

could explain why the incidence of dysbaric osteonecrosis is higher now than it was in the middle of the 1970's.

ADVICE TO THE SPORTS DIVER

What can we make of this? Sports divers who do not go below 30m, and observe the tables properly are most unlikely to develop lesions.

Those who dive below 30m, to 50m, have approximately a 1% chance of developing lesions. On the basis of the MRC figures, which do not give the lesions associated with each depth, 36% of lesions will be juxta-articular, probably in the humerus. Recorded attacks of decompression sickness increase the incidence of bone lesions nearly five times. In Australia, many cases of decompression sickness are associated with rapid ascents.

Various surveys of both new and in use depth gauges have shown that a large proportion are inaccurate. Luckily many overestimate the depth. But many underestimate the depth and can lead the diver astray in his depth-time profile.

Careful diving, using a recently calibrated depth gauge, a waterproof watch, staying within the no-decompression limits and avoiding sudden unscheduled ascents and running out of air should allow the sports diver to enjoy his or her fun without risking any joints.

REFERENCES

1. Harrison JAB. Aseptic bone necrosis in naval clearance divers: radiographic findings. *Proc Roy Soc Med.* 1971; 64: 1276-1278
2. Hunter WL Jr, Biersner RJ, Sphar RL, Harvey CA. Aseptic bone necrosis among US Navy divers: survey of 934 non-randomly selected personnel. *Undersea Biomed Res.* 1978; 5: 25-36
3. Ohta Y, Matsunage H. Bone lesions in divers. *J Bone Joint Surg Br.* 1974; 56: 3-16
4. Amako T, Kawashima M, Torisu T, Hayashi E. Bone and joint lesions in decompression sickness. *Seminars in Arthritis and Rheumatism* 1974; 4: 151-190
5. Williams B and Unsworth I. Skeletal changes in divers. *Aust Radiol.* 1976; 20: 83-94
6. Decompression Sickness Central Registry and Radiological Panel. Aseptic bone necrosis in commercial divers. *Lancet.* 1981; ii: 384-388.

ACKNOWLEDGMENT

We are grateful to the editor of "The Lancet" and the authors of the Decompression Sickness Central Registry and Radiological Panel report for permission to reproduce Figure 1 and tables 3, 4, 5, 6 and 7.

THE SAFETY OF THE UNITED STATES NAVY DECOMPRESSION TABLES AND RECOMMENDATIONS FOR SPORTS DIVERS

Bruce Bassett

I will quickly review what Haldane found and what the United States Navy (USN) modifications to the original Haldane model were, as a result of several years of development of decompression tables. Then I will analyse the safety of the USN standard air decompression tables, leading on to recommendations for sport divers based on safety analysis.

Haldane basically had two observations. Testing his animals by exposing them to increasing depth, keeping them there long enough to attain equilibrium with the inert gas pressure, saturating them, and then decompressing them, he developed the concept that there was a critical supersaturation ratio. This is often expressed as a pressure ratio. One can always reduce the pressure by one half within the realm that he worked in, to pressures of 6 atmospheres absolute. However the important aspect is the driving force for inert gas to form bubbles. Therefore it is expressed as a ratio of the nitrogen pressure, trying to force gas out of solution, versus the barometric pressure trying to keep the gas in solution. That was the empirical observation. There was some critical supersaturation ratio and if he observed it, he did not get the animals in trouble with decompression sickness (DCS).

After looking at what factors were involved in inert gas uptake and elimination, he decided that handling all the variables was difficult. So he developed a mathematical model based on the half time equation. Haldane knew that there was an infinite number of curves that described the uptake and elimination of nitrogen in various regions of the body, depending on the combinations of fat and perfusion. Of course these rates may change with other variables such as cold and exercise. By choosing a number of time constants to put into the equation one can approximate to what is really happening in the body. That was his second concept.

The first decompression tables were built using the half times 5, 10, 20, 40 and 75 minutes, applied to the half time equation. As an example, if a diver went to a depth where the nitrogen pressure in compressed air was 4 atmospheres absolute for 40 minutes one can use this equation to calculate the amount of nitrogen that is taken up. A 5 minute half time after 40 minutes will have been exposed for 8 units of half time, so that tissue would be 100% saturated. It would have a nitrogen pressure of 4 atmospheres. A 10 minute tissue after 40 minutes would have been exposed to 4 units of half time so would be about 93.75% of 4 atmospheres. The 20 minute tissue would be 75% saturated, it would hold 3 atmospheres of nitrogen pressure and so on. Using the empirical observation that a nitrogen pressure to barometric pressure ratio of 1.58 is safe, one can calculate the barometric pressure that the diver can safely ascend to. One multiplies the calculated nitrogen pressure by 1.58 which gives you the barometric.

pressure that you can ascend to.

Haldane built decompression tables based on this empirical observation of the critical ratio and a mathematical model. Compared to what was happening at the turn of the century in terms of divers getting bent like pretzels, his tables worked because diving became much more successful and the incidence of bends went down. Sometime after 1900 when the USN was doing its diving using the Haldane tables, which were fairly limited in scope, both in depth and bottom times, it became necessary to go beyond the Haldane tables. So, using the Haldane calculation method and the Haldane observations, they went to greater depths and greater bottom times and produced a set of tables, the older pre-1955 tables. They can be recognised because they had an ascent rate of 25 feet per minute. Also within each depth range there is an asterisk for the optimum bottom time at a given depth time. I am not sure what was meant by an optimum bottom time. They had times longer and shorter, but one was labelled optimum. They were used by the USN for diving for a number of years. The old tables did not have a repetitive dive system. One simply added the bottom times together and came up with the decompression requirement after the second or third dive. They did not give any credit to the off gassing that occurred on the surface.

USN Standard Air Tables

When scuba came into military use, its short duration demanded repetitive diving for useful work to be achieved. The decompression penalties of the old system were unacceptable. Perhaps there was some incidence of decompression sickness with the old tables. So in the early to mid-50's, the USN went through the whole process again, using basically the Haldane equations for half times. Then they tested them at the experimental diving unit on real live divers in water, in a wet pot, in their equipment, doing work. With all this testing, if a diver bent, that was not an acceptable schedule. They had to go back, look at the half times and the calculated nitrogen pressures, and see which one was the likely culprit for having caused that bend. Then they would reduce that calculated value. That is, reduce the bottom time. Nowadays, with statisticians breathing down our necks in research, to test a given schedule to an end point of a half percent bends with 95% confidence limits requires about 150 individual man tests. That is very expensive. Obviously they did not do that. The best that they could do was to produce a set of tables with an end point of zero bends. The result was that the tables that were produced in 1955 have not changed one iota since.

The USN had to extend the half times beyond Haldane's slowest tissue, which was 75 minutes. That was a whole body saturation time of 7 1/2 hours, six times 75 minutes. The USN tables, the standard air tables and the repetitive dive tables, have half times of 5, 10, 20, 40 and 80 and the slowest half time is 120 minutes. If one multiplies that 120 minutes, the slowest tissue, by 6, 6 units of half time, it takes 12 hours to reach total saturation. Assuming that excretion is the mirror image of uptake any excess nitrogen

that is put into that slowest tissue takes six times 120 minutes to be got rid of. So 12 hours is the magic number in the repetitive dive scheme of the USN tables. Once the diver has gone beyond 12 hours he is considered to be "clean". Theoretically there is no excess nitrogen in the slowest tissue.

So that was number one finding. They found they needed a 120 minute tissue basically by running dives longer than Haldane did. Maybe they discovered it as a result of repetitive dives. I am not sure.

The other change from Haldane's observations was the critical ratio. The USN found that there was a different supersaturation ratio, apparently a different critical ratio for each of the half times. At first one says, well why? Why can one tissue hold more nitrogen than another tissue? It probably has nothing to do with a physical force. It may be simply time and risk. Nitrogen molecules have to move within the body, to get together and perhaps overcome forces like surface tension and so on to form a bubble. There may be a time element for this to occur and for a bubble to come into being. If one reaches the surface with a 5 minute tissue which has 1.35 atmospheres of nitrogen in it, 5 minutes later half of the excess gas has gone because it is eliminated at the same fast rate as it is taken up. If one surfaces with a 120 minute half time tissue with 1.35 atmospheres in it, it takes a long time for that to decay down. The differing critical ratios represent time at risk, rather than a physical ability for that tissue to hold more nitrogen.

Why are these ratios different from Haldane's? Haldane based his observations on saturation divers. So he was only dealing with the slowest compartment. Under those conditions no other tissue can have any more nitrogen than that. The USN 80 minute critical ratio is essentially the same as Haldane had with his 75 minute tissue. The critical ratio is 1.58 to one and a little bit less with the 120 minute tissue. But consider a bounce dive down to 165 feet for ten minutes. For ten minutes there is a large pressure gradient. But the 120 minute tissue has not taken up very much nitrogen, nowhere near its limit. So if one tests the safety of a bounce dive and the diver is not bent it becomes apparent that the faster tissues can withstand a higher ratio.

Very simply half times and critical ratios are the essentials when describing the USN standard air decompression tables. If one can add, subtract and fiddle around a little bit with the half time equation, one can calculate these schedules. It is a very simple set of calculations. There is no deep magic in it.

M Values

Some people are confused by M values. It is simply the calculated partial pressure of nitrogen in a half time tissue allowed when you reach a given decompression stop. What I have been talking about is strictly the surfacing value. For decompression diving, the M values change, as the amount of nitrogen you can add for each 10 feet is greater than what you can have when you reach the surface.

But it also works out that the critical ratios are different. The ratios actually decrease with depth. The allowable supersaturation level is less with increased depth and it reaches its maximum on surfacing. M values are expressed in feet of sea water (fsw) absolute, which is a rather funny pressure measurement. It assumes that one is always under 33 feet of sea water. Of course feet of sea water is a pressure measurement and so one can use it in absolute terms. One uses it because then the equation gives the answer in feet of sea water which is what one needs in terms of decompression stops. It is more convenient than using M values in millimetres of mercury or pounds per square inch or atmospheres. M values can be divided by the surfacing barometric pressure to give the critical ratio. Dividing M values by the barometric pressure at sea level, 33 feet of sea water absolute, will give the critical ratio.

SAFETY OF USN STANDARD AIR TABLES

The USN standard air tables were produced in 1955. The next question is how good are these tables? They have been used by many, many people around the world for all these years. For a long time the USN did not have any idea of how good the tables were. Individual diving doctors would probably back me up on that. One would say that they had 5% bends on that particular project, or another would say that they had 10%, or another would say that he did not have any. There was a paper published in the mid 60's by Rivers, who analysed 935 cases of decompression sickness treated in the USN over a fifteen year span. But one has no idea of the incidence, because there was no denominator. The USN had no recording system for the number of dives made.

In 1970, the USN adopted a recording system, so all dives made by USN divers or other divers under the auspices of the USN were logged. I have used the first years statistics an awful lot. It was a very brief report which showed that the total number of dives made was 30,039. Of the 30 accidents in USN divers, 25 were decompression sickness. The figures were broken down by the kind of equipment that was used. Extracting just the air dives because I am considering sport diving, there are two ways of looking at the results. There were 26,035 air dives. The other 4,004 dives led to over half the accidents, so one would not want to be a heliox diver, a saturation diver, an experimental diver or a nitrox diver, the categories that made up those 4,004 dives. In the air category there was deep sea air, the use of USN standard dress, fairly deep diving, hard working diving, probably a good percent, if not all, decompression dives. Three decompression accidents gave 0.081% bends, a very respectable incidence record.

Then there was lightweight air, using full face mask, a band mask, moderate work, moderate depths, probably a mixture of decompression and no-decompression dives, with a slightly lower incidence. Finally, open circuit scuba, the biggest category of all in that year's reporting, had an incidence of 0.035%. All in all, one accident out of every 2,173 dives is a pretty good safety record. It is also a good reason for you to log your dives, so you can quit at 2,172.

I have used that information for years to promote the use of the USN tables amongst sport divers. You can not beat those statistics. However, there are some fallacies there. One big question is "How does the USN use open circuit scuba?" There were 17,266 dives on scuba. If none of those dives were made anywhere near the no-decompression limits, then one is just inflating the denominator when calculating an incidence of accidents or incidents of decompression sickness. If scuba is used primarily to scrub the sides of ships the diver is never deeper than 30 feet, probably a lot shallower than that and never anywhere near the no-decompression limits. So this inflated denominator will influence the statistics. These figures are probably the least incidence when all dives are considered. It may well equate to what sports divers do - I think that sport divers dive conservatively, so maybe over all this is what the sport diver may expect too. But the question that really comes up for sports divers is "If I dive to the limits of no-decompression, what happens?"

There is a more recent report from the USN. It is a couple of years old now, but it confirms my impressions about that inflated denominator. This analysis looked at the standard air tables and from the reporting system took only dives made to schedules, that is times and depths actually printed in the USN standard air tables. For example, at 60 feet the first entry is 60 minutes. There is no entry for less than 60 minutes. So the first entry is the no-decompression limit. Then it goes to 70 minutes, 80 minutes and so on. So for a 60 foot dive anything less than a dive of 60 minutes was not included in this analysis. As a result there was a difference in the overall numbers. This report covered a seven year span and the total number of dives reported to be on a Schedule to be found in the USN tables was only 16,167, compared to that one year's report of 17,266 open circuit scuba dives, which right away confirms that 17,000 of those dives were probably nowhere near the no-decompression limits. If one eliminates those dives the incidence goes up. Get rid of the inflated denominator and one sees a more realistic incidence of decompression sickness - 202 cases, 1.25% over all (Table 1). 6,712, 41.5% of all dives reported, were between 40 to 140 feet, the depth range of interest to sport divers. 86% of those were decompression dives. 14% were no-decompression dives. There were 98 cases of decompression sickness (48.5% of the cases) an incidence of 1.5%. That was a little higher than the overall incidence which included dives down to 300 feet. In the deeper dives the incidence actually dropped a little bit. The thing that is interesting from the point of view of sport divers, is table 1. Remember that 86% of the dives were decompression dives, and 13.9% were no-decompression dives. 86% of the cases of decompression sickness were from decompression dives and 13% were from no-decompression dives. That says that the risk of decompression sickness in USN diving is no different in no-decompression or decompression diving.

Many sport divers, when they learn to dive and learn about decompression tables, are told not to do decompression dives as they are not safe. I will agree with that for sport diving. But not with the inference that decompression dives give a higher chance of getting bent. That appears

TABLE 1

USN DIVES MADE TO DIVING MANUAL SCHEDULES 1971-1978

DEPTH IN FEET	DECOMPRESSION DIVES (%)	DCS (%)	INCIDENCE	NO-STOP DIVES (%)	DCS (%)	INCIDENCE	TOTAL (%)	DCS	INCIDENCE (%)
40-140	5,782 (86.1)	85 (86.7)	1.5%	930(13.9%)	13(13.3%)	1.4%	6,712(41.5)	98(48.5%)	1.5%
150-190	5,512 (99.4)	49 (100)	0.9%	35 (0.6%)			5,547(34.3)	49(24.3%)	0.9%
200-300	3,908(24.2)	55(27.2%)	1.4%				3,908 (100)	55 (100)	1.4%
ALL DEPTHS	15,202	189		965	13		16,167	202	1.25%

not to be true. One does not stand a higher chance of getting bent, unless one does not do it right. Sport divers cannot do it right if they do not plan enough and do not have the same standard of surface control as the USN. So when you tell sport divers not to do decompression dives, do not imply that they are going to get bent if they do decompression dives. If one does it right it is no worse and no better than no-decompression diving.

I do not promote deep diving amongst sport divers in any way. However, 5,547 dives (34.3% of the total) were between 150 feet and 190 feet. There were 49 cases of DCS (24.3% of the total) giving an incidence of 0.9%, a slightly less chance of getting bent than with the shallower dives! 99% of those dives were decompression dives. One does not dive to those depths as a sport diver, because sport divers do not do decompression dives. They are not easily handled. It gets beyond sport to do decompression dives. Between 200 feet and 300 feet the incidence went back up to about 1.4%. Obviously all of those were decompression dives.

DO THESE FIGURES APPLY TO SPORTS DIVERS?

We have to consider the question "Can one expect that kind of incidence as a sport diver?" The answer is "yes", "maybe", and "no".

The answer is "yes" if one dives the same way the USN dives and one is in that segment of the population curve that describes the divers from whom these statistics were derived. Then one might expect the same statistics.

Fitness

A lot has been made in the United States about the USN tables being made for USN divers. They are supermen. They are in top physical condition and all that. Actually the usual bell shaped curve describes the USN diver population. Some are superfit and some are not so fit. Extremes are what makes the difference between the sport diver and a USN diver.

Age

There are extremes in age. There are no USN divers younger than about 18. By the time they get into the

military and go into training, they are over 18. There are sport divers younger than that. So in terms of whether they match the USN divers if they are younger than 18 they do not. So we are not sure. That puts the answer in the "maybe" category. Maybe the statistics apply. At the other end of the scale, there are not very many active USN divers beyond the age of 35. By then they move up to the supervisor class and they are not the active divers. They go into the USN at 18 and they start to retire out at about 38, after 20 years service. So the USN does not have many active divers over 40. Obviously there are many of us in this room who can say "maybe" the statistics apply because I am not in that population, I am over 38.

Sex

None of those statistics apply to women divers. The USN only started taking in woman as divers very recently. They would be insignificant in that set of statistics. So if you are a woman, you can say that you are not described in that population.

General Health

Obviously, if you are not healthy enough, to pass the physical for the USN, then you would not be in that population.

Obesity

Chronic obesity is frowned upon in the military and they will take them off diving service if they are frankly obese. But I have measured body fat in military subjects. There is a range of fatness in the USN. I think that everyone at this meeting would pass a measurement of acceptable lean to fat ratio for military diving. Other things may hold us back. It is hard to find differences between military divers and sport divers, except for those I have mentioned.

Diving Patterns

When one talks about sport divers in general, many are in their 20s so they are like the USN divers. The real problem is whether sport divers dive the same way as the USN divers. That is an unknown. The USN tables say one can go to 60 feet for 60 minutes and come straight to the surface. But if for some reason the USN never dives to 60

feet for 60 minutes, and they do not tell us about it, then they are diving differently from sport divers.

If a USN diver makes a dive to 100 feet for 25 minutes and records it as having been made to schedule, it gets logged as 100 feet for 25 minutes. What he may have done was anything from a 90, 92, 93, and so on up to 100 foot dive from anything from 21 to 25 minutes. A 10 by 5 matrix of possible combinations of depth and bottom time which has been recorded as a 100 feet for 25 minutes dive. Only one out of 50 possibilities has actually been made to the limit. If one does a 60 feet dive for 60 minutes it is a 10 by 10 matrix. 100 possible combinations of depth and time which would be recorded as a 60 feet for 60 minutes dive. Then there are other little things that come out, like the USN 2 foot and 2 minute rule which is not in the diving manual. It is not mentioned on any of the tables or sport diver tables that if one is within two minutes or two feet of a schedule one goes to the next one. But the USN does this. So it is not a 60 feet for 60 minute schedule. At 58 feet you go to the 70 feet schedule and at 58 minutes you go to a 70 minute bottom time. That makes one wonder if sport divers do dive the same way as the USN does. I wonder, because it does not show up in this report, just how much repetitive diving the USN does. Sport diving is a sport of repetitive diving. It may be only once a year that one does this kind of diving. But when we do it we dive a lot on a sport diving vacation. So there are some differences to worry about.

recompression chamber after the dive. So any one of the 100 possible dives which can be logged as 60 feet for 60 minutes would be decompressed for 70 feet for 70 minutes which is 14 minutes at 10 feet.

I should not bring up reporting accuracy, but apparently in that first year there were some paper dives in those 30,000 dives. That is people who had to make proficiency dives did not get them in but nevertheless a paper was submitted indicating the dive had been made. How many there were or how significant that was, I do not know. Again, I do not know the repetitive dive frequency in the USN.

Let us take some individual schedules from the USN and also look at some laboratory studies. (Table 2). For a 60 foot for 60 minute schedule, the USN reported a 1.1% incidence of bends. If a sport diver slips past 60 minutes and does a 60 feet for 70 minute dive with its proper decompression, is that a better dive form? In the Navy's experience, no, although the numbers are pretty small, three out of 62. It looks as if he does increase his risk of bends.

Really more important are dives made in a laboratory to no-decompression limits. Spencer in Seattle has done a lot of work with no-decompression limits, using the Doppler ultrasonic, precordial bubble detector. He recorded one bend from 13 exposures to 60 feet for 60 minutes, 7.6% bends. 31% of the subjects had venous gas emboli detected.

COMPARISON OF USN, SPENCER AND BASSETT
SCHEDULES, DECOMPRESSION SICKNESS (DCS) AND VENOUS GAS EMBOLI (VGE)

SOURCE	DEPTH/TIME	DCS/DIVES	DCS	VGE
USN	60/60	2/183	1.1%	No record
USN	60/70	3/62	4.8%	No record
SPENCER	60/60	1/13	7.6%	31%
BASSETT	60/60 (E)	1/18	5.6%	27.8%
USN	80/40	0/40	0	No record
USN	80/50	2/34	5.9%	No record
BASSETT	80/40 (E)	1/16	6.3I	37.5%

(E) Equivalent Flying After Diving Schedule

So what happens when one really makes dives to no-decompression limits? There is laboratory evidence. Some of the USN statistics may make us wonder a little bit about the no-decompression limits. Firstly, how close do the USN divers go to the limits? I suspect not very often, both by probability and by Navy diving supervisor unwritten laws in addition to the two foot and two minute rule. When I went through the USN diving school medical programme back in 1964, the Master USN divers were saying "Always cheat the government, never cheat the diver. Time and air are cheaper than bone and brains". They put them on the next schedule as they did not want them coming up bent. They did not want to spend a lot of time working a

My own contribution is an equivalent flying after diving schedule. My project in the last three years before I retired from the US Air Force was to validate some schedules for flying after diving. The first round of this was to test 20 odd man exposures to 6 different schedules. We made a dive in a hyperbaric chamber to a bottom time calculated so that when we ascended to the surface and continued on up to 10,000 feet altitude, it produced the same surfacing ratio as the USN no-decompression limits surfacing at sea level. In my schedule, I did not do a 60 feet for 60 minutes dive. I did a 60 feet for 20 minutes dive. But when the "diver" surfaced and continued on up to 10,000 feet, the ratio that he attained on reaching 10,000 feet was the same as

coming to the surface after a 60 feet for 60 minutes dive. I called it equivalent. That was by design. The statistics back up that it was equivalent, because I had about 5.6% bends on that schedule and about 30% or less intravascular bubbles, much the same as Spencer's 60 feet for 60 minute dives.

At 80 feet for 40 minutes the USN had no bends. But at 80 feet for 50 minutes they had 6% which is the same as the dive to 80 feet in my equivalent dives, 6.3%. 100 feet for 25 minutes was the worst for the USN. It gave 4 cases in only 43 exposures, but that is a 9.3% incidence. Remember that probably only one out of 50 dives is actually made to that limit. My 100 feet for 25 minutes equivalent dive, as with all my equivalent dives, had a 6% incidence of bends. It is interesting and this will come to light when I finally give you my recommendations for sport divers, that when you go deeper the bends rate decreases. There is a reason for this in the design of the tables. I was totally clean on the 130 foot for 10 minute equivalent dive and the USN was almost clean at 130 feet for 10 minutes.

When we actually dive to the no-decompression limits in the laboratory you can see 5 to 8% bends. Depth is controlled. Bottom times are controlled. Rates of ascent are controlled. All was according to the USN tables both in Spencer's and in my laboratories.

PREVENTION OF DECOMPRESSION SICKNESS

What can you do to prevent that 6% bends incidence? One study by Pilmanis at the University of Southern California used a few divers for open water no-decompression dives made in a controlled way, to a measured depth of 100 feet, with a measured bottom time of 25 minutes and a measured ascent rate of 60 feet per minute. Some subjects produced intravascular bubbling to a great degree on that exposure. They found that if they put in a 3 minute stop at 10 feet, it drastically reduced the degree of bubbling in those subjects. If they put a 2 minute stop at 20 feet and another 3 minute stop at 10 feet they could eliminate the bubbles. This indicates that perhaps the no-decompression limits are on a knife's edge in terms of bubble production and the risk of bends. The tables were developed and tested to an end point of bends not bubbles. After a bend they cut back

slightly to produce the final bottom time and tested it a few times. If there were no bends it was fine. Perhaps 30% of those people were bubbling at that time. When you put those tables into the big world, you must expect a few cases of bends to pop up. However if you cut back a bit more you can drastically reduce the bubbles so you should be able also to decrease the incidence of bends.

Sport divers represent the world's largest population of divers. More than all military divers, commercial divers, scientific divers, abalone divers, put together. There are no accurate statistics and never will be. So we do not know what the incidence is, and probably never will know.

Generally speaking the sport diving instructors tell us not to push the tables. Sport divers are instructed to avoid decompression dives, maybe for the wrong reason, but nevertheless I think it is valid. Various instructors that I have come across in my years of talking to diving groups have come up with their own safety factors. Some take 5 minutes off all the no-decompression limits across the board. Others reduce them by 2%, which actually has a little more logic to it because you end up reducing the shallower depths more than you do the deeper depths, and that in fact is what probably is needed. The other thing that is common among sport divers is that, unlike a navy diver who goes down to the bottom and stays a certain period of time and then comes up, they are up and down and all over. What influence this multilevel diving has on the risk has yet to be determined.

Revised No-Stops Limits

It seems to me the nice way to go about putting some safety factors into sport diving and to give a definition to not pushing the tables, is to re-design the tables. That is what I have done with my sport diver table (Table 4). It is not in its final form yet. I have already modified part of it. In Table 3 the half times used for the USN tables on the left, the next two columns are the H values and ratios used for the no-decompression limits of the USN tables. The H values and ratios that I am proposing for sport diver tables are presented on the right. Where did I come up with those? Did I just pull them out of my ear lobes? I told you that when I flew my man to 10,000 feet after exposures to

TABLE 3

LIMITING VALUES OF USN AND SPORT DIVER TABLES

HALF TIME	US NAVY		SPORT DIVER TABLE	
	M VALUE	RATIO	M VALUE	RATIO
5	104	3.15	95	2.88
10	88	2.67	83.2	2.52
20	72	2.18	67	2.03
40	58	1.76	53.8	1.63
80	52	1.58	46.5	1.41
120	51	1.51	44	1.33

depth I had 5 or 6% bends. That was unacceptable. We still had the problem of giving our military divers a schedule that would allow them to fly immediately after diving. We then reduced the altitude from 10,000 feet to 8,500 feet. Money and manpower was short so we could only test three schedules. Taking a group of man to 8,500 feet after their dive did not produce any bends at all. That cut back from 10,000 feet to 8,500 feet is presented in Table 3 in terms of surface and surface ratios for my sport diver table compared with the USN no-decompression limit values. It certainly makes sense to me and I have a few man tests behind it. We reduced the USN no-decompression limits to those in Table 4. These were tested. Of course sport diver tables and sport diver problems never get tested. Because there is no money. So I was happy to use a little military money and have a spin-off for sport diving. These ratios worked in flying after diving. I am convinced that my dives were equivalent to no-decompression dives. Taking these numbers and plugging them back in to calculate allowable bottom times gives Table 4. The reduction is about a five minute reduction at the greater depths, a 10 minute reduction in the intermediate depths, and very significant reductions shallower than 60 feet. A 30 minute reduction at 50 feet, an 80 minute reduction at 40 feet and actually putting a limit on the 30 foot dive.

Spencer was able to bend people at 25 feet by exposing them for over 12 hours. I was able to bend 5% if I kept them at 10.75 feet for 24 hours and then took them to 10,000 feet. In this situation the ΔP was equivalent to being saturated at 22 feet of sea water. The shallowest bend so far.

Table 4 shows the no-decompression limits that I recommend. I have put them in some publications. I hope the National Certifying Agencies in the United States will start to push them.

I would like to see, along with this, some revision of the repetitive dive system.

The repetitive dive system in the USN is based on only a single half time, the 120 minute half time tissue. Each repetitive group letter was initially set up to represent an increase in nitrogen pressure of 2 feet of sea water absolute. 79% of 33 feet is 26 feet. If you had not been diving today, if you were clean on the slate, you would have 26 feet of sea water nitrogen pressure. Repetitive group A represents a nitrogen pressure in the 120 minute half time tissue of 26.1 to 28 fsw. Group B would represent by design 28.1 to 30 fsw and so on. At the end of the dive one can calculate how much nitrogen pressure is in the 120 minute tissue. Something goes wrong when one analyses the tables. The range of partial pressures of nitrogen represented in a given repetitive group ranges from 1.5 fsw to as high as 8 fsw. This is from unpublished data. I have gone through every single entry in the USN tables and calculated the nitrogen tension after any given exposure at the end of bottom time, on reaching a stop and leaving a stop and so on, and then the surfacing values. When you correlate the surfacing values with the repetitive groups assigned by the tables there is a range of about 6 to 8 feet of sea water in some groups. The dive which gives the diver a repetitive group

M may have as much as 6 or 8 fsw nitrogen pressure more in the 120 minute tissue than another which also puts the diver in repetitive group M. There is an anomaly and I do not know whether it is calculation, testing or what. I have never been able to find the answer.

But it may lead to some of the anomalies that you run into. Take a 60 foot dive for 30 minutes with a surface interval of 30 minutes and then another 60 foot dive for 30 minutes. The USN dive tables tell you that one has to do an 8 minute stop at 10 feet on the second dive. The USN table also says that one could have gone to 60 feet for 60 minutes and gone directly to the surface. The reason that happens is that each repetitive group designation assumes that the diver reached the surface at the high end of that 2 foot of sea water. Likewise in the surface interval table, it assumes that one has the highest nitrogen pressure for the next repetitive group. When one goes on to the residual nitrogen table it assumes that you have the highest residual nitrogen. The table calculates the time that it would take at that depth to reach that amount of nitrogen. If in fact one was at the lower end of the nitrogen pressure one gets credited with more residual nitrogen than one had which explains the minus for that 60 foot 30 minute dive. There are some anomalies and I think it would be a nice thing for sport diving if we could eliminate them. That is going to be the most difficult one, because it will be impossible.

TABLE 4

REVISED "NO-DECOMPRESSION" LIMITS FOR SPORT DIVERS

DEPTH IN FEET	TIME IN MINUTES	
	USN	REVISED
30	UNLIMITED	220
35	310	180
40	200	120
50	100	70
60	60	50
70	50	40
80	40	30
90	30	25
100	25	20
110	20	15
120	15	12
130	10	10
140	10	5

RECOMMENDATIONS FOR SPORT DIVERS

Until such time as I am able to satisfy myself that there is a better repetitive dive system my recommendations are to use the revised no-decompression limits (Table 4). In addition to that I recommend that all dives to greater than

30 feet end with 3 to 5 minutes at 10 to 15 feet. Do I really recommend belt and suspenders (braces) to be used together? Lower the no-decompression limits and add a safety stop? Yes, I do. And I do it myself, because sport diving is supposed to be fun and anyone who has treated a case of bends knows that bends is not fun. Anything you can do to prevent decompression sickness makes a sport of diving rather than it being the pain of diving. The question comes up "If you throw in these safety stops, how do you get your repetitive group?" The answer is easy. You count the total dive time for selecting a repetitive group. No-decompression limits are based on bottom time. You come up. You make an additional stop. If you use my schedule 50 feet for 70 minutes, you actually use that 70 minutes. Then you come up and hang on for 3 to 5 minutes at 10 feet. You then take the total underwater time of 75 minutes to enter the repetitive group selection process.

Question:

How do the BSAC/RNPL tables compare with the USN tables for safety?

Dr Bruce Bassett

I have not done that. Over the years I have played around with these tables, I have been working mainly with military divers and sport divers. I have concentrated all my efforts on the USN tables. I have not studied the British tables enough to know, I understand they are much more conservative.

They are based on a different model. The Canadian tables are based on a different model. The Swiss tables are also based on a different model. It is a half time, M value model, but more conservative M values. They all say that they have got good results with their tables. I have not analysed their tables nor their results. I am only commenting on the USN tables.

Question:

It is said that all dives greater than 100 feet, when at the no-decompression limits or longer, produce bubbles.

Dr Bruce Bassett

I have not seen evidence, as yet, that all such dives produce bubbles. I am not one of those who believes that. Or maybe I have got my head in the sand. You cannot detect bubbles in all dives. My dives were made to the no-decompression limits and I got 30% bubbles. That includes all grades of bubbles, from the occasional one to the constant stream. If people claim bubbles on every dive, they are visualising bubbles. They cannot detect them. They are assuming that they are there. I think a lot of this comes from Brian Hills' theory that bubbles form on every dive because supersaturation is thermodynamically unfeasible. It is said that the body does not tolerate that metastable state and therefore phase separation occurs on every dive. I think

there are some things that are missed on that analysis. Humans become supersaturated at an altitude of 7,500 feet. Commercial airliners fly with cabin altitudes of 8,500 feet. One is beyond just being supersaturated, one is supersaturated by 1,000 feet of altitude. Many, many military aircraft fly with cabin altitudes above 8,000 feet, up to the bends threshold of 18,000 feet with literally millions and millions of manned exposures with no problems. In fact one forms bubbles whenever one is exposed to a barometric pressure less than what the tissue nitrogen pressure is at sea level, one should be bubbling at these heights. Yet with all those millions and millions of exposures there is zero incidence of problems. So I think something is being missed in the concept that you bubble whenever you have excess gas pressure. One thing that seems to be overlooked is surface tension. The forces opposing bubble formation, *de novo*, are enormous. This is ignoring bubble nuclei. Once the microbubble forms, the likelihood of it existing is very, very small because a very small bubble has almost an infinite surface tension which is of course trying to collapse it. I have not seen laboratory evidence that humans do bubble whenever they exceed supersaturation. If we do so, be careful getting out of the shower.

Dr Ian Unsworth

I entirely agree with you. We were trying Doppler detection of VGE a few years ago at Prince Henry Hospital. We decided to use the US Navy Exceptional Exposure table, which I think you would agree, offers a reasonable expectation of venous gas emboli. As the director of the study and older than the others, I made the run. We did 25 or 20 minutes at 190 feet. The Doppler, as we ascended, produced an extraordinary amount of noise which the outside staff said was interference. They were tearing their hair at this. They could not get rid of it. They thought they were going to be in trouble when I came out of the chamber. At about 30 feet I was furious that my staff were not getting a decent recording. At about 20 feet I got a sledgehammer in my hip. I do not know if any of you have been bent, but it is very painful indeed. I was put back to 60 feet and successfully treated. Then I selected a female volunteer from the other members of the unit. We repeated with some trepidation and some expectation, exactly the same dive. She did not get bent. We did not even get venous gas emboli from the same exposure. That backs up what you were saying that not everyone will bubble after the same exposure to 100 feet.

Dr Bruce Bassett

I took the USN statistics and looked at the depths I wanted. Actually, when all the USN dives are considered, all depths and all bottom times, there is no correlation between bends and depth. Depths greater than 100 feet were no worse than those less than 100 feet. Gas loading seems to be more important than depth. There was a time correlation. Dives over 60 minutes did start to see an increased incidence. Other statistics seem to show that short deep dives are safer than long shallow dives. On one 130 foot dive I had 98% with skin bends - itches. There is a very positive correlation

between skin itches and depth. But there is no correlation whatever between bends or detectable gas emboli and depth.

Females have about a 3 to 4 fold greater incidence of decompression sickness on altitude exposure. This has also been reported in diving.

My final recommendation is to use belt and suspenders, reduce your bottom time and do decompression stops as well.

Dr Fred Bove

As you know I have been associated with USN diving for many years. I will describe how USN diving operations are done. It will alter your thinking about the USN decompression tables.

The USN diving tables are pinned up at all dive stations, often in very large print. There are big red "X's" on some tables because the divemasters have found some tables at certain depth and time combinations, have a high incidence of bends. One of the notorious ones is 150 feet for 30 minutes. The USN has experienced about 15% bend incidence with this table in the field, so they do not use it any more. There is nothing in the diving manuals that tells you that.

The divemasters seldom use the prescribed depth and time to decompress the diver. The usual practice in the USN is that, if they are anywhere near the depth or time limits, they move to the next schedule. Some dive masters will use two minutes, some will use three, some will even use five. That is, if the diver is within five minutes or five feet, or two minutes or two feet, of a limit for decompression, he is decompressed on the next schedule. The divemasters also will make the table more conservative if the diver is overworked, underworked, in cold water, in warm water, in current, has a tough job to do, was up late the night before, or for anything at all. They will use the decompression one or two steps beyond that of the actual depth and time, to decompress the diver.

So in the USN statistics, the actual depth and time of the dive are often lies. The statistics show an incidence of bends from these wrong dives. The recording system also has in it the decompression that was used. When one studies the depth and time log, one finds that the decompression that was prescribed by the tables was not used, but a more conservative one was chosen. One of the reasons why there is reasonably low incidence of decompression sickness in the USN is because the divemasters on the dive stations are extremely conservative. They factor in almost anything they can find in the environment to make the tables mere conservative.

The USN has certain physical requirements which are fairly stringent. Reserve divers, and sailors from the fleet coming into diving, are often not fit enough to meet the basic entry requirements for the USN Diving School. Those entry requirements are higher than the average

population of, say, 25 year old sailors. At the diving school, the day begins at 0630 with a four mile run for everybody, then PT exercises - that is, vigorous callisthenics - timed by one of the divemasters for another half hour before the classroom and the diving begin. This continues throughout the course, eight weeks for the medical officers, sixteen weeks for the second class diver and twenty-four weeks for the diving officer. Everybody, including the medical officers, goes through that. When one graduates from the diving school, and joins a diving team, that same routine is followed. Navy divers are generally fit. The master divers somehow manage to extricate themselves from the exercise, but at the same time they do not dive very much, they are up on the platform supervising.

The USN assigns two people with watches to time the dive, and one or two people to watch the depth gauge. So the time is accurate to the second and the depth is accurate to the foot.

Not much of the scuba diving is done close to the no-decompression limits. Most of the scuba diving is done shallower than 30 feet. The USN does not use scuba for deep diving. Most scuba diving is shallow, less than 100 feet, often for short, inspection operations.

All in all, the USN tables are quite successful for the military operation where the diver goes over the side, goes down to a depth, does a job comes back up and rarely does a repetitive dive. There is a dive team on site, so diver number one does one part of the job and diver number two another part, diver number three, and so on. It is rare that the USN does a repetitive dive. A repetitive dive stresses the dive station, and it is not routinely used.

With all that, to take the Navy tables and the statistics related to them, with some knowledge of what operational diving in the USN is like and apply them to sport divers, who dive so very differently, is difficult. I generally tell sport divers to knock five minutes off all their bottom times for no-decompression dives. Bruce Bassett has said to take off more than five minutes at the shallow end, I think that is right. I think sport divers should be instructed not to dive right to the second of the no-decompression limits, because they will get a higher incidence of decompression sickness.

Decompression diving seems to be riskier in sport diving, probably because of the operational aspects. The divers do not do the timing right, they do not quite get their stops right, they are not prepared to have the excess gas supply and all the rest of that stuff. Remember also that a lot of military and commercial diving is done with surface decompression. When the diver gets to the 30 feet stop, they pull him out of the water and put him in a chamber. So he finishes the dive in a nice warm environment with a cup of tea in his hand. It is not quite the same as a sport diver sitting at 30 feet, 20 feet and 10 feet stops waiting to decompress in cold water with surface action of the waves and everything else. It is interesting to look at your depth gauge when there is wave action and you are at 10 feet. Half the time you are at 5 feet and the other half at 12 or 13 feet. So you are never quite sure where your 10 feet stops are.