know many other divers who have similar experience. The procedure has also been verified by computer and by renowned physiologists. For legal purposes, however, I am required to advise use of the procedure at your own risk. I am hopeful to soon be able to recommend it without reservation.

ALTITUDE CONCERNS

There is one other application of the dive tables of concern to sport divers – that of using the tables at altitude. Diving at altitudes above sea level is complicated and a specialty. Be trained for this activity prior to participation in it. If flying up to a cabin altitude of 8,000 feet (typical for most flights) after diving, remain at sea level for a length of time required to be classified as at least a Group D diver. Verify the maximum cabin altitude with the crew before flying, and inform them divers will be on board.

SUMMARY

I hope this chapter has helped you to review the use of the dive tables, learn a new method to diagram your repetitive dives, figure dives shallower than 40 feet properly, use the Navy tables for multi-level diving, and to know what to do when flying after diving. Be sure to avoid decompression at all times, and to use the dive tables conservatively.

THE DECOM METER – A USEFUL TOOL

By John Hardy

ABSTRACT

The decompression meter is a useful tool that has been excessively criticized by some in the diving community, without offering any viable alternatives. Coverage will include the fundamental problems of decompression, the partial solutions, the abuses of the meter, the proper use of the meter, and the future solutions to decompression for sport divers. Emphasis will be on an intelligent user's guide to the decom meter. Information will be based on accident reports, independent tests, manufacturer specifications and records, extensive field use and the current literature.

INTRODUCTION

1. Successful uses of the meter.
2. Number of meters manufactured.
3. Legal claims concerning the meter.
4. Other meters have been made and recalled.
5. Extremely expensive meters are available.
6. Several companies are working on meters.
7. Sport divers are constantly safely diving with decompression meters in spite of the irresponsible criticism by some scientists and instructors.

THE FUNDAMENTAL PROBLEM

1. Decompression is a complex, time/pressure relationship with many variables.
2. Henry's and Dalton's gas laws plus Haldane's principles apply only in an approximate way to the situation.
3. Human bodies vary greatly in their decompression needs and tolerance.
4. All solutions, be they decompression meters or tables have to be modified based on field experience.
5. It is extremely difficult to design and build an instrument that can handle the complex and variable decompression situation and still market it at an affordable price.

THE PARTIAL SOLUTIONS

1. Do not dive at all.
2. Only skin dive.
3. Only scuba dive to less than 33 feet.
   **These are not acceptable solutions for those who enjoy scuba diving.*
4. Use decompression tables.

5. Use the various simplified sport diving rearrangement of the tables.
6. Use the sport diving procedure of on any dive, start deep and end shallow to avoid decompression.
7. Use the mathematical modifications to the tables for altitude diving and flying after diving.
8. In addition, while using the tables, carefully use the accepted safety procedures, such as:
   - Make deep dive first, end the dive or the day's diving in less than 33 feet of water.
   - Make surface intervals as long as possible.
   - Make all possible dives as "no decompression" dives.
   - Pause at 10 feet before surfacing from dives.
   - Move one repetitive group letter back from the maximum "no decompression" time for your maximum "no decompression" time allowed.
   - Use the "cold and arduous" dive procedure of next greater depth and time for any condition that increases the likelihood of bends.
9. Use a decompression meter.

THE ADDITIONAL PROBLEMS

1. Sport divers do not understand the decompression tables, use the tables incorrectly or do not use the tables at all.
2. Sport divers are not accurate at recording diving or decompression depths and times.
3. Diving instruments such as depth gauges are sometimes not accurate, mainly due to user abuse.
4. Decompression tables were not intended for sport divers but for Navy divers.
5. Decompression tables were not intended for multi-level diving.
6. The decompression tables have no safety factor and when used correctly by Navy divers, have a bends rate of 0.3 to 1.5 percent.
7. The decompression tables are complex and difficult to use, particularly in the sport diving situation.
8. The sport diving "simplifications" to the tables are just rearrangements of the numbers and still require understanding and using the correct procedures. If decompression stops are required, these tables are either inadequate or even more difficult to use.
9. Mathematical modifications to the tables for altitude diving are virtually untested.
10. The sport diving procedure of starting the dive deep and ending the dive shallow still must be based on the use of decompression tables or a meter.
11. There are conditions which may increase the likelihood of bends, such as:
    - Age, usually over 40.
    - Obesity.
    - Fatigue.
    - Alcohol or drug use before or immediately after the dive.

- Old injuries which cause poor circulation.
- Poor physical condition.
- Illness.
- Heavy work during or immediately after the dive.
- Extremes of water temperature, particularly a cold dive or a hot shower immediately after the dive.
- Smoking immediately after the dive.
- Dehydration.
- Pregnancy.
- Restricting blood flow by having an arm or leg in a cramped position.

12. Sport divers regularly exceed the 60 foot per minute ascent rate.
13. Sport divers exceed the standard air decompression tables.
14. Sport divers not counting so called "bounce" dives in their decompression needs.
15. Decompression stops are often difficult for sport divers to accomplish.
16. The decompression meter does not follow the decompression tables exactly, but tends to be a smooth curve rather than the irregular steps that the tables are in.
17. The decompression meter is subject to quality variations due to materials and assembly plus later use.
18. Improper use of the decompression meter.
19. You can still get bent doing everything "correctly" with the decompression tables or the meter.

THE PROBLEMS AND SOLUTIONS

There are actually four areas of difficulty with the use of the meter. These are: Abuses, Incorrect Meter Procedures, Improper Decompression Procedures, and Unintended Uses of the Meter.

PROBLEMS	**SOLUTIONS**
Abuses	
1. Leaving meter out in the sun.	Put meter in a bag or in the shade.
2. Banging the meter around excessively.	Protect meter with carrying case and reasonable care while diving.
3. Meter used with no servicing.	Depending on use or abuse of the meter, it should be serviced at least annually or more often if some condition indicates, such as: meter does not return to the blue zone after 12 hours of non-use at sea level, if the needle does not move during dives, if the needle moves in an erratic way, if the meter is subject to hard banging, excessive heat, high altitude or the meter is significantly different than other meters or the tables.
4. Meter subjected to decreased pressure, as at altitude.	The meter should be protected by use of the pressure sealed carrying case.
5. Not washing the meter after dives.	The meter should be washed thoroughly with fresh water at normal temperature as soon after the dive as is practical.
Incorrect Meter Procedures	
6. Using a meter for extremely deep dives beyond 100 feet.	Use the meter normally for dives to less than 100 feet. Add a safety factor for dives between 100 feet and 130 feet by decompressing for 5 minutes at 10 feet. Use the tables beyond 130 feet. Do not dive beyond 190 feet.
7. Meter used without other instruments or gauges.	You still need to use a depth gauge with a a bottom timer or watch.
8. Meter used without decompression tables.	The meter is an easier to use adjunct to the tables, not a total substitute for the tables.
9. Meter not compared to other meters.	Whenever possible, several meters should be compared with each other. Any meter that varies significantly should be serviced. Decompression should be based on the most conservative meter that is not significantly different from the other meters.
10. Meter not compared to decompression tables.	Whenever a dive is made to only one depth, the meter can be easily compared to the tables. If the meter is significantly different from the tables, it should be serviced.
11. Using the meter for repetitive dives over six hours apart.	The meter has a memory of six hours and should be used for dives less than six hours apart. Dives over 12 hours apart are not repetitive dives and either the tables or the meter may be used.
12. Using the meter for repetitive dives requiring decompression stops.	The meter is best suited for the no decompression range or for one stop on the first dive. Sport divers should avoid decompression stops, particularly on repetitive dives.
13. Using the meter for bottom times in excess of two hours.	The meter is designed for use with bottom times of less than two hours. If bottom times are greater than two hours, either use the tables with the meter or make the dives over the two hour limit in shallow water of less than 40 feet.
14. Not using the supplemental decompression stop zones on the meter.	The first shorter zone applies for initial dives of 30 to 60 minutes. The second and longer zone provides for accumulative dive time of 60 to 120 minutes or any repetitive dive. These zones provide for an additional

	decompression stop. The needle is to move out of these zones before surfacing from the 10 foot stop. The normal 10 foot zone provides for dives of less than 30 minutes.
15. Not checking the meter during ascent.	As you ascend, nitrogen is still being taken up by your body (in-gassing). At some point due to reduced pressure, the process reverses itself and nitrogen starts coming out of solution (out-gassing). During the first part of the ascent, the meter may still be moving to indicate the continued ingasing. If you are close to the red decompression area, the needle may move into this area. From 50 to 20 feet, carefully check both your depth gauge and the meter, then pause at 10 feet and be sure the meter has moved out of the decompression zone which applies to your dive.
16. Using the same meter for two divers.	Due to variations in depth, bottom time, surface interval, number of dives, plus personal and environmental conditions, it is not a good procedure to have two divers use the same meter unless the divers perform the same dives and the diver with the meter is the one who always has the greater depth, greater bottom time, greater number of dives and shorter surface intervals. Even then it is far better to use the two meters. This also provides for comparison between the meters.

Improper Decompression Procedures

17. Using the meter in situations where some condition increases the likelihood of decompression sickness.	In these situations, either the tables or the meter should be modified for these conditions.
18. Ascending at greater than 60 feet per minute.	The vast majority of divers exceed the 60 foot per minute ascent rate. (Ascending at rates of 80 to 240 feet per minute). The correct ascent rate is very slow. The rate can be gauged by watching your depth gauge and watch while ascending. Take your time, go slowly and easily, using buoyancy control. Stay well behind small bubbles.
19. Using the meter for deep decompression stops at 30, 40 or 50 feet.	Dives being made of such a length and depth that require these stops are not sport dives. If done, they should be done on the decompression tables.

20. Not making the deep dive first.	It is important for all scuba diving to make the deep dive first. This aids in out-gassing on subsequent dives.

Unintended Uses of the Meter

21. Using the meter on working dives, such as scientific, military or commercial.	The meter was not intended for this type of use.
22. Using the meter at high altitude.	The meter was not designed for use at altitude. It should only be used at sea level.
23. Using the meter for mixed gas diving.	The meter was designed for compressed air diving only.

THE CURRENT SOLUTIONS

1. Properly use the U.S. Navy Decompression Tables with the currently accepted safety procedures (see the partial solutions.)
2. Provide a "margin of safety" if any condition exists that might increase the likelihood of bends (this is true for most sport divers).
   - With the decompression tables, use the next greater depth and time.
   - With the meter, do not surface until the needle pases the "E" of the word "SURFACE".
3. Properly use the decompression meter as it is intended to be used.
   - Most sport diving is done within the most useful range of the meter.
   - Dives less than 6 hours apart.
   - Total bottom time of less than two hours.
   - Depths of less than 100 feet.
   - At sea level, in salt water.
   - Using compressed air.
   - The best use of the decompression meter is within this most useful range for repetitive, multi-level, no decompression diving.

THE FUTURE SOLUTIONS

1. It seems simple enough – pressure and time compared to decompression table limits.
2. But there is only one successful meter.
3. Several companies are doing research and development on meters.
4. There needs to be consumer pressure and a market.
   - Products are only manufactured if they can be sold to fulfill a need.
   - More divers need to properly use the current meter and ask for something better.
   - You cannot get a better product by ridiculing and not using the current product.
   - Regulators are much better today because of the increased use of them.
5. Features of future decompression meters:
   - Really need two meters, one simple, less costly one for no-decompression diving, and one more complex one for limited

decompression diving and no decompression diving.

- May well need to stay with a needle so divers can visualize changes.
- Should have a way to allow for conditions that increase the likelihood of bends.
- Should be as simple, small and rugged as possible.
- Should handle multi-level repetitive diving with no problem.
- Should have an accurate 9-hour memory and be capable of 12-hours.
- Should be very accurate to 130 feet and function to 190 feet.
- Should be able to accurately handle 3 hours of diving time and be capable of 4 hours.
- May need to use warning indicators (red light or sound). If sound is used there should be an override or the sound should stop after a predetermined time.
- Only needs to have 10 and 20 foot decompression stops.
- Should make a smooth curve of the decompression tables, but on the no-decompression side, rather than on the decompression side.

CONCLUSION

1. A complex and difficult problem.
2. Decompression meter is a useful and practical safety tool.
3. More divers should be using the meter properly within it's designed range of operation for no decompression.
4. The diving public needs an even better decompression meter in the future.
5. It has become obvious with automobiles that is better to build the car to be as easy to use and as safe as possible rather than trying to turn the general public into excellent drivers. So it is with scuba diving and decompression. Equipment needs to be provided to make it safeer and easier while continuing efforts are made to train divers as well as possible, but realizing that the general public is not willing or able to become excellent divers any more thatn they will become excellent drivers.
6. You may still get bent, but the odds are way on your side if you properly use the meter and tables while providing yourself a "margin of safety".

THE PHYSIOLOGY OF DECOMPRESSION SICKNESS

By Charles V. Brown, M.D.

Decompression is reduction of ambient pressure, and decompression sickness is any ailment resulting thereby, except for some. We don't count reverse squeeze, lung over-pressure, or hypoxia of altitude. DS (Decompression sickness or bends) is essentially bubble trouble. Innumerable other factors enter in, but bubble formation is the primary event, and bubble behavior is the prime source of grief. Therefore, this paper is concerned mostly with how and where bubles form, how they make mischief, and how we get rid of them.

The answers seemed reasonably clear after the excellent work of Bert and Haldane many years ago. Bubbles formed because a 2:1 supersaturation ratio was exceeded. They distorted tissues and blocked blood vessels. They were banished by recompression. Experience has shown those answers overly simplistic. There are too many things they don't explain. Divers get hit while obeying Navy rules; others don't in spite of flagrant violations. Many divers with proven bubbles have no symptoms, while others are bent in the absence of detectable bubbles. Some serious DS cases recover without treatment; others do not, even if recompressed. Bends is more likely after two 40-minute dives three hours apart than after one 80-minute dive, in spite of out-gassing during the surface interval. Yet frequent diving confers partial immunity. It's plain that we're talking about a very complex disorder. Today, after thousands of studies by hundreds of investigators, we're more confused than ever, but we have learned a few things.

HOW BUBBLES FORM

First, you've got to have micronuclei, or so it seems. Put a glass of water into a chamber and run it to 20 atm's. If you then decompress it rapidly, it bubbles. But, if while still saturated at 20 atm the water is poured into a cylinder that has no air space, and is further compressed by a piston to 2,000 atm, when decompressed to the surface it won't bubble at all. We infer that water contains micro-bubbles that are normally stable, but can be dissolved by immense pressure. We call them gas micronuclei. Without them, water tolerates huge supersaturation stress without bubbling.

How do people get micronuclei? The stuff we drink is one source. Scientists say that cosmic rays from space, and radioactive decay of trace elements in our diets cause micro-explosions that make more. And statistical analysis of the random movement of dissolved gas molecules shows that frequently some of them come close enough together to crowd out other molecules and so find themselves out of solution. What stabilizes micronuclei is not known. Surface tension forces, huge at small diameters, would inhibit their growth, but would also tend to squeeze them back into solution. Maybe they escape surface tension by hiding in tiny tissue crevices. Or maybe they're really something other than micro-bubbles.

Anyway, real bubbles can form in the body in a number of ways even without reduction of ambient pressure. Pull a finger till the knuckle pops. The pop announces sudden gas in the joint, caused by the vacuum you made in pulling. Let go, and the gas goes away in 20 minutes.

Exercise generates cavitation forces along muscles and tendons that produce bubbles. And bubbles can form in the skin by a process known as counter-diffusion. If you breathe nitrogen while surrounded by Helium (as commercial divers often do), the two gases diffusing through the skin in opposite directions cause local super-saturation and bubbling – a common form of skin bends. A similar mechanism might help explain the high incidence of vestibular hits in deep diving. Theoretically, bubbles could form in tissue saturated with gas while cold, and then quickly warmed, because gas solubility falls as temperature rises. Strong sound waves can also cause bubbles.

Any or all of the above may contribute to DS, but there's no doubt that the most effective way to get a lot of bubbles in a hurry, short of boiling a diver, is to rapidly decompress him. How much supersaturation a diver will tolerate before bubbles form is not known. Haldane thought the total tension of dissolved gases would have to be more than double the ambient pressure before bubbles would form – hence his exhortation not to exceed a 2:1 supersaturation ratio during ascent, and his stipulation of 33 feet as the no-decompression limit. He was wrong. How do we know? Weighing a diver underwater before and after decompression shows that he gains buoyancy, implying a gas phase separation. Also, dives to 33 feet, or even less have on occasion produced DS. The connection is confirmed by Doppler monitors which, placed over the vena cava, sound off upon decompression.

Since Haldane, others have held that super-saturation tolerance is properly expressed not as a ratio, but as a pressure differential – so many feet sea water less than tissue gas tension. Both methods for building tables share a common fault – they really aim at defining how much super-saturation stress can be tolerated without producing symptoms, not bubbles. More recently, Brian Hills came up with the astounding notion that divers can count on little or no super-saturation tolerance. A glass of 7-up sitting still tolerates considerable super-saturation, but stir it and bubbles burst forth. A diver is more like 7-Up being stirred than sitting still. What he tolerates is not so much a specific super-saturation stress as a certain silent bubble load.

WHERE BUBBLES FORM

Where do bubbles form? Given really severe stress, the whole body would fizz. In the usual case though, we'd expect bubbling where nitrogen concentration and super-saturation are highest. Keep in mind that these two conditions don't necessarily go together. Concentration is the amount dissolved per unit volume, and for any given nitrogen tension, fat holds five times as much as water. Super-saturation is gas tension in excess of that obtained at saturation. For example, after about two hours at depth, blood would be saturated with nitrogen, and fat about half-saturated. Blood would have the higher nitrogen tension, but the same volume of fat would be holding more nitrogen. Both factors help determine bubbling. Upon ascent, because fat has poor circulation, it can't unload its nitrogen as fast as most other tissues, so before long it will have not only the most nitrogen, but the highest nitrogen tension too.

In practice, bubbles are commonly detected in veins and in fat. The electron microscope reveals bubbles in fat breaking through capillary walls to reach the blood, and some think that may be a main source of venous bubbles. Another source is lymph, which drains tissue fluid into veins. With increasing provocation, we'd expect bubbling in other tissues. Last to bubble would be arterial blood. It's fresh from the lungs, which swept out excess nitrogen, and it's at a higher hydrostatic pressure than obtained elsewhere in the body. This is fortunate, since bubbles in arteries are particularly dangerous.

HOW BUBBLES MAKE MISCHIEF

Bubbles do indeed distort and disrupt tissues and block blood vessels. But this doesn't necessarily hurt. If you place your hand into a little chamber that seals around the wrist, and pump the air out, your hand swells with bubbles, yet you feel no pain. To feel pain, you need pain nerves, and most tissues don't have them.

Painful DS is mostly limb bends. The site of the bubble in a limb bend has long been debated. Recently, bubbles have been seen in tendons. Maybe they arise from small fat inclusions, which tendons have. Other factors fit. Tendons have poor circulation, so they lose gas slowly. They have a structural pattern which a growing bubble would deform, and they have pain nerves to complain about it. Exercise, known to favor bends, creates a relative vacuum in a tendon by stretching it, and generates shear forces by sliding it; both favor bubbling. And finally, injecting saline into a tendon produces bends-like pain. Of course other tissues such as ligament, cartilage, and periosteum have not been ruled out as sites of limb bends pain.

Pain can also be a feature of serious DS. When the bubbles bother pain fibers in the spinal cord, pain is felt wherever the fibers originate – usually the lower limbs, and often the back and abdomen.

Bubbles can cause pain with or without doing much damage, and they can cause damage with or without pain. Bubbles in the spinal cord or a coronary artery cause both pain and damage. Bubbles in the inner ear can cause ringing noise, hearing loss, dizzyness, staggering, and nausea, all without pain. Bubbles in the brain can cause stroke symptoms – no pain. Bubbles blocking vessels in various large organs cause no pain. They don't even cause damage if collateral circulation is good enough that blood flow bypasses the block. If it doesn't, damage must result. Evidence for it is a feeling of great fatigue several hours after diving. A blood sample taken then will show elevation of enzymes released from damaged cells. In this latter case, healing seems to be prompt and complete, else a lot of us wouldn't be functional.

Finally, bubbles (or other emboli) in bone cortex may cause silent damage that erupts in painful disability months or years later. We're talking about aseptic bone necrosis, or as it is now termed, bysbaric osteonecrosis. When such areas of bone death occur near a major joint, and eventually the joint surface collapses into them, it's sudden crippling. Dysbaric osteonecrosis correlates poorly with limb bends, and not at all with serious DS. Nobody knows why. An intriguing hypothesis is that uranium ^{238}, which tends to concentrate near the ends of long bones, insures a plentiful supply of gas micronuclei to initiate bubble formation in those areas.

THE PULMONARY BUBBLE TRAP

Since ordinary dives produce bubbles capable of blocking blood vessels, why isn't DS far more common? Recall that most bubbles either arise in veins or are delivered to venous blood. Venous blood goes to the right heart, which pumps it through the lungs. A lung happens to be a superb bubble trap. Bubbles big enough to block vessels are filtered out, and remain stuck till their gas diffuses out to the alveoli.

Isn't this hard on the lungs? It appears that a diver won't notice symptoms until 25-60% of his pulmonary circulation is blocked, depending on how active he is, and on whose figures you read. Near the limit, there are warnings. Greek sponge divers learned that when a drag on a cigarette sets off a fit of coughing, it's time to pack in the day's diving and take an underwater decompression stop. Even a deep breath may provoke the coughing.

CHOKES

If the lung's capacity to trap and scrub bubbles is exceeded, a lot of bad things can happen – like the chokes, spinal hits, and arterial gas emboli. The chokes is a syndrome of pain, shortness of breath, and coughing. The lungs get water-logged and stiff – it's harder to breathe. Reflex or chemically induced bronchospasm further reduces air delivery. Alveoli without blood flow can't exchange gas, so oxygen uptake goes down. Yet these alveoli are still ventilated, so part of the work of breathing is wasted. All this blockage causes high resistance to flow of blood through the lungs. Back pressure builds up in the pulmonary artery, and the right ventricle must work harder to pump the blood it gets from the systemic circulation. When it can't maintain the pace, circulation slows and back pressure builds up in the systemic veins. Nitrogen delivery from tissues to lungs falls off, and this slows out-gassing and favors more bubbling. When the capillary beds feel the back pressure, there is a shift of water from blood to tissue, reducing the blood volume – a prelude to shock.

SPINAL HITS

Serious DS can occur well before the bubble load in the lungs is large enough to cause chokes. Spinal bends is a special case. It is often due to blockage of the veins that drain the spinal cord – the vertebral venous plexus. It is most apt to occur when circulation is slow, and it's aided by an anatomic peculiarity. Most veins have one way valves to prevent back flow. The veins of the azygous system, which drains the vertebral plexus, do not. If anything increases the pressue in the chest, like say a cough, or exhaling against airway obstruction, there could be a temporary back flow of blood through the azygous system pushing bubbles just emerged from the vertebral plexus back into it, where they hang up. Indeed, venous blockage isn't unique to the spinal cord. Studies of other tissues have shown bubbles first apparent in venules to grow back into capillaries. And spinal hits can also result from arterial emboli.

ARTERIAL EMBOLISM

Bubbles gain access to the arteries when allowed to by-pass the pulmonary trap, or when it is somehow released. An unborn baby has a hole in the wall between the upper heart chambers, so that blood can flow directly from the right to the left side, by-passing the nonfunctioning lungs. This opening (the foramen ovale) is supposed to close after birth, but doesn't always. Up to 50% of adults retain at least a pin-hole defect, and the vast majority don't know it. Normally it doesn't matter. But when lung circulation is blocked and back pressure in the right atrium builds up, a significant amount of blood and bubbles will take the short cut to the arterial side of the circulation.

Lungs themselves have shunts that by-pass their own capability beds. These seem to be closed most of the time, but they open as the bubble load increases. In one experiment, tiny beads of various sizes were injected intravenously. A few beads with diameters larger than lung capillaries always got through. What opens the shunts is uncertain – maybe increased pressure, hypoxia, elevated CO_2, or all three. Or conceivably, bubbles could rupture pulmonary arterioles and break directly into venules, to by-pass the trap.

Finally, a repetitive dive could spring the bubble trap by squeezing some of the bubbles down small enough to pass through. More nitrogen is taken aboard during the dive, and upon ascent, it diffuses into those pre-existing bubbles and enlarges them to more than original diameter. Any that happen to be in the arteries at the moment they become too big to transit the micro-circulation become arterial emboli. As mentioned before, the harm they cause depends upon where they happen to lodge. This helps explain the random incidence of DS for a given provocation – the fact that if you plot the incidence on a graph, you get the bell-shaped curve that reflects pure chance.

Since some bubbles do reach the arteries, the question arises why brain hits are so rare in DS, while so common in the air embolism of lung over-pressure accidents. There is disturbing news. Maybe carotid brain hits are not so rare. After lung tear, a lot of air enters the carotid artery all at once. DS bubbles are much smaller, but they keep coming. They would tend to block much tinier vessels in more scattered areas. It has been reported that very careful neurological examination of DS patients often does show evidence of subtle brain damage. It has also been casually observed that some commercial divers of long experience seem to undergo personality changes. Finally, autopsies of goats exposed to frequent decompression stress showed unequivocal brain damage. The pathologiest opined that one of the brains couldn't have been more than fifty per cent functional. Yet none of the goats had demonstrated abnormal behavior.

BIOCHEMICAL DISORDERS

So far, we've been looking at DS as a mechnical disorder – the gas laws in action. There's another side – biochemistry in action – and it's a whole new ball game. It's tempting to say that blood recognizes bubbles as foreign invaders and counter-attacks. That's probably nonsense, since the counter-attack does more harm than the bubbles would if left alone. More likely, bubbles trigger the damage control system for plugging up leaks in vessels, but at the wrong time and in the wrong places.

It all starts with blood globulins – large, complex, biologically potent molecules. These have one pole that attracts to water, and another that attracts to fat, and typically arrange themselves in groups with the fat loving poles inward. Bubbles change this. For reasons best known to biophysicists, the blood-bubble interface generates an electro-kinetic force that makes the molecules flip. They re-align with their fat loving poles at the interface. This somehow activiates them to do strange things. Nearby blood platelets become sticky. They adhere to bubbles and to each other, whereupon they too become activated. The result is the release or the induction of a witch's brew of highly bio-active substances with odd names like serotonin, bradykinin, kallikrein, histamin, SMAF, prostaglandins, etc. Then things really liven up.

The blood clotting mechanism is cranked up. Lipids split off of lipoproteins and coalesce into globules of fat. Capillary permeability is increased, and fluid leaks from blood into tissue spaces, decreasing blood volume. Arterioles constrict intensely, reducing and sometimes shutting off circulation to capillary beds. By the time waste accumulation and hypoxia make the arterioles relax, the capillaries have been damaged. Some of their lining cells peel off and are swept into the blood stream. Plasma leaks through the damaged capillaries into tissue spaces, so blood loses more volume, and becomes further concentrated. This increases it's viscosity, which slows circulation, favors more clotting, and makes red cells sludge together in clumps.

How far all this goes depends upon the bubble load. When the body's compensatory mechanisms are overwhelmed, the victim slides into shock. This is one reason why it's so important to get potentially serious DS into a chamber fast. Wait till the victim's in bad shape, and the results of recompression will be disappointing. You can't squeeze out the platelet masses, fibrin clots, fat globules, red cell clumps, and other cellular debris clogging up his circulation. He needs a lot of medical intervention – intravenous hydration, anticoagulants, etc.

In practice, of course, the mechanical and biochemical effects of bubbles interact. Bubbles might hang up where tiny arteries branch into two smaller ones because surface tension opposes deforming a sphere into two wieners. But why should bubbles hang up in small veins? Doubtless because they attract platelets, which become sticky.

PREDISPOSING FACTORS

Some things predispose to DS, and we may now ask how. The most important seems to be obesity, age, exertion, and illness. After a long dive, fat holds a lot of nitrogen which, because of poor circulation, it can't unload. So it bubbles. Also, overweight people tend to have elevated blood lipid levels, which favors the biochemical derangement in DS. Incidentally, fatty meals temporarily raise blood lipids and so favor DS.

Estimates of the importance of age vary, up to an 11% annual increase in bends liability for young men. All agree that the risk increases sharply at middle age and beyond. The simplest explanation is increase in body fat, and more important, in arteriosclerosis, which reduces circulatory efficiency.

Exercise during a dive speeds up circulation and, therefore, nitrogen uptake. It also generates lots of CO_2, which, because ventilation is impaired at depth, results in elevation of the CO_2 tension. We don't know why, but CO_2 seems quicker than nitrogen to promote early bubble growth. Once bubbles form, any excess CO_2 enlarges them faster. Upon ascent, exercise promotes bubbles by cavitation and shearing forces, and by generally shaking up the body.

A few years ago, aspirin got an underserved reputation for causing bends. The real culprit turned out to be the condition for which the diver had taken the aspirin. Though the mechanism is not understood, illness seems to predispose especially to serious DS. In this context, illness includes alcohol abuse and other conditions that lower metabolic efficiency. Dehydration predisposes at least in part because it's a head start to hemoconcentration. Divers shouldn't be thirsty.

DE-DISPOSING FACTORS

Caisson workers and people who dive a lot acquire partial immunity to bends. This is said to peak in two weeks at a level of 75% protection. We think it results from subclinical bubbling, since intravenous injections of air in animals also confers immunity. A favored explanation is that silent bubble showers from repeated decompressions consume micronuclei faster than they can be replaced. The curious fact that immunity for one depth does not extend to deeper depths is consistent, if we assume that some micronuclei are more stable than others and require more supersaturation stress before they will commence expansion. Consumption of blood clotting factors faster than replacement might further add to the protection. To avoid unpleasant surprises, it is most important for a diver to remember that immunity is lost in 2-3 weeks of not diving.

OUT-GASSING

We'll now address our final question. How do all these divers running around with silent bubbles ever get rid of them? Say for example, you've just completed a nice, legal dive – 50 minutes at 60 feet. You have silent bubbles. When all of your excess dissolved nitrogen has diffused either into the bubbles or into the alveoli, and equilibrium is reached, what's to keep those bubbles from becoming permanent guests? They're at ambient pressure, so why should any gas leave them? One reason is that a bubble is never really at ambient pressure. Surface tension and tissue elastic recoil exert at least a little compressive force upon it. Another and far more important reason is the inherent unsaturation of living tissue.

INHERENT UNSATURATION

Full equilibration between tissue and alveolar air cannot be reached, but rather a steady state in which tissue gas tension is less than ambient, and therefore, less than bubble gas tension. This is trickly to grasp, but it's very important. Here's how it goes. We say that by the laws of Henry and Dalton, dissolved gas tensions in the body are in equilibrium with gas tensions in alveolar air, which must add up to ambient pressure. But it's not quite true. Actually, only arterial blood equilibrates with alveolar air. When arterial blood gets into capillaries, oxygen is lost and CO_2 is picked up. Oxygen is poorly soluble in blood plasma, and the small amount dissolved is rapidly soaked up by the tissues, so oxygen tension drops way down. True, hemoglobin unloads more to meet tissue needs, but only at this low tension. Conversely, the CO_2 picked up is very soluble, and most of it is bound in chemical combinations anyway, so while oxygen tension drops a lot, CO_2 tension rises very little. Therefore, the sum of all dissolved gas tensions is lower in venous blood than in arterial blood. Since tissues in equilibrium with venous blood, their total gas tension is also less than ambient pressure, and therefore, less than gas tension in bubbles. Thus, a bubble is always supersaturated relative to the tissue it occupies, and the tissue is insaturated relative to the bubble. Bubble gas must slowly dissolve into tissue fluid until there is no more bubble.

The magnitude of inherent saturation has been measured in rabbits at the surface as 80-94 mm of mercury. At depth, breathing compressed air, arterial oxygen tension is very much greater, but venous oxygen tension is not. Inherent saturation, determined by the difference between them, becomes much greater. This has surprising implications for decompression practice. Take a commercial diver who has put in four hours at 150 feet wants up. Haldane would bring him up half way to achieve maximal tolerable supersaturation and thus, maximal out-gassing gradient. Hills says that's wrong. People don't tolerate much supersaturation, so you'll just produce a lot of bubbles. Once bubbles appear, excess dissolved nitrogen will diffuse into them. Gas tension in tissues and blood will drop toward ambient, and the out-gassing gradient in the lungs will become low. The diver must then wait until inherent unsaturation and slow alveolar diffusion remove a lot of gas from the bubbles before he can safely ascend to the next stop. The more shallow he gets, the smaller is the inherent unsaturation, so the stops have to be longer. What a drag!

The right way, by Hills, is the opposite. Start the ascent slowly, with much deeper stops, so any bubbles starting to form will be promptly banished by the high inherent unsaturation at those depths. This is greatly facilitiated if the bubbles are never permitted to grow, for with tiny bubbles, you get much more help from surface tension, and the surface to volume ratio is very great, permitting rapid re-solution of gas.

This approach has good experimental support, and is now being used in some commercial operations. The Navy tables are based on the Haldane model, but extensively modified through experience. Let us emphasize that as of now, they are the only one thoroughly tested and currently recommended for sport diving.

OXYGEN IN DS TREATMENT

Since inherent unsaturation results from oxygen metabolism, it is sometimes called the oxygen window for out-gassing. To open the window wider for faster safe ascents (in commercial diving) or for treatment of DS, you need simply replace all or part of the diver's air supply with oxygen. This trick further improves the out-gassing gradient for nitrogen because it lowers inspired nitrogen. Another advantage of oxygen for treatment is that at three atmospheres absolute, enough dissolves in plasma to supply basal tissue needs without help from red blood cells. At such high tensions, oxygen will diffuse through tissue fluid around blocked vessels enough to keep some of the deprived cells alive.

OTHER ASPECTS

We're done with bubbles, but before we are done with DS, we must at least consider the possibility that other factors associated with decompression may play a role. Notable is osmotic pressure – the tendency of water to flow (along its own concentration gradient) from areas where the concentration of dissolved materials is low to where it is high. During ascent, fast tissues lose gas more rapidly than slow tissues, and the resulting osmotic gradients would tend to pull water from the fast into the slow tissues. A special case is blood, which is thought to equilibrate with tissues by the time it traverses capillaries. In the arterial portion of the capillary, up to where equilibrium is reached, blood would lose water to the tissue. As we've seen, hemoconcentration favors DS.

Osmotic gradients created by the *descent* phase of the dive could also be significant. Dissolved gas in working muscle and in bone marrow would rise much faster than in the adjacent bone cortex, tending to dehydrate it. Hemoconcentration in the cortex capillaries would favor red cell sludging and blood clotting, and thus osteonecrosis. If this is significant, as animal studies suggest it may be, dysbaric osteonecrosis becomes, to the extent, *compression* sickness.

AND YET ANOTHER APPROACH TO THE PROBLEMS OF ALTITUDE DIVING AND FLYING AFTER DIVING!

By Bruce E. Bassett, Ph.D.

SUPERSATURATION AND HALF-TIMES

Calculation of decompression schedules for diving at sea level is based on a mathematical model originally used by the English physiologist J. S. Haldane[1]. His original observation, using experimental animals (goats) which had been saturated at chamber depths up to 165 feet of sea water (fsw), was that the animals were not "bent" if the subsequent decompression resulted in no greater than a halving of the total pressure. Thus, animals saturated at 6 atmospheres absolute (ATA) could be immediately decompressed to 3 ATA (66 fsw), from 2 ATA (33 fsw) to 1 ATA (sea level) and so forth. In all cases, the *critical supersaturation ratio* was found to be 1.58 to 1. When translated, the *critical supersaturation ratio* means the body tissues and fluids could apparently tolerate 1.58 times as much nitrogen pressure within them than the total barometric/hydrostatic pressure on the body without suffering from decompression sickness, presumably because bubbles were not formed.

Armed with this basic finding, Haldane then constructed decompression schedules which did not allow this critical supersaturation ratio of 1.58 to 1 to be exceeded in any of the five theoretical tissue compartments. These five theoretical tissues were chosen arbitrarily from a mathematical model which describes an exponential curve as seen in Figure 1.

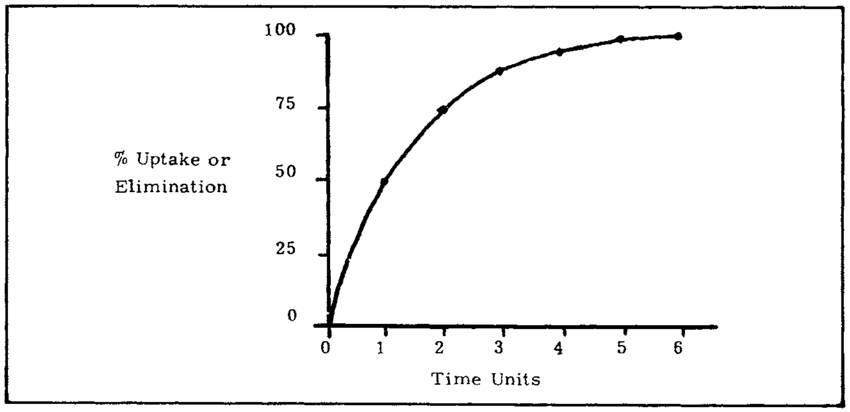


FIGURE 1.

The tissue time units chosen, which are then called *tissue half-times* since each unit of time results in a gain or loss of 50% of the available gas pressure, were 5, 10, 20, 40 and 75 minutes.

M-VALUES

In the years between the time of Haldane's original publication of his decompression tables and the publication of the present version of the U.S. Navy Standard Air Decompression Tables in the mid-1950's[2], only a few modifications were made to Haldane's original model. By empirically performing deep "bounce" dives and by expanding the range of depths and times covered by tables, the U.S. Navy found that six tissue half-times were necessary for constructing decompression schedules and that each half-time tissue had it's own critical supersaturation ratio. In addition, the critical supersaturation ratio for each tissue also decreased with increasing depths of decompression stops. The half-times used in constructing the present U.S. Navy Standard Air Decompression Tables and their respective surfacing supersaturation ratios are presented in Table 1 along with another entity, the M-value.

TABLE 1.

HALF-TIME	5	10	20	40	80	120
SURFACING RATIO	3.15	2.67	2.18	1.76	1.58	1.55
SURFACING M-VALUE	104	88	72	58	52	51

The M-value is the maximum allowable tissue nitrogen pressure that can be tolerated by the tissue compartment during pressure reduction, and is expressed in feet of sea water *absolute* (fswa). The ratio is obtained by dividing the M-value by the absolute depth (depth + 33 fsw) at which the M-value applies. In calculation of decompression schedules, the M-value is used so that results are obtained directly in the units of interest, i.e., feet of sea water, but it is still the supersaturation ratio which represents the driving force for bubble formation.

PROBLEMS OF ALTITUDE

The physical parameter which changes at elevations above sea level, in terms of decompression considerations, is the barometric pressure. The reduction in barometric pressure will, if the sea level M-values are used, result in an increased supersaturation ratio which, in theory, increases the likelihood of bubble formation. For example, if we use the surfacing M-value of 58 fswa for the 40 minute half-time tissue from Table 1, and apply it at an altitude of 7,000 feet above sea level (absolute depth = 25.5 fswa), the result is 58/25.5 = a surfacing ratio of 2.27 compared to the maximum allowable sea level ratio of only 1.76. Table 2 presents the barometric pressure at altitudes to 10,000 feet, expressed in fswa.

TABLE 2

ALTITUDE	BAROMETRIC PRESSURE IN mmHg	ABSOLUTE DEPTH IN fswa
Sea Level	760	33
1,000	732.9	31.8
2,000	706.6	30.7
3,000	681.1	29.6
4,000	656.3	28.5
5,000	632.3	27.5
6,000	609.0	26.4
7,000	586.4	25.5
8,000	564.4	24.5
9,000	543.2	23.6
10,000	522.6	22.7

THE CROSS-CORRECTIONS FOR DIVING AT ALTITUDE

Appearing in *Skin Diver* magazine first in 1967 and again in 1970[3], the so-called Cross-corrections are probably the most widely known, yet least understood procedures proposed for diving at altitude and flying-after-diving. This use of these recommendations involves determining the apparent depth (also referred to as the equivalent theoretical depth) for the exposure depth and also altering the depth of standard decompression stops. The apparent depth is used to select the decompression stops. The apparent depth is used to select the decompression schedule from the U.S. Navy Standard Air Decompression Tables. The equation for determining the apparent depth is:

$$\text{Apparent Depth } \frac{D \times 760 \text{ mmHg}}{P_{Balt}}$$

where: D = actual gage depth in fsw
760 mmHg = barometric pressure at sea level
P_{Balt} = barometric pressure at altitude in mmHg

Again, using 7,00 feet altitude and a gauge depth of 30 fsw, the equation gives us an apparent depth of

$$30 \times \frac{760}{586.4} = 38.88 \text{ fsw}$$

or, 8.88 fsw *deeper* than the same depth at sea level. Thus, the correction says that for a 30 foot dive at 7,000 feet above sea level we would select a 40 foot schedule from the U.S. Navy Standard Tables. The maximum no-decompression limit for 40 fsw is 200 minutes. At the end of a 200 minute exposure (or a series of repetitive dives bring a diver to the equivalent) the nitrogen tensions in the slower half-time tissues would be as seen in Table 3.

TABLE 3

HALF-TIME TISSUE	SURFACING NITROGEN TENSION (fswa)
40	43.2
80	39.7
120	36.4

These calculations assume that the diver has been at 7,000 feet for over 24 hours and that all of his tissues are therefore equilibrated at the new, reduced nitrogen tension at the start of his dive.

Comparison with Table 1 reveals that these values are less than the maximum allowable M-values for sea level. But, how about the surfacing ratios? Dividing each of the nitrogen tensions in Table 3 by the absolute depth at 7,000 feet from Table 2 (25.5 fswa) gives the ratios seen in Table 4.

TABLE 4

HALF-TIME TISSUE	SURFACING RATIO AT 7,000	MAXIMUM ALLOWABLE RATIO AT SEA LEVEL
40	1.69	1.76
80	1.56	1.58
120	1.43	1.55

Thus, it can be seen that the driving force for bubble formation, i.e., the pressure differential, is less than that allowed at sea level for all of these tissues.

Another example is in order using the Cross-corrections. Let us now assume that a diver suddenly ascends to 7,000 feet, allowing no time for the body to lose any of its sea level nitrogen burden before making a dive to 30 feet for 200 minutes. The surfacing nitrogen tension and ratios under these conditions will be presented in Table 5.

TABLE 5

HALF-TIME TISSUE	SURFACING NITROGEN TENSION (fswa)	SURFACING RATIO	MAXIMUM ALLOWABLE RATIO AT SEA LEVEL
40	43.3	1.70	1.76
80	40.7	1.60	1.58
120	38.2	1.50	1.55

Under these described (contrived?) conditions, it can be seen that the driving force for bubble formation is *greater* than that allowed at sea level for the 80 minute half-time tissue. However, this higher ratio equates to only 0.4 fsw or 0.18 psi or 9.21 mmHg greater nitrogen pressure, which hardly seems significant.

Since, in actual practice divers would either be equilibrated at altitude due to residing there or would attain partial equilibration in route there by air or ear, it appears that the Cross-corrections for diving at altitude will provide the same degree of safety as the U.S. Navy Standard Tables provide at sea level, based on observing the same set of supersaturation ratios.

THE CROSS-CORRECTIONS FOR FLYING AFTER DIVING

The proposed use of the Cross-corrections for flying following dives made at sea level was to simply follow the same procedures as if a diver were diving at high altitude. Therefore, if a diver were going to fly immediately to 7,000 feet following sea level diving to 30 fsw, he would again choose the 40 foot schedule (apparent depth of 38.8 fsw) and the no-decompression limit of 200 minutes. However, because of the higher tissue nitrogen level due to equilibration at sea level prior to the dive and due to the higher nitrogen pressure at 30 fsw at sea level (49.8 fswa) than at 30 fsw at 7,000 feet (43.9 fswa), the tissues end up with the surfacing nitrogen tensions and ratios upon an immediate ascent to 7,000 feet seen in Table 6.

TABLE 6

HALF-TIME TISSUE	SURFACING NITROGEN TENSION (fswa)	SURFACING RATIO	MAXIMUM ALLOWABLE RATIO AT SEA LEVEL
40	49.1	1.93	1.76
80	45.6	1.79	1.58
120	42.3	1.66	1.55

These differences in nitrogen pressures, ranging from 2.8 fsw in the 120 minute tissue to 5.7 fsw in the 40 minute tissue could be expected to have a significant impact on bubble formation. However, it is not realistic under sport diving conditions to envision an *immediate* ascent to 7,000 feet upon surfacing from a dive made at sea level. Within 37 minutes after surfacing and remaining at sea level, the nitrogen tensions in these tissues have decayed to levels such that arrival at 7,000 feet would not exceed the maximum allowable supersaturation ratios. Which brings us next to the recommendations of Edel, *et. al.*[4], the NOAA Diving Manual[5] and C. L. Smith[6].

OTHER RULES FOR FLYING-AFTER DIVING

Edel and co-workers, under contract to NASA, provided guidelines for flying in commercial, pressurized aircraft (maximum cabin altitude of 5,000 to 8,000 feet) following dives made at sea level. Their recommendation was that a two hour surface interval be observed prior to flying in commercial aircraft following dives made only within the no-decompression limits of the U.S. Navy Standard Air Decompression Tables during the preceding 12 hours. If decompression dives were made (or *should* have been made) then the divers should allow 24 hours between surfacing and flying.

Table 7 presents the highest surfacing nitrogen tensions in the various half-time tissues attained on no-decompression schedules, the M-values for reaching 8,000 feet based on maximum sea level supersaturation ratios and the time required at sea level for the surfacing nitrogen tensions to decay to the M-value levels. As seen, all of these cases will allow ascent to 8,000 feet if the surface interval is the two hours recommended by Edel, *et. al.*

The NOAA Diving Manual stated it is safe to fly in a commercial aircraft following diving as long as the divers repetitive group is D (or less, i.e., A, B, C). Table 8 presents the highest surfacing nitrogen tensions in the various half-time tissues for no-decompression schedules which result in a repetitive group of D. Again, the M-values for reaching 8,000 feet based on maximum sea level ratios and the time required at sea level for the surfacing tensions to decay to the M-value are also presented. This table shows, therefore that it is indeed safe to fly in commercial aircraft following no-decompression dives which result in a repetitive group of D or less. Similar calculations, not presented here also show it is safe to fly to 8,000 feet following any dive, as long as the surface interval brings the diver to repetitive group D.

TABLE 7

HALF-TIME TISSUE	HIGHEST SURFACING P_{N_2}	SCHEDULE(S) PRODUCING HIGHEST P_{N_2}	M-VALUES FOR REACHING 8,000 FEET	TIME REQUIRED AT SEA LEVEL
5	102	140/10	77	3 minutes
10	88	100/25,100/20	65	7 minutes
20	72	30/40,90/30,100/25	53	15 minutes
40	59	50/100	43	38 minutes
80	52	40/200	30	83 minutes
120	48	40/200	38	106 minutes

C. L. Smith, in his publication, presents the highest repetitive group letters available when ascending to altitude form 1,000 to 15,000 feet following ocean dives. These recommendations are seen in Table 9, through a maximum altitude of 10,000 feet. When the surfacing nitrogen tensions for all dives resulting in the same repetitive group letter are compared with the calculated M-values for all half-time tissues at altitudes from 1,000 to 10,000 feet, seen in Table 10, many schedules are found which result in violation of the safe supersaturation ratios. The number of violations are too great to expand on in this report, but in summary, Smith's recommendations are *NOT* considered to be conservative enough to be safe under *all* conditions.

TABLE 8

HALF-TIME TISSUES	HIGHEST SURFACING P_{N_2} (GROUP D)	SCHEDULE(S) PRODUCING GROUP D	M-VALUES FOR REACHING 8,000 FEET	TIME REQUIRED AT SEA LEVEL
5	101	190/5	77	3 minutes
10	76	190/5	65	3.5 minutes
20	55	120/10, 190/5	53	2 minutes
40	42	120/10	43	none
80	35	120/10	39	none
120	32	130/8	38	none

TABLE 9

ALTITUDE	HIGHEST ADVISABLE GROUP LETTER
1,000	M
2,000	L
3,000	K
4,000	J
5,000	I
6,000	H
7,000	G
8,000	F
9,000	E
10,000	D

THE VALIDITY OF EXTRAPOLATED M-VALUE

The preceding discussion has been based on extrapolating M-values using a barometric pressure ratio to maintain the same surfacing supersaturation ratio in each of the six half-time tissues used in constructing the U.S. Navy Standard Air Decompression Tables. Dr Richard Bell has reported on calculating altitude decompression tables based on a *linear* (not a pressure ratio) extrapolation[7]. It was stated previously that the allowable supersaturation ratios decreased with increasing depth of decompression stops, and when the M-values obtained from these ratios are plotted graphically against depth, a linear relationship exists as seen in Figure 2. These straight lines can then be extrapolated to negative depth, that is, to altitude and thus M-values can be obtained for surfacing at altitudes above sea level. Table 11 presents the M-values and supersaturation ratios obtained in this manner.

TABLE 10

HALF-TIME	ALTITUDE (x 1,000)										
	0	1	2	3	4	5	6	7	8	9	10
5	104	100	97	93	90	87	83	80	77	74	72
10	88	85	82	79	76	73	70	68	65	63	61
20	72	69	67	65	62	60	58	56	53	51	49
40	58	56	54	52	50	48	46	45	43	42	40
80	52	50	49	47	45	43	42	40	39	37	36
120	51	49	48	46	44	43	41	40	38	37	35

As can be seen, this extrapolation results in an increasing allowable supersaturation ratio, i.e., a greater driving force for bubble formation, with increasing altitude. If this linear approach to extrapolated M-values is valid, then it should predict the altitude at which the sea-level-saturated individual would encounter altitude decompression sickness. Considering only the longest half-time, i.e., the slowest tissue, this altitude is calculated to be 23,000 feet. However, this prediction is unsafe because sea-level man begins to encounter decompression sickness at 18,000 feet.

When the slowest tissue M-value is extrapolated by a *barometric pressure ratio*, as seen in Table 10, the predicted altitude agrees with the historical data, i.e., 18,000 feet. It is therefore concluded that linear extrapolation of

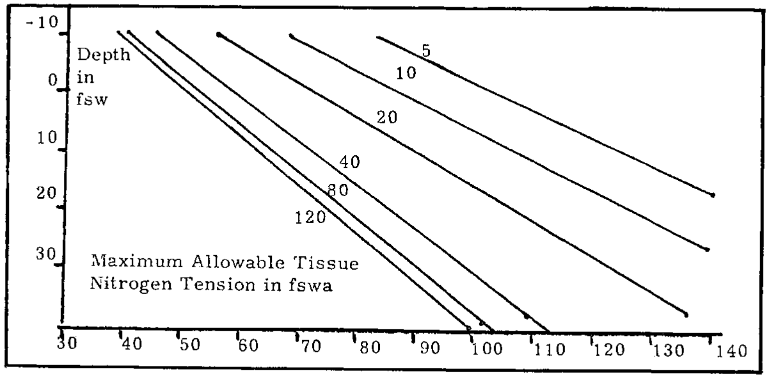


Figure 2.

TABLE 11

ALTITUDE	HALF-TIMES:	5	10	20	40	80	120
Sea-level	M-value:	104.00	88.00	72.00	58.00	52.00	51.00
	Ratio:	3.15	2.67	2.18	1.76	1.58	1.55
2,000	M-value:	98.80	83.40	68.10	54.80	49.90	48.10
	Ratio:	3.22	2.72	2.22	1.78	1.60	1.57
6,000	M-value:	89.00	74.80	60.70	48.80	43.50	42.60
	Ratio:	3.37	2.83	2.30	1.85	1.65	1.61
10,000	M-value:	80.60	67.40	54.40	43.60	38.70	37.90
	Ratio:	3.55	2.97	2.40	1.92	1.71	1.67

M-values for use in the calculation of altitude decompression tables or for flying-after-diving procedures will result in supersaturation ratios that are likely to produce decompression sickness.

SILENT AND NOT-SO-SILENT BUBBLES

The use of the U.S. Navy Standard Air Decompression Tables by the Navy produces a very low incidence of decompression sickness, amounting overall to less than 0.04%[8]. However, intravenous gas bubbles have been detected in man, using the Doppler ultrasonic bubble detector, following safe dives within these tables. The work of Spencer[9], Pilmanis[10], and others has shown, particularly at the limits of the no-decompression tables, that some individuals will routinely have venous gas bubbles. It is suspected, and there is some experimental evidence on which to base such elimination from the tissues, which further enhances bubble formation – the proverbial vicious cycle. If such is the case, then such an individual would be at great risk if he attempted to fly, or drive, to an altitude where the barometric pressure reduction would cause existing bubbles to grow, perhaps to symptomatic size, and would promote the formation of even more bubbles in the tissues which have impaired nitrogen elimination. In other words, the Surface Interval Credit Table may not apply to an individual who is forming intravascular bubbles, and should probably not be used as the basis for deciding when to fly after diving.

THE NEW APPROACH

A new set of M-values for diving at altitude and flying after diving was developed using a generally more conservative set of sea level M-values developed by Workman[11]. These M-values were extrapolated for use at altitude by the application of the barometric pressure ratio as previously discussed. The tables for diving at altitudes above sea level thus produced are more conservative than either the tables produced by the method of Bell or by the decompression schedules/no-decompression limits obtained with the Cross-corrections. For flying-after-diving, only no-decompression diving to a maximum depth of 130 feet has been considered, and no-decompression limits have been calculated for direct ascent to various altitudes and for surface interval requirements for ascent to these same altitudes.

MANNED VALIDATION TESTS

The tables and procedures outlined above are not included in this report because manned validation tests have not yet been performed. The planned tests will be commencing in the Fall of 1977 and are designed to validate the calculation model used, in addition to selected schedules. The worst-case approach will be used in the validation tests, i.e., sea level saturation with maximum calculated time at a given depth with moderate exercise performed, followed by a direct five minute ascent to 10,000 feet above sea level for four hours. Doppler ultasonic bubble detectors will be used to monitor for venous bubbles and a final ascent to 16,000 feet for one hour will be used to determine the effectiveness of the calculation model in preventing bubble formation. Each of six selected schedules will be validated by 20 manned exposures. Once the schedules and the model have been validated, the tables, schedules and procedures will be published.

SUMMARY

Analysis of previously published procedures for diving at altitudes above sea level and for flying-after-diving have been performed. Based on a barometric-pressure-ratio-extrapolation of the maximum allowable tissue nitrogen tensions (M-values), the altitude diving corrections of Cross appear to provide decompression that is limited by the same supersaturation ratios used in constructing the Standard Air Decompression Tables for use at sea level. As such, the Cross-corrections are used for flying following ocean dives, the supersaturation ratios may be exceeded, particularly if altitude exposure quickly follows the dive.

The recommendations of both Edel and NOAA Diving Manual regarding flying after diving also appear to abide by the supersaturation ratios used in the standard tables while the recommendations of Smith will result, in some cases, in exceeding these ratios.

Linear extrapolation of M-values for the construction of altitude decompression tables or for procedures for flying after diving result in much higher supersaturation ratios being allowed. Also, such extrapolations predict a threshold altitude for decompression sickness in sea-level-man which is 5,000 feet above the historically documented threshold altitude. It is concluded that tables produced on such a basis may have a greater incidence of decompression sickness than the present standard tables.

Because of the observation of intravascular bubbles on dives performed within the U.S. Navy Standard Air Decompression Tables and the suspected impact of such bubbles on inert gas elimination, a new model for calculating altitude decompression tables and schedules for flying-after-diving has been developed. These tables and schedules will be published only after manned validation tests confirm the validity of the model in terms of preventing bubble formation. These validation tests are expected to be started in the Fall of 1977.

REFERENCES

[1] Boycott, A. E., Damant, G. C. C., and Haldane, J. S., *The Prevention of Compressed-Air Illness*, J. Hyg. (Lond), 8:342-444, (1908).

[2] ________________, *U.S. Navy Diving Manual*, NAVSHIPS 250-538, U.S. Government Printing Office, January 1959.

[3] Cross, E., *Technifacts: Decompression for High-Altitude Diving,* Skin Diver 16(8):49; 16(2):60, 62-64, 66 (1967) and *Technifacts: High Altitude Decompression,* Skin Diver 19(1):17-18, 59 (1970).

[4] Edel, P. O., Carroll, J. J., Honaker, R. W. and Beckman, E. L., *Interval at Sea-Level Pressure Required to Prevent Decompression Sickness in Humans Who Fly in Commercial Aircraft After Diving*. Aerospace Med. 40:1105-1110 (1969).

[5] ________________, *The NOAA Diving Manual*, Diving for Science and Technology, Manned Undersea Science and Technology Office, United States Department of Commerce, National Oceanic and Atmospheric Administration (1975).

[6] Smith, C. L., *Altitude Procedures for the Ocean Diver*, NAUI Technical Publication Number Five, National Association of Underwater Instructors (1975).

[7] Bell, R. L. and Borgwardt, R. E., *The Theory of High-Altitude Corrections to the U.S. Navy Standard Decompression Tables: The Cross Corrections*. Undersea Biomed. Res. 3:1-23 (1976).

[8] Berghage, T. E., Rohrbaugh, P. A., Bachrach, A. J. and Armstrong F. W., *Navy Diving Summary Statistics, Proceedings of the Working Diver*, 1976 Symposium:285-303 (1976).

[9] Spencer, M. P., *Decompression Limits for Compressed Air Determined by Ultrasonically Detected Blood Bubbles*, J. Appl. Physio. 40:231-235 (1976).

[10] Pilmanis, A. A., *Intravenous Gas Emboli in Man After Compressed Air Ocean Diving*, Final Report 5/1/72-6/30/75 to the Office of Naval Research under contract N00014-67-A-0269-0026 (1976).

[11] Workman, R. D., *Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives*, Res. Rept. 6-65, U.S. Navy Experimental Diving Unit, Washington, D. C. (1965).

THE THEORETICAL STRUCTURE AND TESTING OF HIGH ALTITUDE DIVING TABLES

by: Richard L. Bell*, Anthony C. Thompson, and Reid E. Borowari*****
University of California, Davis, California

Introduction

Virtually every serious diver will log a dive in a lake, river or stream located at an altitude above sea level at some time in his or her diving career. Lake Tahoe, California, at an altitude of 6,200 feet, with it's clear water and spectacular underwater cliffs, is becoming an increasingly popular sport and research diving area. At the 1975 NAUI High Altitude Diving Conference, we learned of sport divers in Colorado who are diving in lakes at 11,000 feet, which must be the record for the United States. However, the world high altitude diving record is probably held by the team of divers under Jacques Cousteau, which in 1958 conducted an underwater survey of Lake Titicaca in Bolivia at an altitude of 12,500 feet. Although few divers will participate in these extremes of high altitude diving, there is an increasing number of inland divers who are trained in lakes and quarries and who spend a significant portion of their underwater careers exploring waters located where the ambient atmospheric pressure is below that at sea level.

Too frequently the question of how a diving schedule should be adjusted for reduced ambient pressure is never asked by experienced divers, students or instructors. Nevertheless, it is a fact that the lower atmospheric pressure at altitude, and to a smaller extent, the lower density of fresh water, can alter the rates of uptake and loss of nitrogen by the body tissues, and in turn, significantly affect the problem of decompression and repetitive diving. In the majority of no-decompression sport dives, the effect is relatively small and the diver is within safe limits. But what of the team on a decompression schedule, or the research group on a tight repetitive dive sequence, or the commercial diver who works close to the limits in order to optimize underwater time? Have you ever been in, or can you conceive of one of your students ever being in such a situation, and what do you tell your students about this problem? How important this topic is to you is probably related to how often you find yourself or one of your students shouldering into a tank at altitude. Our interest is high because we train research personnel to dive in many of the high California lakes on a regular basis. The heated arguments and lively discussions around the campfire at Lake Tahoe, among ourselves and with others who were as uninformed as ourselves generated our first interest in the high altitude diving problem. Later, when we became

*Department of Chemical Engineering and Physiological Sciences
**Department of Chemical Engineering and Physical Education
***Department of Chemical Engineering

responsible for the students who were there making repetitive training dives, some of which were on decompression schedules, our early curiosity about a confusing issue changed to a very personal need to understand the problem of high altitude diving and decompression.

It is the purpose of this paper to discuss the theoretical basis for high altitude corrections to the U.S. Navy Tables. To do so requires an understanding of the structure and development of the U.S. Navy Tables. We will not discuss the several alternate approaches to decompression such as the Isobaric Oxygen Window as developed by Behnke (1976), or the work of Hills (1969) on Thermodynamic Decompression. There is considerable merit in the approaches of these authors and others. However, the usual student of diving becomes well acquainted with the U.S. Navy Tables and consequently we shall focus in this paper on the extension of the theory of these tables to altitude.

A central factor in understanding the high altitude problem is first becoming familiar with the specifics of how the decision was made to require a decompression stop in the USN Tables. We will illustrate this by discussing the basic model for decompression used in the development of the tables and how the present correction method relates to the tables. We will also show why the present method fails, evidently in a systematically conservative way. In this portion of the discussion we will assume that the diver has been at altitude sufficiently long to allow his tissues to become equilibrated with the reduced ambient pressure before entering the water. Frequently, however, a diver will drive to altitude and commence diving immediately. His tissues, which were initially in equilibrium with air at a higher atmospheric pressure, at sea level for example, have not had time to reach equilibrium with the atmosphere at altitude. Consequently, relative to the new atmospheric environment, the diver enters the water with some residual nitrogen, as though he were in a repetitive group. We will discuss this situation relative to the USN repetitive dive tables to illustrate the basis for the repetitive dive tables and to demonstrate that the U.S. Navy repetitive dive tables do not cover the altitude problem and that new repetitive dive groups are required.

EXTENSION OF U.S. NAVY DECOMPRESSION THEORY TO ALTITUDE DIVING

The stage decompression methods used in the USN Tables had their origin in the work of J.S. Haldane (1922). While studying the occurrence of decompression sickness in goats, Haldane found that following equilibration at a given depth in a hyperbaric chamber, the pressure in the chamber could be reduced by a factor of 2 without producing symptoms of decompression sickness. For example, an animal which had been held at 6ATA could be quickly exposed to 1 ATA. This so-called "Haldane 2 to 1 ratio" has contributed to the widely held, but erroneous notion that the no-decompression limits for dives to 33 feet or less are infinite. The stage decompression model proposed by Haldane required that following exposure on a dive requiring decompression, the diver move toward the surface by stages in such a way that the calculated tissue pressure based on a 100% nitrogen atmosphere never exceeds the absolute hydrostatic pressure acting on the body by more than a factor of two.

Haldane recognized that a multiplicity of tissues existed which absorb nitrogen at different rates in different amounts. For example, oil, which corresponds to fatty tissue, will dissolve approximately six times as much nitrogen as water which corresponds to muscular tissue. In principle, it would require a very large number of tissue types to characterize the bone, tendon, muscle, fat, viscera and other tissues which are present in the body. In actual practice, the U.S. Navy adopted six tissue types of "compartments" which are characterized by their half-times and do not correspond specifically to any tissue except insofar as the shorter half-times may be characteristic of tissues with high blood perfusion such as muscle and the longer half-times may correspond to poorly perfused tissue such as tendon or bone. The half-times selected were 5, 10, 20, 40, 60, 80 and 120 minutes and were chosen because they gave the best fit to the experimental data. The implication is that tissues with half-times greater than 120 minutes did not absorb sufficient nitrogen during the exposures covered by the Standard Air Decompression Tables to be considered in the decompression problem. However, for exposures beyond those in the standard tables, such as saturation dives, half-times as long as 720 minutes have been considered.

The half-time of a tissue is a measure of the ease or difficulty of transferring nitrogen to or from the tissue. If the nitrogen pressure on a tissue were suddenly reduced, the 80 minute half-time tissue would require 80 minutes for the tissue pressure to drop half-way to the new equilibrium value. It would require another 80 minutes to halve the remaining difference and so on. For example, if the initial equilibrium tissue pressure were 100 PSIA and the new equilibrium pressure were 50 PSIA, in 80 minutes the tissue pressure would be 75 PSIA or one-half of the original difference. In another 80 minutes, it would be reduced by one-half of the remaining difference of 25 PSIA for a tissue pressure of 62.5 PSIA and so on.

An important assumption of the U.S. Navy model is that it is the blood perfusion rate that controls nitrogen transport to the tissues rather than the diffusional transport from the capillary to the tissue cell. In terms of the transport model this means that the driving force for nitrogen transport is the difference between the nitrogen partial pressure in the alveoli of the lung and the nitrogen pressure in the tissue. Moreover, the transport to other tissue compartments as shown schematically in Figure 1. The mathematical expression describing the model is given in Equation 1.

$$\frac{d\pi_i}{dt} = \frac{1}{\tau_i} [p_a - \pi_i] \qquad (1)$$

where:

π_i = tissue nitrogen pressure in the i^{th} tissue compartment.

τ_i = time constant for the i^{th} tissue compartment = (half-time/0.693).

t = time

P_a = alveolar partial pressure of nitrogen.

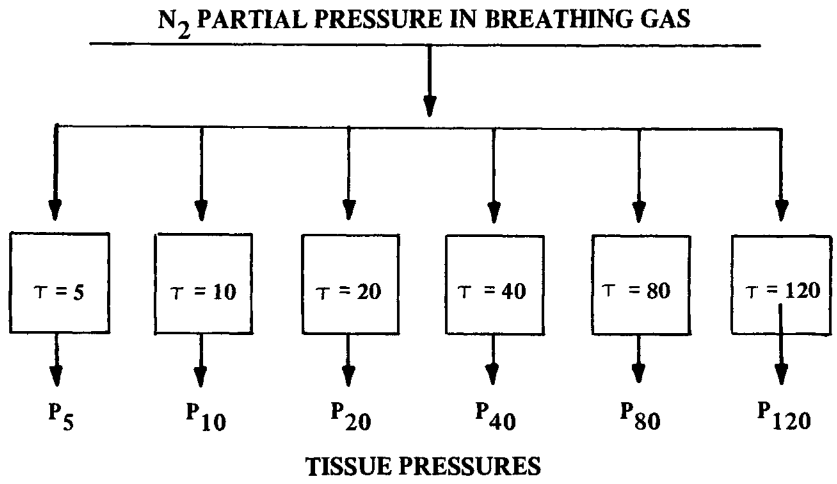


Figure 1. Schema of the six tissue compartment model used as the basis for the U.S. Navy Standard Decompression Tables.

If the contribution of water vapor and carbon dioxide to the gas in the alveoli is ignored, P_a is given by

$$P_a = xP \tag{2}$$

where:

x = partial pressure of nitrogen in the breathing gas for air x = 0.79.

and P is the absolute local hydrostatic pressue. At sea level P is simply the atmospheric pressure of 14.7 PSIA. However, under the surface of any water mass P is given by

$$P = p'D + P^o \tag{3}$$

where:

p' = rate of change of pressure with depth.
Salt water p' = 0.444 PSI/feet
Fresh water p' = 0.433 PSI/feet
D = depth under the surface of the water.
P^o = atmospheric pressure acting on the surface of the water.

Clearly the value of P for the same depth beneath the surface will be different for the ocean from that in a lake at an elevation of, for example, 6,000 feet. Table 1 shows the change in atmospheric pressure with altitude taken from the U.S. Standard Atmosphere (1962). The pressure variation with depth in sea water at sea level and fresh water at an altitude of 6,000 feet is shown in Table II. Comparison of the values of P_a for equal depths show significant differences with the value at altitude always being less than the value in the ocean. This leads to two important conclusions: (1) solutions to equation 1 for different altitudes will always yield different values of tissue pressure for dives of equal depth and (2) the tissue pressures at altitude will always be less than for the same dive at sea level. The significance of this fact will become clear when we discuss the criteria for making decompression stops.

There are several assumptions regarding the application of equation 1 which were adopted by the U.S. Navy and which we will adopt in this paper.

1. The diver descends to the bottom instantaneously. The tissue pressure on the bottom at the start of the dive is therefore taken to be equal to the partial pressure of nitrogen in the atmosphere at the elevation of the surface of the water mass. This assumption does not hold if the diver has not been at altitude for a sufficiently long time to allow the tissues to reach equilibrium with the reduced pressure of the atmosphere (approximately 12 hours).
2. Ascent from the bottom to the first stop or the surface is assumed to be at a constant rate of 60 feet/minute.
3. Ascent between decompression stops is instantaneous.
4. The breathing gas is air.

TABLE I

Pressure Variations with Altitude (U.S. Standard Atmosphere 1962)

ALTITUDE (feet)	PmmHg	P	ATA
0	760.0	14.70	1.000
1000	732.9	14.17	0.964
2000	706.7	13.67	0.930
3000	681.2	13.17	0.896
4000	656.4	12.70	0.864
5000	632.4	12.73	0.832
6000	609.1	11.78	0.801
7000	586.5	11.35	0.772
8000	564.6	10.92	0.743
9000	543.3	10.51	0.715
10000	522.8	10.11	0.688
11000	502.8	9.73	0.662
12000	483.5	9.35	0.636
13000	464.8	9.00	0.612
14000	446.6	8.64	0.588
15000	429.1	8.31	0.565
16000	412.1	7.97	0.542
17000	395.7	7.66	0.521
18000	379.8	7.35	0.500
19000	364.4	7.04	0.479
20000	349.5	6.76	0.460

NOTE: There are seasonal and geographic variations in these values which can be as much as 5%. See U.S. Standard Atmospheric Supplements 1966.

TABLE II.

Pressure Variation with Depth
Pressures in Pounds/Square Inch

Depth	SEA LEVEL			FRESH WATER 6000 FEET		
	P^o	P/P^o	P_a	P^o	P/P^o	P_a
0	14.7	1.00	11.6	11.8	1.00	9.3
10	19.1	1.30	15.1	16.1	1.37	12.7
20	23.6	1.60	18.6	20.4	1.74	16.1
30	28.0	1.91	22.1	24.8	2.10	19.6
40	32.5	2.21	25.7	29.1	2.47	23.0
50	36.9	2.51	29.2	33.4	2.84	26.4
60	41.4	2.81	32.7	37.8	3.21	29.9
70	45.8	3.12	36.2	42.1	3.58	33.3
80	50.3	3.42	39.7	46.4	3.95	36.7
90	54.7	3.72	43.2	50.8	4.31	40.1
100	59.1	4.02	46.7	55.1	4.68	43.5
110	63.6	4.33	50.2	59.4	5.04	46.9
120	68.0	4.63	53.7	63.8	5.42	50.4
130	72.5	4.93	57.3	68.1	5.79	53.8
140	76.9	5.23	60.8	72.4	6.15	57.2
150	81.4	5.54	64.3	76.8	6.52	60.7
160	85.8	5.84	67.8	81.1	6.89	64.1
170	90.3	6.14	71.3	85.4	7.26	67.5
180	94.7	6.44	74.8	89.8	7.63	70.9
190	99.1	6.74	78.3	94.1	8.00	74.3
200	103.6	7.05	81.8	98.4	8.36	77.7

Under these assumptions, there are two distinct phases to the dive for which solutions to equation 1 must be found in order to calculate tissue pressures. The first is for the diver remaining stationary at a given depth whether it is the bottom, a decompression stop or the surface. During this time P and P_a are constant. The second is the ascent from the bottom to the first stop. During this period P and P_a are linearly decreasing functions of time. The solutions to equation 1 for these phases are shown below.

I. Diver stationary at a given depth:

$$\pi_i = P_a + \left(\pi_i^o - P_a\right) e^{-\theta_i} \qquad (4)$$

P_a = calculated from equations 2 and 3

π_i^o = the tissue nitrogen pressure at the beginning of the respective stop

θ_i = dimensions time = t/τ_i.

II. Diver ascending at a constant rate:

$$\pi_i = P_a' + \left(\pi_i' - P_a'\right) e^{-\theta_i} + xR\rho'\tau_i\left(1 - 0_i - e^{-\theta_i}\right) \qquad (5)$$

P_a' = the value of P_a on the bottom

R = ascent rate

π_i' = tissue pressure at the beginning of ascent from the bottom.

The U.S. Navy Experimental Diving Unit reports that in Dwyer's (1956) method of calculating diving schedules which was later adapted by Workman (1965), equation 4 is used exactly. However, in their suggested method for calculating tissue pressure changes during ascent, the third term in equation 5 is discarded and P_a' is taken as the average pressure during the ascent to the first stop. This introduces some error into the calculation and those familiar with Workman's method may not get precisely the same results using equation 5. However, even though equation 5 is a bit more cumbersome, it is exact.

As discussed earlier, in Haldane's original experiments, the ratio of tissue nitrogen pressure (π_i) to the local absolute hydrostatic pressure (P), was the factor which determined whether a decompression stop was required. Should this ratio exceed 1.58 (based on air being 79% nitrogen), the diver was required to make a stop and remain there until the tissue pressure was reduced sufficiently that he could proceed to the next stop without exceeding the ratio. Subsequent to these early experiments, it was that the problem was more complex, and separate critical pressure ratios were required for each tissue compartment. If this were the final step in the story then the ratio method for correcting altitude dives to sea level would work. Unfortunately, there was another factor which was introduced into the development of the USN Tables which causes this method to fail. It was found that not only did the critical pressure ratio change with tissue half-time, but it also depended on the magnitude of the tissue exposure as indicated by the absolute tissue pressure at the start of the ascent from the bottom. The implications of this will be discussed later.

ANALYSIS OF THE CROSS TABLES

The method of correcting the USN Tables for altitude which is probably the most widely used is that presented by E. R. Cross (1970) and known as the Cross Tables, although they were evidently sent to Cross by H. J. Smith, Jr. (Cross, 1967). The theoretical development of the Cross Tables and their relationship to the USN Tables is presented in detail by Bell and Borgwardt (1975) and only the results will be presented here. The Cross method depends on correcting a dive at altitude to a theoretically similar dive in the ocean. The criteria for similarity is that the ratio of tissue nitrogen pressure to local absolute hydrostatic pressure (π_i/P) be the same for the similar dives at every point in time. Cross neglected the relatively small effect of the difference in density between salt water and fresh water. He also neglected an important correction for ascent rate which is required to assure similarity of the dives under the definition used above. A table including both density and ascent rate corrections was developed for Lake Tahoe by Dr. Jon Pegg in May, 1965, but evidently was never generalized to other altitudes or published. The mathematical transformation from a depth at altitude designated by the subscript 2 to a theoretically equivalent depth in the ocean, designated by the subscript 1 is shown in equation 6.

$$D_1 = \frac{\rho_2}{\rho_1} \frac{P_1^o}{P_2^o} D_2 \qquad (6)$$

$$P_1^o = 14.7 \text{ PSIA}$$

or

$$D_1 = \frac{14.34}{P_2^o} D_2 \qquad (7)$$

The correction for ascent rate takes exactly the same form.

$$R_1 = \frac{14.34}{P_2^o} R_2 \qquad (8)$$

As an example, consider a dive to 100 feet in a lake at an altitude of 6000 feet. The atmospheric pressure at 6000 feet is 11.78 PSIA, and substituting into equation 7 yields an equivalent depth in the ocean of 121.8 feet. Using the same ratio, a 10 foot decompression stop in the ocean is similar to an 8.2 foot stop in the lake. The required ascent rate at 6000 feet corresponding to 60 feet/minute in the ocean is 49.3 feet/minute, as calculated from equation 8. Providing no decompression stops are made, the ratio π_i/P, designated byΩ, is exactly the same for the tissue pressure at altitude is significantly less than that for the theoretically similar dive at sea level. This is illustrated in Figure 2, in which the profiles are shown for the diver surfacing directly from the bottom, even though the USN Tables call for a stop at 10 feet. The application of the Cross Tables would be to enter the USN Tables at exactly the theoretical ocean depth (121.8 feet) or the next greater depth (130 feet), use the actual bottom time (30 minutes) and determine the decompression schedule. If a stop is required at 10 feet, it would, using these tables, actually be made at 8.2 feet for the time designated in the USN Table.

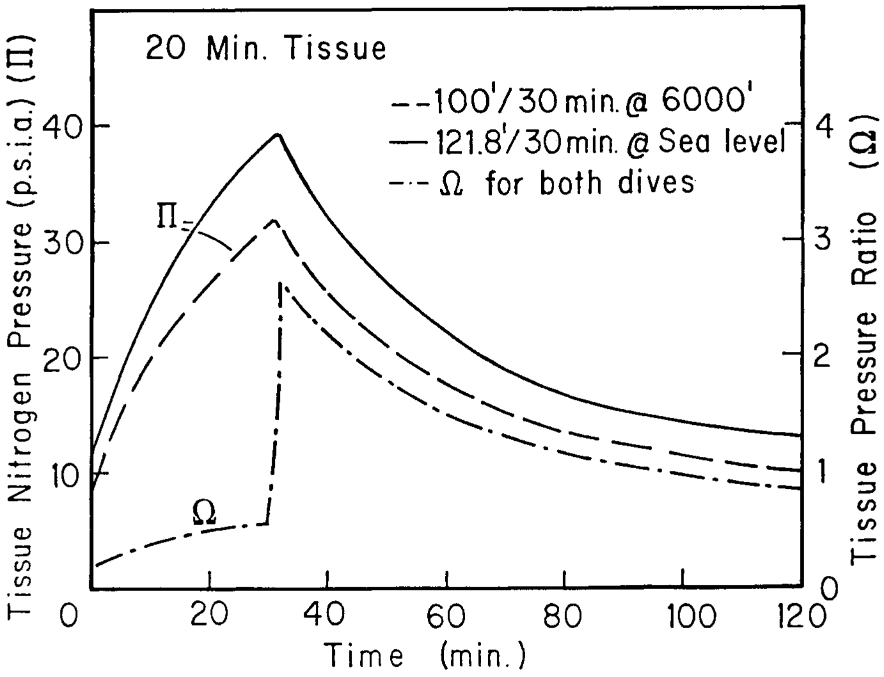


Figure 2. The twenty minute half-time tissue nitrogen pressure curves for similar dives and the ratio (Ω) of tissue nitrogen pressure to local absolute hydrostatic pressure corresponding to both dives. No decompression stops. (Taken from Bell and Borgwardt, 1975)

We will now include the decompression stop in the example dives presented in Figure 2. Only the 20 minute half-time tissue will be used. However, it must be understood that all tissues must remain below the critical pressure for the respective tissue. As a consequence, one tissue or more may control a particular stop while other tissues may control subsequent stops. The results from the 20 minute tissue can be qualitatively generalized however.

First consider the dive at an altitude of 6,000 feet. After the 30 minute bottom time at 100 feet the diver starts toward the surface at an ascent rate of 49.3 feet/minute. The critical pressure at the 8.2 foot decompression stop, as calculated from the equation for the 20 minute tissue given in Table IV in the next section, is 33.33 PSIA, and the critical surfacing pressure 27.43 PSIA. When the diver arrives at 8.2 feet, the 20 minute half-time tissue pressure is 31.17 PSIA. Consequently, the diver can pass the 8.2 foot mark but cannot surface. By convention, the diver must remain at 8.2 feet for a decompression stop of 7.77 minutes after which time the tissue pressure has

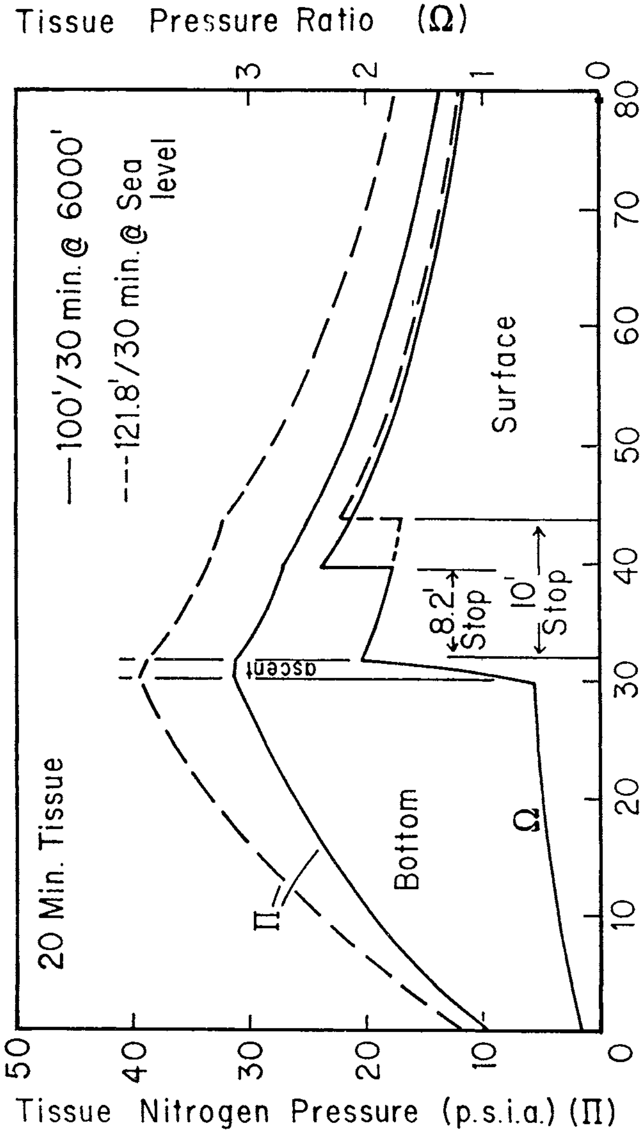


Figure 3. The tissue nitrogen pressure and the ratio (Ω) for similar dives at 6000 feet altitude and sea level, demonstrating the failure of the similarity transformation during the first decompression stop. (Taken from Bell and Borgwardt, 1975).

dropped to 27.43 PSIA and the diver can surface directly. The tissue pressure curve and the $\frac{\pi_i}{p}$ or Ω curve are shown in Figure 3.

Now consider the theoretically similar dive in the ocean. After a 30 minute bottom time at 121.8 feet, the diver starts toward the surface at 60 feet/minute. The critical pressure at the 10 foot stop is calculated to be 39.66 PSIA and the critical surfacing pressure is 32.38 PSIA. The tissue nitrogen pressure at 10 feet is 38.89 PSIA or 5.56 PSI greater than the similar dive at altitude at the 8.2 foot stop. Although the diver can safely pass the 10 foot level, he cannot surface. Consequently, he must remain at the 10 foot stop for 11.76 minutes, after which time the tissue nitrogen pressure has dropped to 32.38 and he can surface direct. The Ω curve for this dive is exactly the same for the altitude dive through 7.77 minutes of the decompression stop. At 7.77 minutes, the similarity fails and the Ω curve for the dive in the ocean does not continue to follow that for a dive at altitude. Had the stop been made, at say, 30 feet, the failure would have occurred during that stop and there would have been no relationship between the two dives for subsequent stops.

We can now make a comparison between these two dives, a dive to a depth of 100 feet in the ocean for 30 minutes and to the table entry depth of 130 feet which would have been used to establish the decompression schedule. The decompression requirement for each of these dives is shown in Table III.

The decompression requirement for the dive to the same actual depth in the ocean as at altitude is approximately one-half that which is required at altitude. Clearly, the USN Table, used without correction for altitude, will substantially increase the liability for decompression sickness. On the other hand, the theoretically similar dive and the table entry dive both result in decompression times substantially longer than required. This means less bottom time or excessive time at the decompression stop.

The fact that beyond the first stop the Cross Tables categorically fail makes the time at subsequent stops even less certain than at the first. The method does not accurately predict decompression requirements at altitude, but rather is apparently a systematically conservative method for correcting for altitude. It is not better than a rule-of-thumb since there is no sound basis for their use.

TABLE III

Decompression Requirements for the Twenty Minute Tissue for the Comparison Dives

Depth and Bottom Time (Feet/minute)	Altitude	Time at Stop	
		20 Foot Stop	10 or 8.2 Foot Stop
100/30	Sea level	---	3.76
100/30	6000 Feet	---	7.77
121.8/30	Sea level	---	11.76
130/30	Sea level	2.08	12.86

THE U.S. NAVY DECOMPRESSION CRITERIA

The decompression experiments conducted by the Experimental Dive Unit (EDU) are reported in detail by des Granges (1957). The critical pressure ratio curves reported by des Granges are reproduced in Figure 4 and can be interpreted as the loci of the maximum allowable or critical tissue pressure for a given local absolute hydrostatic pressure. The curves terminate at their lower extremes on a line which represents decompression at sea level pressure. The intersections of this line with the curves are the surfacing ratios at sea level for the respective tissues.

Consequently, these criteria were never tested at ambient pressures less than 1 ATA. In order to apply these curves to the altitude problem, they must be extrapolated to pressures below 14.7 PSIA. Bell and Borgwardt (1975) have proposed a method of extrapolation which is based on the fact that the curves in Figure 5 can be fit almost exactly with hyperbolas. As a result, plotting the maximum allowable pressure as a function of local absolute hydrostatic pressure yields straight lines. These lines can then be extrapolated to reduced pressure as shown in Figure 5. The equations for these lines are given in Table IV. Using these equations, the critical pressure and the surfacing ratio at any altitude can be calculated and the curves extrapolated as shown in Figure 6. It was the purpose of our 1978 Tahoe experiments to validate these extrapolations. Those experiments will be discussed in a later section of this paper.

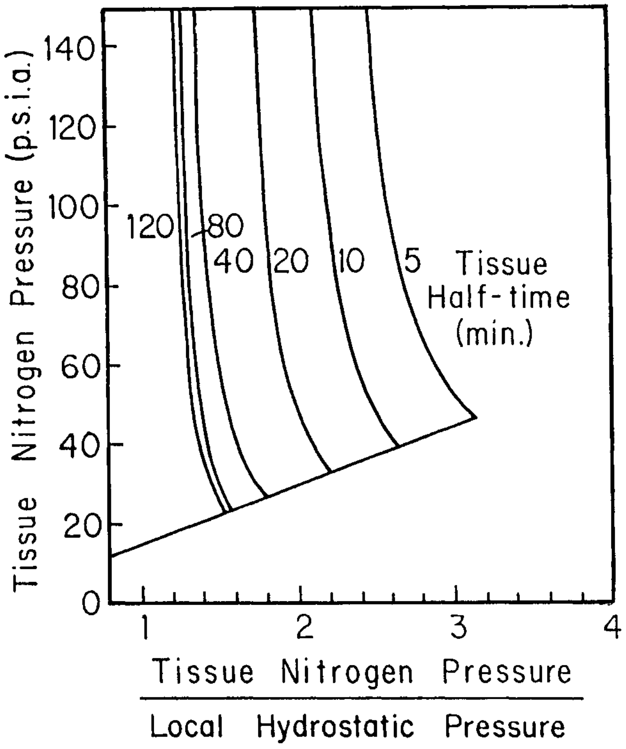


Figure 4. Maximum tissue pressures as a function of the ratio (Ω) of tissue nitrogen pressure to local absolute hydrostatic pressure for the tissue half-times used in the USN Tables (From des Granges, 1956).

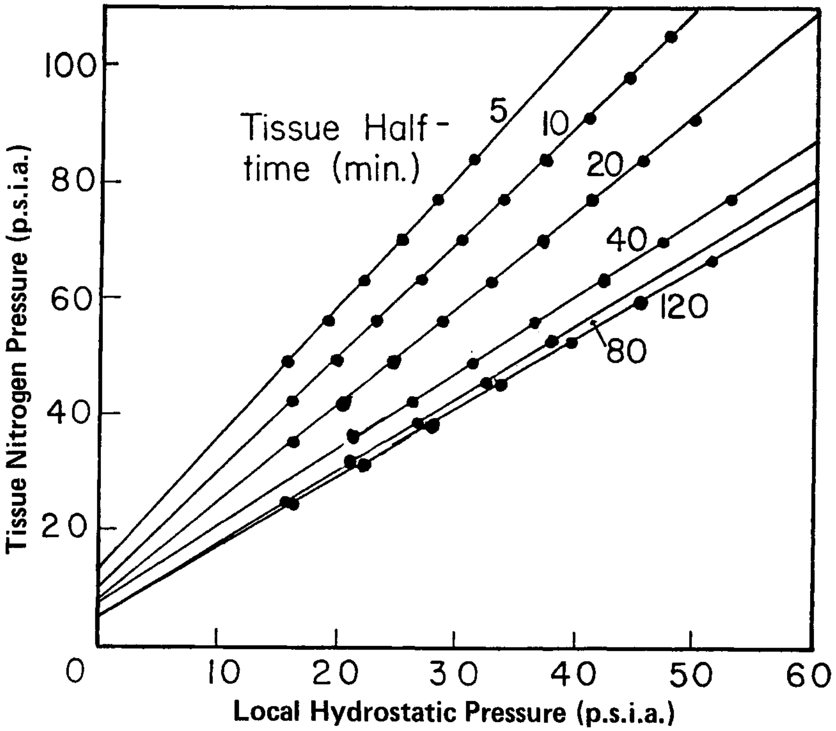


Figure 5. Correlation of maximum tissue nitrogen pressure as a function of local hydrostatic pressure. (Taken from Bell and Borgwardt, 1975)

TABLE IV

Correlating Equations for Critical Tissue Pressures

Tissue Half-Time (Min)	Constants for Equation P = A + B local (PSIA)	
	A	B
5	12.859	2.285
10	9.794	2.000
20	7.850	1.662
40	7.311	1.331
80	4.811	1.262
120	5.030	1.207

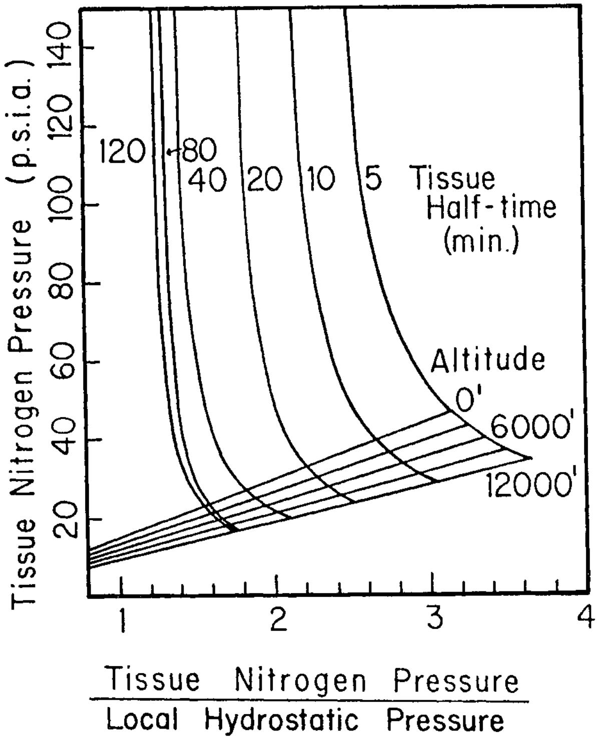


Figure 6. **Extrapolation of the maximum tissue pressure curves to altitude. (Taken from Bell and Borgwardt, 1975).**

An alternate method of graphically representing a dive is the scheme used by des Granges (1956) in developing the USN Tables as shown in Figure 7. The Figure is entered on the left at a tissue nitrogen pressure of 31.17 PSIA corresponding to the start of ascent. The change in pressure during ascent is shown by the line segment directed toward A. This line crosses the 8.2 foot stop, but does not intersect the surfacing line before reaching the critical pressure locus (line segment B-A). Consequently, the diver must remain at 8.2 feet for 7.77 minutes (line segment B-C) until the tissue pressure drops to 27.43, and he can surface (line segment C-D). Note, that had the diver experienced a longer exposure, the tissue nitrogen pressure would have been greater at the start of ascent. The ascent line would then have been approximately parallel to the line segment B, but would have intersected the stop line at a higher pressure, requiring a longer decompression time to reach C.

An important feature of this method is that the decompression calculation starts with the pressure at the beginning of ascent. It makes no difference whether this pressure is reached by short exposure at great depth or long exposure at shallow depth. It is the magnitude of the tissue nitrogen pressure that governs the decompression schedule.

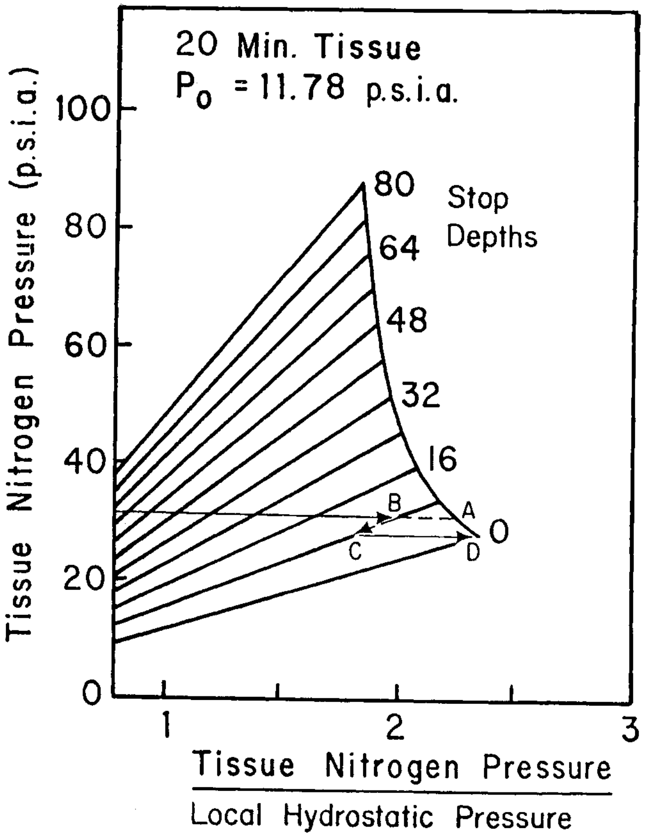


Figure 7. **Decompression diagram for a 100 foot/30 minute dive at an altitude of 6000 feet. (Taken from Bell and Borgwardt, 1975)**

REPETITIVE DIVE GROUPS FOR ALTITUDE DIVING

As with the decompression problem, it is necessary to understand how the U.S. Navy Repetitive Dive Tables were developed in order to make any extensions of the theory to altitude. The development of these tables is outlined in detail by des Granges (1957). To illustrate how the repetitive groups were developed and how they can be used at altitude, the specific example of residual nitrogen times (RNT) resulting from travel from sea level to altitude level will be considered.

Perhaps the most important factor for this discussion is the definition of a repetitive group. Des Granges (1957) stated that "The proposed method is based on the premise that all schedules can be catalogued by their calculated surfacing conditions." and "We now believe that it is possible to consider schedules in groups. The groups used are based on 2 foot increments of pressure in the 120 minute tissue." Consequently, repetitive group designators simply identify the pressure interval in which the 120 minute tissue pressure falls.

TABLE V

Diving schedules and tissue nitrogen pressures* which fall in the H repetitive dive group (Tissue pressure in the 120 minute tissue between 47 and 49 FSW).

120 Minute Tissue Pressure in the Range 47 to 48 FSW

SCHEDULE	5	10	20	40	80	120
20/208	53.0	53.0	53.0	52.5	49.7	47.0
25/142	58.0	58.0	58.0	55.9	50.7	47.0
30/110	63.0	63.0	62.3	58.6	51.5	47.0
120/20	112.7	110.1	58.3	68.1	52.7	47.0
210/10	102.0	107.9	89.9	68.3	52.9	47.0
100/25	120.2	111.8	90.6	68.6	53.0	47.2
35/90	66.6	67.2	66.2	60.5	52.0	47.5
160/15	101.9	108.1	91.1	69.5	53.6	47.6
70/40	97.5	96.2	84.8	68.0	53.7	47.9
220/10	95.7	106.8	91.0	69.7	53.8	47.9
MAXIMUMS	120.2	111.8	91.1	69.7	53.8	48.0

120 Minute Tissue Pressure in the Range 48-49 FSW

SCHEDULE	5	10	20	40	80	120
20/240	53.0	53.0	53.0	53.0	50.5	48.0
25/160	58.0	58.0	58.0	56.4	51.7	48.0
30/120	63.0	63.0	62.6	59.2	52.4	48.0
50/60	80.3	80.8	76.3	65.2	53.3	48.0
90/30	113.4	108.4	90.5	69.7	54.0	48.0
40/80	71.2	71.9	70.1	62.9	53.1	48.1
130/20	100.3	104.9	91.2	70.3	54.2	48.2
60/50	89.0	89.2	81.7	67.7	54.3	48.5
110/25	108.9	110.3	93.2	71.3	54.9	48.5
230/10	87.0	102.6	91.1	70.8	54.9	48.5
35/100	66.6	67.3	66.6	61.7	53.3	48.6
170/15	90.8	104.0	91.5	71.1	55.0	48.6
MAXIMUMS	113.4	110.3	91.5	71.3	55.0	49.0

*Pressures are those calculated assuming the atmosphere to be 100% Nitrogen. To get nitrogen pressure, multiply by 0.79.

Taken from des Granges (1957).

TABLE VI

Repetitive Groups Used by the U.S. Navy

	Pressure in the 120 minute tissue	
Group	Feet of Sea Water	PSIA N_2
A	33 – 35	11.59 – 12.29
B	35 – 37	12.29 – 12.99
C	37 – 39	12.99 – 13.69
D	39 – 41	13.69 – 14.40
E	41 – 43	14.40 – 15.10
F	43 – 45	15.10 – 15.80
G	45 – 47	15.80 – 16.50
H	47 – 49	16.50 – 17.20
I	49 – 51	17.20 – 17.91
J	51 – 53	17.91 – 18.61
K	53 – 55	18.61 – 19.31
L	55 – 57	19.31 – 20.01
M	57 – 59	20.01 – 20.72
N	59 – 61	20.72 – 21.42
O	61 – 63	21.42 – 22.12
Z	63 – 65	22.12 – 22.82

It does not matter by what schedule the diver arrives at a specific tissue pressure. As with decompression schedules, the controlling tissue pressure can be reached by short dives at great depth or long dives at shallow depth. This is illustrated in Table V which was taken from des Granges (1957) report. This table is for the H group, and the dive schedules resulting in the H group, calculated using the USN Tables, range from 20 feet for 240 minutes to 230 feet for 10 minutes. Since the repetitive groups depend entirely on the absolute pressure in the 120 minute tissue, any attempt to arrive at a correction for altitude based on ratios would fail.

The groups used by des Granges are shown in Table VI together with their equivalent in terms of PSIA of nitrogen pressure in the 120 minute tissue. As the tissues of a diver move toward equilibration with reduced atmospheric pressure at altitude, the tissue nitrogen pressures will drop below that which would be in equilibrium with atmospheric pressure at sea level. If, for example, a diver were equilibrated with the atmosphere at 12,000 feet, the tissue nitrogen pressure would be 7.39 PSIA. This value is well below the lowest value of 11.59 PSIA for the U.S. Navy repetitive group A. Keeping in mind that the repetitive group designation relates only to the pressure in the 120 minute tissue, it is clear that there are no repetitive groups which correspond to equilibration with atmospheric pressures above sea level.

At this juncture there is no reason to believe that the same system of grouping tissue pressures used for higher tissue pressures will not work equally well for lower tissue pressures. We have chosen to designate these repetitive groups by numerals to clearly differentiate them from the U.S. Navy groups. We have started our grouping at 32.9 feet of sea water, or a nitrogen pressure of 11.59 PSIA. The groupings for altitude are shown in Table VII.

Before calculating RNTs at altitude, some consideration must be given to the manner by which the diver arrives at altitude. One extreme is to assume the diver reaches altitude instantaneously. Under this assumption the tissue nitrogen pressure at the start of the altitude sequence will be that which was in equilibrium with the atmosphere at sea level, or 11.61 PSIA. Only when a diver flies to the dive site will he approximate instantaneous ascent. An alternate assumption would be to choose some reasonable path which would approximate driving to altitude. In the example presented here we call on our own experience. From the Sacramento Valley to Lake Tahoe requires a driving time of about two hours. The change in elevation is approximately 6000 feet, giving an ascent rate of about 50 feet/minute. We will therefore compare this case of constant ascent rate of 50 feet/minute to the extreme of instantaneous ascent. Upon arriving at altitude, some time will usually elapse before the diver enters the water, so we will also consider the affects of time at altitude.

TABLE VII

Repetitive Groups for Altitude

Pressure in the 120 Minute Tissue

Group	USN Designation Feet of Sea Water	N_2 Tissue Pressure mm Hg
1	31 – 33	535.0 – 570.5
2	29 – 31	500.4 – 535.0
3	27 – 29	465.9 – 500.4
4	25 – 27	431.4 – 465.9
5	23 – 25	396.9 – 431.4
6	21 – 23	362.4 – 396.9
7	19 – 21	327.9 – 362.4
8	17 – 19	293.4 – 327.9
9	15 – 17	258.8 – 293.4
10	13 – 15	224.3 – 258.8

It is first necessary to determine the relationship between altitude, time at altitude and repetitive group. Equation 4 is solved for time as shown in equation 8.

$$t = {}_{120} \ln \frac{P_a - A}{P_a - G} \qquad (8)$$

P_a = alveolar nitrogen pressure at depth given by equation 2.

A = tissue pressure upon arrival at altitude.

G = the pressure corresponding to the final pressure in a repetitive group.

τ_{120} = time constant for the 120 minute half-time tissue τ_{120} = 120/0.693 = 173.6 minutes.

For the case of instantaneous ascent, π_A^0 is the same for all altitude, and is equal to 11.61 PSIA. The method of determining the time range of each repetitive group is illustrated in Figure 8. The curves represent the nitrogen loss from the 120 minute tissue, calculated by equation 4. The pressure intervals corresponding to the repetitive groups are shown as horizontal regions. There will be a certain time period counted from arrival at altitude that the tissue pressure lies within the repetitive groups. These time periods

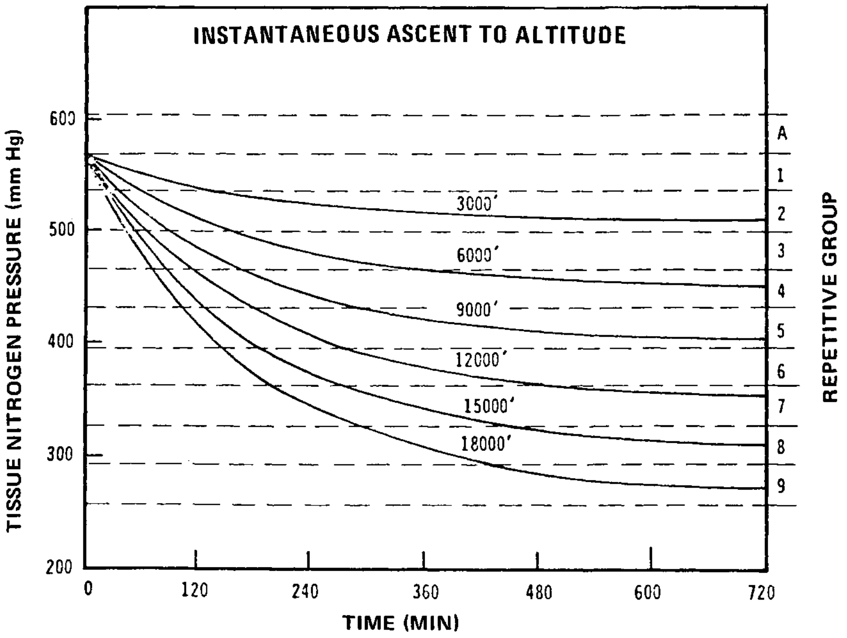


Figure 8. Tissue nitrogen pressure as a function of time for instantaneous ascent to altitude showing repetitive group intervals

are calculated from equation 8 and listed in Table VIII. The entries in the table are the time periods during which the diver is in a given group. For example, after arrival at 6,000 feet, the diver is in Group I for 29 minutes. After two hours, the diver will be in group III, and so forth.

The case for constant ascent to altitude is more complex because not only is the diver driving to altitude but the pressure changes with altitude as he is traveling. To simplify the calculations, it was assumed that atmospheric pressure varied linearly with altitude passing through the values at sea level and 6,000 feet taken from Table 1. This introduces some error, but it is entirely within the bounds of the error in assuming linear ascent. Equation 5 was used to calculate the pressure at various altitudes during ascent. These pressures were then used as the initial pressure for the time interval at altitude. Equation 8 was used to calculate the time period, counted from arrival at altitude, that the 120 minute tissue was in a given repetitive group. The pressure curves and repetitive groups for this case are shown in Figure 9. The time periods are presented in Table IX. Note that in this case the diver may pass through repetitive groups while ascending and arrive at altitude in a higher group. Although after two hours at 6,000 feet, the diver would be in group III, as he was from Table VIII, he reached group III in about one-half the time at altitude required for instantaneous ascent. As a general guideline, Table IX is probably closer to reality than Table VIII, and consequently, the linear ascent model is used for all subsequent calculations.

Similar calculations can be made for the diver starting in equilibrium with the atmosphere at any lower altitude. This results in a new table which we have designated as the "Arrival Table", which must be used in addition to those developed by the U.S. Navy. An example of the "Arrival Tables" is shown in Table XA.

Four factors must now be considered to complete the no-decompression tables. The no-decompression limits must be determined, the repetitive groups for no-decompression divers as a function of depth and time must be assigned, surface interval time (SIT) must be calculated and residual nitrogen time (RNT) as a function of depth must be determined.

TABLE VIII

Repetitive Groups for Time Intervals at Altitude Assuming Instantaneous Ascent to Altitude

	Repetitive Group									
ALT	1	2	3	4	5	6	7	8	9	10
1000	0-oo									
2000	0-312	313-oo								
3000	0-145	146-oo								
4000	0-98	99-329	330-oo							
5000	0-75	76-203	204-oo							
6000	0-61	62-152	153-357	358-oo						
7000	0-52	53-123	124-247	247-oo						
8000	0-45	46-104	105-194	194-394	395-oo					
9000	0-40	41-91	92-162	163-287	288-oo					
10000	0-36	37-81	82-141	142-233	234-444	444-oo				
11000	0-33	34-72	73-124	125-198	199-330	330-oo				
12000	0-31	32-67	68-112	113-174	175-271	272-514	515-oo			
13000	0-29	30-61	62-102	103-156	157-234	235-379	380-oo			
14000	0-27	28-57	58-94	95-142	143-207	208-313	314-639	640-oo		
15000	0-25	26-54	55-88	89-130	131-187	188-271	272-443	444-oo		
16000	0-24	25-51	52-82	83-121	122-171	172-242	243-363	364-oo		
17000	0-23	24-48	49-77	78-113	114-158	159-218	219-312	313-533	533-oo	
18000	0-22	23-46	47-73	74-107	108-148	149-201	202-280	281-428	428-oo	
19000	0-21	22-44	45-70	71-101	102-139	140-187	188-254	255-367	368-784	785-oo
20000	0-20	21-42	43-67	68-96	97-131	132-175	176-234	235-325	326-528	529-oo

NOTE: This table is untested and subject to revision

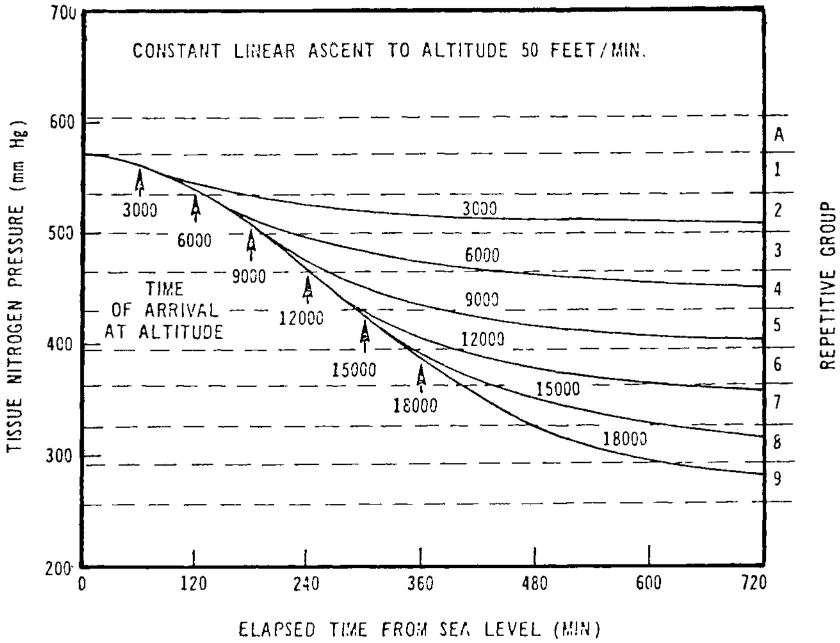


Figure 9. Tissue nitrogen pressure as a function of time for linear ascent to altitude at 50 feet/minute showing repetitive group intervals

NO-DECOMPRESSION LIMITS

The no-decompression limits for a given depth of dive are back-calculated from the critical tissue pressures (π_{ci}) which are allowable upon surfacing following the dive. The critical tissue pressures are calculated for each tissue using the equations in Table IV, in which P local is set equal to the absolute atmospheric pressure at the altitude dive site.

TABLE IX

Repetitive Groups for Time Intervals at Altitude Assuming a Linear Ascent Rate to Altitude of 50 Feet/Minute

	Repetitive Group									
ALT	1	2	3	4	5	6	7	8	9	10
1000	0-oo									
2000	0-295	0-296								
3000	0-117	118-oo								
4000	0-60	61-291	292-oo							
5000	0-27	28-155	156-oo							
6000	0-3	4-94	94-300	301-oo						
7000		0-55	56-179	180-oo						
8000		0-26	27-117	118-317	318-oo					
9000		0-3	4-75	76-200	201-oo					
10000			0-44	45-136	137-348	349-oo				
11000			0-19	20-92	93-244	245-oo				
12000				0-59	60-156	156-400	401-oo			
13000				0-32	33-110	111-256	257-oo			
14000				0-10	11-75	76-181	182-509	510-oo		
15000					0-46	47-131	132-304	305-oo		
16000					0-22	23-93	94-215	216-oo		
17000					0-2	3-62	63-156	157-378	379-oo	
18000						0-37	38-116	117-265	266-oo	

It is now necessary to calculate the tissue pressure for each tissue which would yield the critical pressure for that tissue following a 60-foot per minute ascent from the bottom. This is done by first calculating the ascent time from the bottom by dividing the depth of the dive by the ascent rate. The dimensionless time θ_i is then found by dividing the ascent time by the time constant π_i for the respective tissue. Substituting the numerical values of $x, \tau_i, \pi_{ci}, \theta_i$, the absolute pressure at the depth of the dive (P_D), the rate of ascent (R) and the rate of change of pressure with depth (P') into equation 9 will yield the required pressure at the end of the bottom time $_{Di}$.

$$\pi_{Di} = (e^{-\theta i}) P_c + P'_a (1 - e^{-\theta_i}) + xRP' \; _i (1 - \theta - e^{-\theta_i}) \qquad (9)$$

The derivation of Equation 9 is discussed Bell and Borgwardt 1976.

The bottom time which is required for the i^{th} tissue to reach the pressure $_{Bi}$ can then be calculated from Equation 10.

$$BT_i = \; _i \ln \frac{\pi_D - xP_D}{\pi_i^o - xP_D} \qquad (10)$$

Table XA. Arrival Table for an Altitude of 6,000 Feet in Fresh Water

ALTITUDE		0-1000	2000	3000	4000	5000	6000
GROUP	2	2	2	3	3	3	4

Since the tissues have different critical surfacing pressures and time constants, the series of calculations outlined above will yield a different bottom time for each tissue. Selecting the minimum bottom time from this set as the no-decompression limit will exceed its' critical pressure upon direct ascent to the surface.

REPETITIVE GROUPS IN THE NO-DECOMPRESSION TABLES

The first repetitive group on the left hand side of Table XB is assigned based on the pressure in the 120 minute tissue which is in equilibrium with the atmosphere at the altitude under consideration. The repetitive groups in Table VII, which includes the equilibrium pressure, is then the minimum repetitive group and is the same for all diving depths at that altitude.

The maximum repetitive group for a given dive depth is determined by the surfacing pressure in the 120 minute tissue for a bottom time corresponding to the no-decompression limit for that depth. The pressure

Table XB. No-Decompression Table for an Altitude of 6,000 Feet in Fresh Water

DEPTH	LIMIT	4	3	2	2	A	B	C	D	E	F	G	H	I	J	K
10	--	0	35	82	147	253	***									
15	--	0	22	50	83	124	178	256	403	***						
20	--	0	16	36	58	83	113	149	195	257	355	***				
25	--	0	13	28	45	63	84	107	134	167	207	258	232	464	***	
30	383	0	10	23	36	51	66	84	103	125	150	179	215	259	318	383
35	202	0	9	19	30	42	55	69	84	101	119	139	162	189		
40	148	0	7	16	26	36	47	58	71	64	96	114	131	148		
50	85	0	6	13	20	28	36	45	54	63	74	84				
60	55	0	4	10	16	23	29	36	43	51						
70	38	0	4	9	14	19	25	30	36							
80	30	0	3	7	12	16	21	26	30							
90	24	0	2	6	10	14	18	23								
100	19	0	2	5	9	13	16	19								
110	14	0	2	5	8	11	14									
120	11	0	1	4	7	10										
130	9	0	1	4	6	9										
140	8	0	1	3	6	8										
150	7	0	0	3	5	7										
160	6	0	0	2	5											
170	6	0	0	2	4	6										
180	5	0	0	2	4											
190	5	0	0	1	3	5										

interval which includes this surfacing pressure is then found in Table VI or Table VII and the group corresponding to the appropriate pressure interval is then assigned as the maximum group is greater than the surfacing pressure of the 120 minute tissue, the no-decompression limit is unchanged. However, if the midpressure is less than the surfacing pressure, the no-decompression limit is recalculated using the midpressure as the surfacing pressure in the 120 minute tissue by the method outlined above. This is done to ensure that the no-decompression limit and the last time entry for a given depth in the no-decompression table are in agreement. This adjustment is always conservative.

The remainder of the entries in the no-decompression table are obtained by calculating the bottom times required to yield a surfacing pressure equal to the midpressure of the respective repetitive groups. All times are rounded down to the nearest minute.

SURFACE INTERVAL TABLES

At the beginning of the surface interval following any dive, the diver is assigned to a repetitive group, which will be referred to as the starting group, based on the tissue pressure in the 120 minute tissue. The time the subject remains in the starting group is determined by the time required for the pressure in the 120 minute tissue to be reduced from that corresponding to the midpoint of the starting group to the midpoint of the next higher group. des Granges (1957) added 10 minutes to this time as a waiting period before the subject entered the starting repetitive group, evidently to avoid those cases where the tissue pressure was greater than the midpoint pressure of the starting group. This 10 minute addition is carried through all the SITs in the table.

As an example, consider a starting group of 1 in Table XC. At an atmospheric pressure of 609 mm Hg, corresponding to an altitude of 6,000 feet, 72 minutes are required for the nitrogen pressure in the 120 minute tissue to be reduced from 552 mm Hg (the midpoint of group 1) to 518 mm Hg (the midpoint of group 2). Since there is a waiting period of 10 minutes before entering the group, the entries in the table are 10 minutes and 82 minutes. At 83 minutes, the subject moves to group 2 where he must wait 124 minutes before moving to group 3 and so on. In all cases the time has been rounded up to the nearest minute.

RESIDUAL NITROGEN TIME TABLES

The residual nitrogen time (RNT) for a given depth and group is obtained by calculating the time at depth required for the pressure in 120 minute tissue to increase from that which is in equilibrium with the atmosphere to that equal to the maximum pressure in the respective repetitive group. All RNTs are rounded up to the nearest minute.

As mentioned earlier, the U.S. Navy critical pressure data had not been tested at reduced atmospheric pressures. The foregoing theoretical development is based entirely on the assumption that the linear extrapolation of the safety criteria shown in Figure 5 would provide safe tables at altitude. The next and most important step in this study was to subject the altitude tables to human tests. These tests were conducted at Lake Tahoe, California (elevation 6,200 feet) during the summer of 1978.

Table XC. Surface Interval Table for an Altitude of 6,000 Feet in Fresh Water

4																				1
																				80
3																			10	**
																			***	**
2																		10	136	**
																		135	***	**
1																	10	83	208	**
																	82	207	***	**
A																10	62	134	259	**
																61	133	258	***	**
B															10	51	101	173	298	**
															50	100	172	297	***	**
C														10	43	82	133	205	330	**
														42	81	132	204	329	***	**
D													10	38	70	109	160	232	357	**
													37	69	108	159	231	356	***	**
E												10	35	62	94	133	183	255	380	**
												34	61	93	132	182	254	379	***	**
F											10	32	55	82	114	153	204	276	400	**
											31	54	81	113	152	203	275	399	***	**
G										10	30	50	74	101	132	172	222	294	419	**
										29	49	73	100	131	171	221	293	418	***	**
H									10	28	46	67	90	117	149	168	239	311	435	**
									27	45	66	89	116	148	187	238	310	434	***	**
I								10	27	43	62	82	105	132	164	203	254	326	450	**
								26	42	61	81	104	131	163	202	253	325	449	***	**
J							10	25	41	57	75	96	119	146	178	217	268	340	464	**
							24	40	56	74	95	118	145	177	216	267	334	463	***	**
K						10	24	38	53	70	88	109	132	159	191	230	281	352	477	**
						23	37	52	69	87	108	131	158	190	229	280	351	476	***	**
L					10	23	36	50	65	82	100	121	144	171	203	242	293	364	489	**
					22	35	49	64	81	99	120	143	170	202	241	292	363	488	***	**
M				10	23	35	48	62	77	93	112	132	155	182	214	253	304	376	500	**
				22	34	47	61	76	92	111	131	154	181	213	252	303	375	499	***	**
N			10	22	33	45	58	72	87	104	122	143	168	193	223	264	314	386	511	**
			21	32	44	57	71	26	103	121	142	165	192	224	263	313	385	510	***	**
O		10	21	32	43	55	68	82	97	114	132	153	176	203	235	274	324	396	521	**
		20	31	42	54	67	81	96	113	131	152	175	202	234	273	323	395	520	***	**
Z	10	21	31	41	53	65	77	91	106	123	141	162	185	212	244	283	334	406	530	**
	20	30	40	52	64	76	90	105	122	140	161	184	211	243	282	333	405	529	***	**
END GP	**Z**	**O**	**N**	**M**	**L**	**K**	**J**	**I**	**H**	**G**	**F**	**E**	**D**	**C**	**B**	**A**	**1**	**2**	**3**	**4**

HUMAN TESTS OF THE HIGH ALTITUDE TABLES

The experimental program was to subject a population of healthy, research trained divers to hyperbaric exposure schedules which would stress the tables. The subject population consisted of 13 males and 2 females. Before entering the tests, the subjects were first required to pass the physical examination given to all diving personnel on the Davis Campus of the University of California. The subjects were then given a series of tests in the Human Performance Laboratory to determine their state of fitness, body composition, maximum ventilatory capacity and heart rate and other physiological variables. The purpose of these tests was to provide baseline

TABLE XD

Residual Nitrogen Tables for an Altitude of 6,000 Feet in Fresh Water

Depth	Z	O	N	M	L	K	J	I	H	G	E	F	D	C	B	A	1	2	3
10	***	***	***	***	***	***	***	***	***	***	***	***	***	***	***	349	193	113	56
20	***	***	***	***	***	***	***	***	***	***	438	300	224	172	131	99	71	48	27
30	***	***	***	***	***	462	358	286	236	197	165	138	115	94	76	59	44	30	18
40	509	396	328	280	242	211	185	162	142	124	107	92	78	66	54	43	32	22	13
50	246	220	198	178	160	144	129	115	103	91	80	70	60	51	42	33	25	18	11
60	173	159	145	133	121	110	100	90	81	72	64	56	48	41	34	27	21	15	9
70	135	125	116	106	98	90	82	74	67	60	53	47	41	35	29	23	18	13	8
80	112	104	96	89	82	76	69	63	57	51	46	40	35	30	25	20	16	11	7
90	95	89	83	77	71	65	60	55	50	45	40	35	31	27	22	18	14	10	6
100	83	78	72	67	62	58	53	49	44	40	30	32	28	24	20	16	13	9	5
110	74	69	64	60	56	52	48	44	40	36	32	29	25	21	18	15	11	8	5
120	66	62	58	54	50	47	43	40	36	33	29	26	23	20	17	13	10	8	5
130	60	57	53	49	48	43	39	36	33	30	27	24	21	18	15	12	10	7	4
140	55	52	49	45	42	39	36	33	31	28	25	22	19	17	14	12	9	6	4
150	51	48	45	42	39	36	34	31	28	26	23	21	18	16	13	11	8	6	4
160	47	45	42	39	37	34	31	29	26	24	22	19	17	15	12	10	8	6	4
170	44	42	39	37	34	32	29	27	25	23	20	18	16	14	12	10	7	5	3
180	41	39	37	34	32	30	26	26	23	21	19	17	15	13	11	9	7	5	3
190	39	37	35	32	30	28	26	24	22	20	18	16	14	12	10	9	7	5	3

data which would yield correlates in the event certain of the subjects experienced decompression sickness during the tests. A summary physiologic profile of the subject population is shown in Table XI. A set of "standard" no-decompression exposures was selected which would stress the same tissues both at sea level and altitude as shown in Table XII.

Each subject was required to complete the 40, 70 and 160 foot exposures under dry resting conditions in a hyperbaric chamber on the UC Davis Campus (elevation 65 feet) before they were allowed to participate in the altitude exposures. The purpose for this was to determine which, if any, of the subjects were sufficiently susceptible to decompression sickness that they could not safely complete a standard U.S. Navy no-decompression schedule at sea level. All subjects completed the schedules at sea level without symptoms. The baseline studies were completed by July 22, 1978 and the laboratory was moved to Lake Tahoe (elevation 6,200 feet (1,889.8m)).

TABLE XI

Summary of Subject Physiological Variables: Number of Subjects: 13 male, 2 female

	Range	X	S_x
Age (yrs)	19 - 44	28.0	7.42
Weight (lbs)	132-218	162.23	27.24
Height (inches)	66.5 - 75.0	70.29	2.63
Body Fat (%)	8.95 - 34.09	17.38	7.79
VO$_2$ Max (ml/kg/min)	28.2 - 51.6	40.49	7.36
Hear Rate Max (BPM)	160 - 205	182.6	11.90

TABLE XII

Depth Feet (m)	Time (minutes)		Controlling Tissue
	Sea Level	Lake Tahoe	
40 (12.2)	200	148	80
70 (21.3)	50		20
80 (24.4)		30	20
160 (48.8)	5	5	5

The laboratory site was located on a private estate owned by Mr. and Mrs. Edward Wallis on the shore of the lake. The hyperbaric chamber and support equipment were self-contained and placed in open shade. A small building was available to house the blood and respiratory gas laboratory. The diving operations were conducted from the private pier associated with the estate. The subjects were brought to Lake Tahoe in teams of five for a period of 10 days each. They were allowed 48 hours for gas equilibration with the atmosphere (0.8 ATA) at altitude before starting their hyperbaric exposure sequence. The subjects lived in a cabin rented for the project where their sleeping, eating and activity were monitored. No alcohol or drugs were allowed while a subject was with the project.

After 48 hours of acclimatization, the subjects were required to complete the 40, 80 and 160 foot resting chamber dives before starting the water exposures. As will be discussed below, our tables were such a dramatic departure from existing tables that at the outset the possiblity of decompression sickness was considered high. Even though the principal investigator successfully completed all dives before the subjects arrival, it was still considered important that each subject complete the lowest risk schedules first. The risk of the dives in increasing order of liability was considered to be: resting chamber dives, resting water dives, exercise chamber dives and exercise water dives.

The water exposures were conducted in a Rat Hat and Yokohama dry suit loaned to the project by the Commercial Diving Center, Wilmington, California. The breathing air compressor used with the Rat Hat was provided by Mr. Leonard Greenstone of Los Angeles. At the outset, the potential risk to the subjects was considered to be high and we chose to minimize the incremental risk of the subjects in the cold waters of Lake Tahoe. Consequently, the subjects were allowed to wear whatever thermal protection seemed appropriate to them. The usual choice was a full or partial wet suit inside the Yokohama suit. In spite of this, on the longer exposures they were frequently worked very hard at some time during the dive for various reasons.

The 160 foot dives were all conducted in wet suits or neoprene "dry" suits on SCUBA.

After the subjects had completed the chamber schedule at altitude and were into the water schedule, they were also allowed to participate in the exercise chamber dives. The depths used were the same as for the resting dives. The exercise consisted of 5 minute bouts of pedaling a bicycle ergometer in the recumbent position. The subjects' heart rate (among other variables) was monitored outside the chamber and the subject was instructed to alter the speed of pedaling to yield a heart rate equivalent to 20% of the difference between their resting and maximum heart rates. As more experience was gained, the exercise bouts were frequently planned so that the subject was exercising during ascent and continuing into the surface phase. During exercise, respiratory gas samples were taken for analysis and the ventilation rate measured.

The definitive indicator of decompression sickness is the presence of pain or other symptoms. However, we used two other indices with which we hoped to find an index of diving stress. The first was listening for bubbles using a doppler pre-cordial bubble detector (Spencer, 1972). The second was monitoring circulating platelets (Martin and Nichols, 1972) levels, packed cell volume, four plasma clotting factors and three clotting times for evidence of disseminated intravascular coagulation (DIC).

During the test period, the subjects were not given a hyperbaric exposure more frequently than 24 hours. Each subject had been trained as a chamber operator and as surface tender for the hard hat diving operation. Between exposures, the subjects were the operators and tenders for those being exposed.

RESULTS AND CONCLUSIONS

A total of 168 exposures were completed. These are summarized in Table XIII. There were no cases of decompression sickness. There were no pre-cordial bubbles detected. Of the twelve subjects studied, only one showed any decrease in circulating platelets and none showed any DIC as indicated by clotting factors.

Based on these results, it appears that the safety criteria derived from the extrapolation of the U.S. Navy data provide no-decompression limits which are safe.

The no-decompression limits for the exposures we used in this study are shown in Table XIV compared to the no-decompression limits obtained from the Cross Corrections (1967), the Galfetti Tables (1971) and the Boni Tables (1976). In Table XV, the decompression stops required by these tables are shown for the dives we completed on a no-decompression schedule.

The no-decompression limits calculated by Bell and Brogwardt[1] are significantly longer than those predicted by others, and exposures which we have tested on no-decompression schedules require significant decompression time under the other schedules. Because there were no objective or subjective indications of significant diving stress, it would appear that the safety criteria we have derived from the U.S. Navy data result in safe exposures. Although

TABLE XIII

EXPOSURE SUMMARY

Total Chamber Dives	113
Total Water Dives	55
Resting Dives	145
Exercise Dives	23
Total Exposures	168

SEA LEVEL DIVES

160 feet/5 minutes	14
70 feet/50 minutes	15
40 feet/200 minutes	15

TAHOE DIVES

Chamber:	160 feet/5 minutes	17
	100 feet/ 19 minutes	5
	80 feet/30 minute rest	17
	80 feet/30 minute exercise	13
	50 feet/84 minutes	2
	40 feet/148 minutes	15
H_2O Dives:	160 feet/5 minutes	23
	80 feet/30 minutes	17
	40 feet/148 minutes	15

TABLE XIV

Comparison of No-Decompression Limits

Depth Feet (m)	Bell and Borgwardt	Cross	Galfetti	Boni
40	148	100	60	50
80	30	25	20	6
160	5	None	None	None

TABLE XV

Comparison of Decompression Required and Bell/Borgwardt No-Decompression Time

Depth Feet (m)	Bell/Borgwardt	Cross		Galfetti	Boni
	No-Decompression Time	Stops	10 Feet	7m, 4m, 2m	3m
40	148	Time (minutes)	21	Not on Table	48
80	30		3	3 6 12	7
160	5		1	2 3 6	2

we have repetitive dive schedules calculated, they were not tested. The "arrival" tables were used on several dives. These tables account for the residual nitrogen liability incurred by diving immediately upon arriving at altitude. No-decompression tables can now be calculated and tested with some confidence. In addition, we now are in a position to calculate and test flying-after-diving schedules. The safety criteria which is required for these calculations is that which we tested in this study. There is no reason to believe at this juncture that these criteria are not safe.

REFERENCES

Behnke, A.R., "The Isobaric (Oxygen Window) Principle of Decompression" in *The New Thrust Seaward*, Trans. 3rd Annual Conference Marine Technology Society, San Diego (1967).

Bell, R. L. and R. E. Borgwardt, "The Theory of High Altitude Correction to the U.S. Navy Standard Decompression Tables: I The Cross Correction." Undersea Biomedial Research (in press).

Cross, E. R., "High Altitude Decompression", Skin Diver Magazine, November, 1970, page 17.

Cross, E. R., "Technifacts", Skin Diver Magazine, December 1967.

des Granges, M., "Standard Air Decompression Table", Research Report 5-57. U.S. Navy Experimental Diving Unit, December 3, 1956.

des Granges, M., "Repetitive Diving Decompression Tables", Research Report 6-57, U.S. Navy Experimental Diving Unit, January 9, 1957.

Haldane, J. S., *Respiration*, Chapter 12, Yale University Press, New Haven 1922.

Hall, P., Fitch, J. W., McMurtry I.F., "The Miniature Pig as a Model for the Study of Decompression". Personal communication July 15, 1975.

Hills, B. A., "Thermodynamic Decompression: An Approach Based Upon the Concept of Phase Equilibration", Chapter 15 in *The Physiology and Medicine of Diving and Compressed Air Work*, P. B. Bennett and D. H. Elliot, editors, Bailliere Tundall and Cossell, London (1969).

U. S. Standard Atmosphere 1962, U. S. Government Printing Office, Washington, D. C. 20402.

U. S. Standard Atmosphere Supplements 1966, U. S. Government Printing Office, Washington, D.C. 20402.

Workman, R. D., "Calculation of Decompression Schedules for Nitrogen-Oxygen and Helium-Oxygen Dives," Research Report 6-65, U. S. Navy Experimental Diving Unit, May 26, 1965.

Spencer, M. P. and H. F. Clarke, Precordial Monitoring of Pulmonary Gas Embolism and Decompression Bubbles. Aerospace Medicine 43(7): 762-767, 1972.

Martin, K. J. and Nichols, G., Observations on Platelet Changes in Man After Simulated Diving, Aerospace Med. 43(8): 827-830, 1972.

Cross, E. R., "Technifacts," Skin Diver Magazine, December 1967.

Galfetti, A., *Sommozzotori in Acquo Dolci*, Tenero, Switzerland. 1971.

Boni, M. R., R. Schibli, P. Nussberger and A. A. Buhlman. 1976. Diving at Diminished Atmospheric Pressure, Undersea Biomed, Res 3, No. 3, 189-204.

QUESTION AND ANSWER SECTION

DR. BASSETT

Q How was it discovered that N_2 is 5 times more soluable in fat?

A Because scientists are inquisitive, some unknown chemist/physicist tried to find out – and did!

Q Is bounce diving more dangerous than longer dives assuming both are within no-decompression limits?

A I wish we really knew! The evidence to date is inconclusive under the parameters (i.e., No-Decompression limits) described.

Q Have you ever known of a documented case of "bends" due to repeated breath hold diving? What were the circumstances?

A Yes. Multiple dives in excess of 80 feet, with minimal (only a few breaths between excursions) surface interval, kept up for a full day of diving.

Q Do you have information available that gives pressure in P.S.I. of Nitrogen for repetitive group letter on Table No. 1-11 and Table 1-13?

A Normally, Nitrogen pressures in calculating decompression are expressed in feet of sea water absolute (fswa). Yes, I have such information, which I have calculated. Write me for details.

Q Is there any single publication giving many of the factors and figures?

A Regarding what? Decompression? If so, the best single publication is "The Physiology and Medicine of Diving and Compressed Air Work", edited by Bennet and Elliot, Williams & Wilkins publishers.

Q Why is N_2 the only gas considered in DS discussion? Why wouldn't you consider CO_2, excess O_2, etc.?

A N_2 is the main culprit with respect to supersaturation. However, once a bubble is formed, O_2, CO_2 and H_2O vapor rapidly diffuse into it causing bubble growth.

Q Is it true that a diver should increase the intake of Vitamins A, E, and C to aide in respiration and nitrogen elevation from the body's systems, as well as improving his physical condition? If this is true, what about the soluable vitamins such as A and E? A and E being dangerous in excess? What's a rule of thumb to go by?

A Eat a balanced diet and let the vitamin peddlers find another source of income besides a gullible public.

DR. CHARLES BROWN

Q What finally happens to the DS patient if not treated at all?

A Most recover, but an unhappy few suffer permanent hearing loss, ringing in the ears, paralysis, and of course, some die.

Q In inner ear ringing an indication of previous decompression violation?

A It can be. Considerations are DS, squeeze and window rupture. Another is damage by loud noise.

Q If a diver is bent, and O_2 is available, is it best to administer it on the way to a chamber?

A Yes. Of course. Very definitely.

Q What is the source of the information that divers are 75% less likely to contract DS after two weeks of regular diving?

A Decompression Sickness: Volume 1, by B. A. Hills, John Wiley & Sons, 1977, discusses the evidence (page 40). I'll send a reference list upon request.

Q All other things being equal, will a diver with a high oxygen uptake rate be more likely to bend than one with a lower rate?

A Usually yes, but it depends. Exertion causes faster in-gassing and more nitrogen aboard. Exertion during decompression from a *conservative* dive will speed out-gassing and reduce the chance of bends. Exertion during decompression from a table-pushing dive increases the risk by releasing tissue gas faster than it can be eliminated.

Q Is it safe to ascend slower than 60 fpm (due to ear problems, etc.)?

A Yes, in shallow dives.

Q Please comment on the use of the tables by older divers?

A If you're a little older, use the next deeper depth or longer time. If your're much older, use both. If you're very much older, also pray.

Q What is your recommendation regarding the practice of taking nonrequired stops at 10 feet before surfacing?

A It can't hurt, and can rarely help. I especially recommend this practice for any dive approaching table limits, or when pre-disposing factors (to bends) are present.

Q Would you consider it good practice to make a decompression stop at 10 feet after every dive, even though the dives were within the no-decompression limit?

A For most sport divers, it would be a waste of time, but if limits were pushed or factors pre-disposing to bends were present, it would be a damn good thing.

Q Since the bodies of females have a higher proportion of adipose tissue than that of male bodies – are the dive tables equally applicable?

A The premise is not valid. Some guys are fatter than gals. Anyway, fatness adds risk to all except conservative dives and table limits should be avoided.

Q Along with fatigue a few hours after diving, I have felt a tingling "pins and needles" feeling for a 10-20 minute period upon occasion. Any educated guesses as to the cause , and should I worry? No definite diving pattern causes this, and I have had no other "symptoms".

A Most if not all sport dives result in "silent" bubbles and some tissue damage. Your symptoms are a common reflection of this damage. Recovery seems to be complete, so there is probably no cause to worry. Still, if the symptoms are more than slight, it seems prudent to dive more conservatively. We really don't know the long-range effects of repeated bubbling in the body.

JON HARDY

Q What effect does altitude have on the decompression meter? Is it safe to use only at sea level?

A Altitude has a detrimental effect on the meter. It is best used at sea level. It should be protected from decreased pressures, as at altitude, with the sealed carrying case.

Q On the decompression meter, what do the blue numbers under the memory zone represent?

A The blue numbers are used by the factory to calibrate the meter.

Q How many instruction manuals for the meter have been issued since the decompression meter became available? If several, plase highlight the changes.

A Several instruction manuals have been issued with two major editions. Check also with Scubapro.

Q What is your reaction to the *Undercurrent* articles critical of the Scubapro meter?

A The *Undercurrent* article was biased and made no attempt to consider the value of the meter.

Q How good is the meter as far as cold or extra hard diving? Is it accurate?

A The meter should be used with care in any conditions beyond normal diving conditions. It and the tables are not accurate under any conditions outside the normal. Both should have safety factors applied.

ANY OR ALL SPEAKERS

Q Do you see any potential physiological problems associated with Graver's multi-level diving concept?

Hardy No, only human confusion leading to decompression problems.

Brown Not for healthy young divers. However, although it increases safety for those who would otherwise neglect the tables, it also might reduce the safety factor for those who would otherwise dive multi-level and obey the tables faithfully.

Bassett No. They are within the limits of diving the standard no-decompression tables in all respects – if you can handle the computation.

Q Is a 10 foot safety stop at the end of a dive a good idea?

Hardy It is particularly good on the last dive of the day.

Brown Yes.

Bassett Yes. Many studies indicate this is a good procedure for sport divers, but see next answer below.

Q Should safety stop time at the end of a dive be added to the bottom time for the dive?

Hardy Yes; a safer procedure.

Brown No; if less than 30 feet.

Bassett Yes. Safety dictates using total dive time to choose repetitive groups, etc., for no-decompression diving.

Q How come whales, dolphins, porpoises, pinnipeds, etc., don't get bent?

Hardy They are different.

Brown Adaptation. Non-rigid thorax. Squeeze pushes air out of alveoli into upper airway where there is no gas exchange. Also, divers reflex closes off peripher circulation/making residual circulation available for the coronaries and the brain. So, N_2 is not carried to the tissues. There may be other factors.

Bassett As I understand it, partly the diving reflex which shunts blood flow away from the periphery – muscles, etc. Thus, no significant N_2 loading of the tissues.

Q A blue whale (100 feet, 130 tons) standing on his head in 100 feet of H_2O with flukes exposed at the surface – how does the whale compensate for three different atmospheres of pressure.

Hardy Who cares?

Brown He doesn't have to. Immersion essentially negates gravity. The head of hydrostat pressure between flukes and snout is balanced by the head of hydrostatic pressure in the sea. The part of the flukes actually out of the water loses external hydrostatic support so blood shifts from it to the body – no problem.

Bassett Did someone really ask this? I expect this question was inserted by Dennis Graver! Give me six months and I'll try to answer it!

Q Is the 130 foot maximum depth limit a realistic limit for recreation divers?

Hardy Yes, for experienced sport divers.

Brown In the main, yes. 80 or 100 feet might be better. Beyond those depth, rewards do not compensate for the rapidly escalating hazards. Yet, there's no absolute standard. Shallower may be hazardous in cold, murky water and deeper safe in warm, clear water. (S. Caicos)

Bassett Yes. As a maximum. I prefer a shallower limit as an optimum.

Q Are short, deeper dives or long, shallow dives recommended if you will be flying after diving?

Hardy Stay well within no decompression limits.

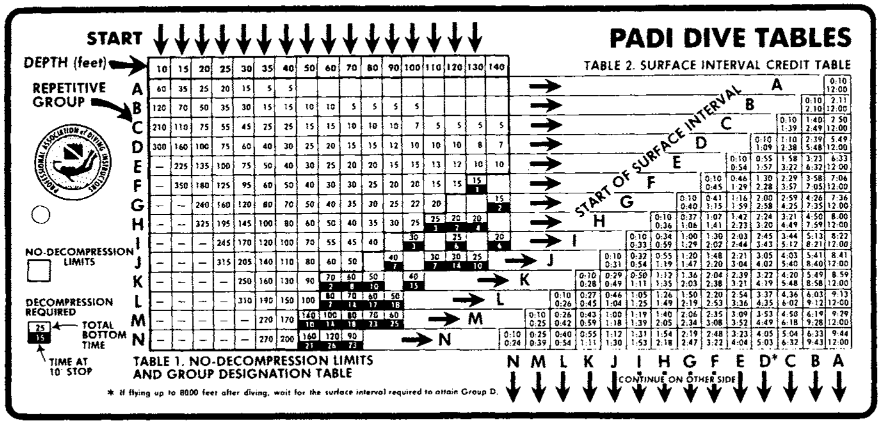
Brown I don't know, but I'll vote for long, shallow dives as safer. Short deep dives result in faster out-gassing, but are more likely to produce bend hits. Long, shallow dives are more likely to produce limb bends; aggravating, but not dangerous. Tell the pilot to fly as low as possible, to pressurize the cabin maximally and to provide O_2, if any symptoms occur.

Bassett At this point, I cannot recommend anything but a long surface interval beween any diving and flying. Stay tuned for future publications on the subject!

PADI DIVE TABLES

*Simplified - as easy as one, two, three
*Many new features
*Designed specifically for sport diving

(Front)



START

PADI DIVE TABLES

NO-DECOMPRESSION LIMITS ☐

DECOMPRESSION REQUIRED: 25 ← TOTAL BOTTOM TIME; 15 ← TIME AT 10' STOP

DEPTH (feet)	10	15	20	25	30	35	40	50	60	70	80	90	100	110	120	130	140
A	60	35	25	20	15	5	5										
B	120	70	50	35	30	15	15	10	10	5	5	5	5				
C	210	110	75	55	45	25	25	15	15	10	10	10	7	5	5	5	5
D	300	160	100	75	60	40	30	25	20	15	15	12	10	10	10	8	7
E	—	225	135	100	75	50	40	30	25	20	20	15	15	13	12	10	10
F	—	350	180	125	95	60	50	40	30	30	25	20	20	15	15	15 1	
G	—	—	240	160	120	80	70	50	40	35	30	25	22	20			15 2
H	—	—	325	195	145	100	80	60	50	40	35	30	25	25 3	20 2	20 4	
I	—	—	—	245	170	120	100	70	55	45	40		30 3		25 6		20 6
J	—	—	—	315	205	140	110	80	60	50		40 7		30 7	30 14	25 10	→ J
K	—	—	—	—	250	160	130	90	70 2	60 8	50 10		40 15	→ K			
L	—	—	—	—	310	190	150	100	80 7	70 14	60 17	50 18	→ L				
M	—	—	—	—	—	220	170	140 10	100 14	80 18	70 23	60 25	→ M				
N	—	—	—	—	—	270	200	160 21	120 26	90 23	→ N						

TABLE 1. NO-DECOMPRESSION LIMITS AND GROUP DESIGNATION TABLE

* If flying up to 8000 feet after diving, wait for the surface interval required to attain Group D.

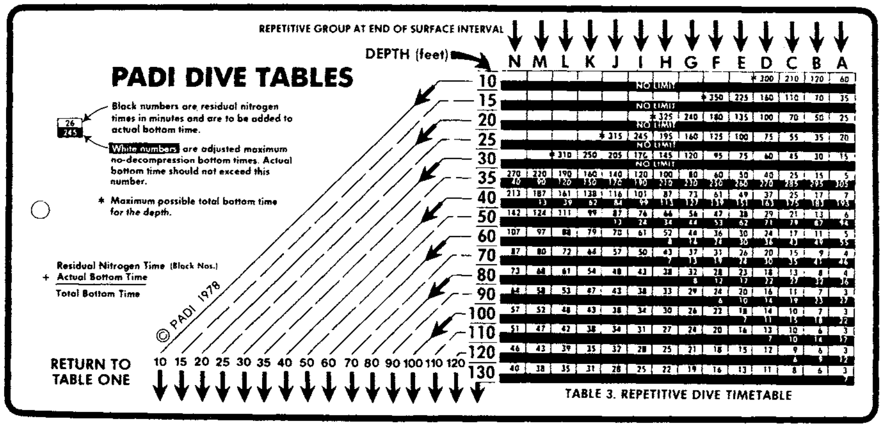
TABLE 2. SURFACE INTERVAL CREDIT TABLE

START OF SURFACE INTERVAL

REPETITIVE GROUP	N	M	L	K	J	I	H	G	F	E	D*	C	B	A
A														0:10 12:00
B													0:10 2:10	2:11 12:00
C												0:10 1:39	1:40 2:49	2:50 12:00
D											0:10 1:09	1:10 2:38	2:39 5:48	5:49 12:00
E										0:10 0:54	0:55 1:57	1:58 3:22	3:23 6:32	6:33 12:00
F									0:10 0:45	0:46 1:29	1:30 2:28	2:29 3:57	3:58 7:05	7:06 12:00
G								0:10 0:40	0:41 1:15	1:16 1:59	2:00 2:58	2:59 4:25	4:26 7:35	7:36 12:00
H							0:10 0:36	0:37 1:06	1:07 1:41	1:42 2:23	2:24 3:20	3:21 4:49	4:50 7:59	8:00 12:00
I						0:10 0:33	0:34 0:59	1:00 1:29	1:30 2:02	2:03 2:44	2:45 3:43	3:44 5:12	5:13 8:21	8:22 12:00
J					0:10 0:31	0:32 0:54	0:55 1:19	1:20 1:47	1:48 2:20	2:21 3:04	3:05 4:02	4:03 5:40	5:41 8:40	8:41 12:00
K				0:10 0:28	0:29 0:49	0:50 1:11	1:12 1:35	1:36 2:03	2:04 2:38	2:39 3:21	3:22 4:19	4:20 5:48	5:49 8:58	8:59 12:00
L			0:10 0:26	0:27 0:45	0:46 1:04	1:05 1:25	1:26 1:49	1:50 2:19	2:20 2:53	2:54 3:36	3:37 4:35	4:36 6:02	6:03 9:12	9:13 12:00
M		0:10 0:25	0:26 0:42	0:43 0:59	1:00 1:18	1:19 1:39	1:40 2:05	2:06 2:34	2:35 3:08	3:09 3:52	3:53 4:49	4:50 6:18	6:19 9:28	9:29 12:00
N	0:10 0:24	0:25 0:39	0:40 0:54	0:55 1:11	1:12 1:30	1:31 1:53	1:54 2:18	2:19 2:47	2:48 3:22	3:23 4:04	4:05 5:03	5:04 6:32	6:33 9:43	9:44 12:00

CONTINUE ON OTHER SIDE

(Back)



PADI DIVE TABLES

Black numbers are residual nitrogen times in minutes and are to be added to actual bottom time.

White numbers are adjusted maximum no-decompression bottom times. Actual bottom time should not exceed this number.

* Maximum possible total bottom time for the depth.

Residual Nitrogen Time (Black Nos.)
\+ Actual Bottom Time
Total Bottom Time

© PADI 1978

REPETITIVE GROUP AT END OF SURFACE INTERVAL

DEPTH (feet)	N	M	L	K	J	I	H	G	F	E	D	C	B	A
10											*300	210	120	60
						NO LIMIT								
15									*350	225	160	110	70	35
						NO LIMIT								
20							*325	240	180	135	100	70	50	25
						NO LIMIT								
25					*315	245	195	160	125	100	75	55	35	20
						NO LIMIT								
30			*310	250	205	170	145	120	95	75	60	45	30	15
						NO LIMIT								
35	270 40	220 90	190 120	160 150	140 170	120 190	100 210	80 230	60 250	50 260	40 270	25 285	15 295	5 305
40	213	187 13	161 39	138 62	116 84	101 99	87 113	73 127	61 139	49 151	37 163	25 175	17 183	7 193
50	142	124	111	99	87 13	76 24	66 34	56 44	47 53	38 62	29 71	21 79	13 87	6 94
60	107	97	88	79	70	61	52 8	44 16	36 24	30 30	24 36	17 43	11 49	5 55
70	87	80	72	64	57	50	43 7	37 13	31 19	26 24	20 30	15 35	9 41	4 46
80	73	68	61	54	48	43	38	32 8	28 12	23 17	18 22	13 27	8 32	4 36
90	64	58	53	47	43	38	33	29	24 6	20 10	16 14	11 19	7 23	3 27
100	57	52	48	43	38	34	30	26	22	18 7	14 11	10 15	7 18	3 22
110	51	47	42	38	34	31	27	24	20	16	13 7	10 10	6 14	3 17
120	46	43	39	35	32	28	25	21	18	15	12	9 6	6 9	3 12
130	40	38	35	31	28	25	22	19	16	13	11	8	6	3 7

RETURN TO TABLE ONE

10 15 20 25 30 35 40 50 60 70 80 90 100 110 120

TABLE 3. REPETITIVE DIVE TIMETABLE

*Available on 4" X 8½" durable plastic, printed in three colors. For use during diving activities.

*Large color-coded instruction wall chart (25"X26") also available.

*For more information, contact:

PADI
2064 N. Bush St.
Santa Ana, CA 92706