It is also obvious that if problems do arise then an adequate insurance policy is mandatory for potential retrieval to recompression facilities, and in some countries for the cost of the treatment.

References

1 DAN 1992 report on Diving Accidents and Fatalities.

Key Words

Altitude, decompression illness, hyperbaric facility, risk, safety, training, treatment.

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STAGED DECOMPRESSION FOLLOWING NO-DECOMPRESSION DIVING

Geoff Gordon

So far we have all gained insights into the safety of diving, the techniques it uses in diver education and some figures on where divers make errors. The medical people have given us a different perspective on the same set of data; namely why are divers ending up in recompression facilities, what were they doing in order that they earned that long dive notation in their log books. My paper today is rather ethereal in that it attempts to look at what data is currently available in the diving literature to support our current diving practice, and is there any clear evidence that we need to change tack? If we sincerely believe that too many divers are being damaged, we need to develop strategies for reducing even further the published incidence of decompression illness (DCI). If, on the other hand, we are agreed that we are doing alright, then this paper will, I hope, stimulate some thoughts in your minds as to how you might reduce your own risk of developing DCI.

The risk of developing DCI following a single air dive has been long studied. Data derived from the theoretical analysis of risks has been combined with that obtained from the analysis of thousands of actual dives, and at least with respect to the single dive, we are now able to predict the probability of an injury following a single dive (p(DCI)).

The morbidity and mortality suffered by divers in the late 1800s stimulated the British Admiralty to commission work into the nature of those afflictions and how they could be overcome. These studies culminated in the publication in 1908 of the first set of tables that provided guidance to the diver on how to avoid Compressed Air Illness. The credit for this work is attributed to John Haldane. His method of "staged decompression" as he called it, dramatically reduced the permanent injury associated with compressed air work and all but eliminated the fatalities. This method has since grown in popularity with many iterations, the most prevalent adaptation of the Haldane computational algorithm being the US Navy Tables.

Up until the 1970s, nearly all the diving being undertaken was primarily commercial or working diving. Given the task to be undertaken a certain "hit rate" of DCI was accepted. Recompression chambers were immediately available, and the diving was rather repetitive and stereotyped. Since this time however, we have seen an almost exponential growth in recreational diving, that only now may be peaking. Associated with this popularity in recreational scuba diving, treatment facilities have seen a new wave of diving morbidity. Although much debate centres on the incidence of DCI in the recreational diving community (the denominator is not known), the percentage of divers afflicted is clearly much less than that which stimulated the British Admiralty into commissioning Haldane's work, but there are undeniably increasing numbers presenting for the treatment of DCI. Perhaps we need to grapple with this problem again. We may feel comfortable with the published rates for DCI, but the results that are being reported following the treatment of these recreational cases is a serious cause for concern as 60% have demonstrable morbidity, usually neuropsychiatric sequelae, 12 months after treatment. Assessment of the data published by the various treatment facilities suggests that some, say 25 to 50% of those presenting for treatment, could have dived more "safely" and by inference avoided developing DCI. In this regard I see that the effort of this symposium is to address the preventable DCI.

While some researchers in the field of hyperbaric medicine are seeking alternatives to the current treatment algorithms, in an attempt to secure better treatment outcomes, it may be more appropriate to rethink our approach to diving, particularly recreational diving. In this regard, we have an analogous societal problem in the treatment of road trauma. Repeated studies have shown tha,t in road trauma, 18-29% of those dying would not have done so if prompt and appropriate medical care was available early. This is called the Possibly Avoidable Death rate. We know that up to 50% of currently treated cases of DCI occur subsequent to dive profiles that have exceeded what is generally considered safe diving practice, a Possibly Avoidable DCI rate! Secondly, although uniform systems for the management of trauma victims have been introduced into Australasian practice and these have seen a modest reduction in hospital mortality rates, road trauma death rates are still adjudged as too high by our society. The "ambulance at the bottom of the cliff" approach is unlikely to make further inroads into the road fatality statistics. As a result of this society is changing tack in its assault on road trauma with the introduction of new legislation, new vehicle safety standards, education programs to change societal attitudes, all in an attempt to prevent the problem from occurring. This may be the approach we need to take in diving if we want to reduce the morbidity associated with diving: better decompression strategies with appropriate education.

Much data is currently available to support changes to the way we currently approach our diving activities. The reverence that divers have for their tables or, more recently, for the algorithm programmed into their dive computer, is not matched by the robustness of the science applied to their development. As stated previously, the method used as a basis of many of the world's currently used dive tables originated with Haldane in 1908.

He made a number of assumptions and empirical conclusions in the development of his tables, many of which are just not tenable. For instance, he assumed that off gassing was a mirror image of on gassing, that nitrogen uptake is perfusion limited, that there is a tolerable supersaturation, his basic tenet. In essence, his system is really nothing more than a book keeping system for keeping track of inert gas tensions in the body, rather than a model per se. Further, he treated air as 100% N_2 in his calculations (this simplified the tedious calculations and he was using ratios after all), relied on empirical experience to adjust his limits and derived his ascent rate empirically. And this model has been worked on subsequently to assist in the development of safer tables! What makes the various tables different is the number of tissue compartments for which calculations are made, the level of tolerable inert gas supersaturation and the surface interval required for complete nitrogen clearance. Even in something as fundamental as this, there is no agreement. The theoretical nitrogen clearance intervals for the various popular tables are: PADI, 6 hours, USN and Comex 12 hours and DCIEM 18 hours. There are no studies that corroborate any of these intervals as being appropriate to the recreational diver. Indeed most computers, which calculate compartment nitrogen saturations, indicate that after a period of typical recreational diving, some 24 to 36 hours are required before the computer indicates that the tissues are "clean". The development of new dive tables has become largely empirical with little consideration being given to advances in our knowledge of the underlying science. No table adequately attempts to model inert gas elimination, and further, no algorithm will ever be able to model the unpredictable effects that bubbling has on inert gas elimination. Perhaps chaos theory can help!

A number of table developers make a plea that their tables have been tested, but the need to test tables is problematic in itself. To test all of the possible schedules is not possible, and a common procedure has been to consider a schedule "safe" if 10 dives were performed without incident. This objective testing is to establish the incidence, if any, of DCI. Given the binomial nature of dive outcome, (DCI/no DCI) such an outcome only determines that, with 95% confidence, there is an 0 to 30.8% chance that that schedule will produce DCI! If the 99% confidence level is desired this becomes a 0 to 41% risk of DCI. The chances are that the rate of DCI will be close to zero, but as can be seen, it could be higher. Some 370 incident free dives per schedule are required to satisfy a 1% risk at the 95% confidence level. It is futile trying to predict the safety of a decompression schedule based on a few test dives. Running a few tests does not tell us very much. Because of this problem, it may be appropriate to adopt a risk-benefit approach to diving activities, and instead of a schedule being safe, it simply has a greater or lesser chance of causing DCI.

The concept of acceptable risk has been much debated, and it is clear that the acceptable risk varies with the task being performed. For instance, the US Navy may accept procedures with a risk of up to 4% in order to satisfy its operational commitments. A rate of 2% has been considered acceptable in caisson workers, 0.1 to 0.5% for commercial divers whilst a rate of 0% is considered acceptable for recreational and scientific diving.

A number of studies are available which enable us to take a "profile risk" approach to our diving. Previously, it has been generally assumed that DCI occurs only when a critical threshold is exceeded. Observation, however, tells us that DCI is unpredictable and behaves as a statistical rather than as a threshold phenomenon. DCI does become more likely, but seldom becomes a certainty when certain limits are exceeded. Introducing the principle of maximum likelihood attempts to solve this conflict. Likelihood analysis compares the profiles of previous dives on which the time/pressure/gas profile and dive outcome are well documented. This technique allows different profiles to be compared, a bit like a "least squares" fit draws a line of best fit through a set of data points. After a large number of carefully controlled dives are analysed and the model calibrated, it can then be used to calculate new dives. The technique works on discrete (binomial) data, in this instance on the presence or absence of DCI.

The link between the mathematical model and diving data is the dose response curve which relates the risk of DCI to the decompression stress as predicted by the model.

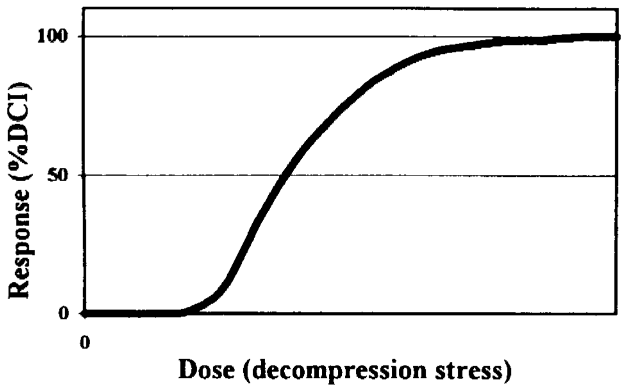

Figure 1. The dose response curve of risk of DCI to decompresssion stress.

The concept of likelihood (L) is extended to a series of observations by multiplying the outcome of the individual responses thus:

L_{trial}= (pDCI, dive 1)(pDCI, dive 2)(pDCI, dive 3)... ..(pDCI dive n)

In maximum likelihood, the p(DCI) is adjusted until the closest agreement exists between it and the observed outcome. For the purpose of this analysis, dose is the pressure history of the diver (dive profile) and response is the occurrence or absence of DCI.

The occurrence of DCI in man is characterised by extreme variability of individual response. In a group of divers experiencing the same dive, seldom do all demonstrate signs of DCI. In all of the animal studies, the fraction of symptomatic animals rises smoothly from zero to 1 over a finite range of decompression stress, so in essence, the absolute value of the likelihood is analogous to the sum of squared errors in analysis of variance.

This technique allows many different types of dive profiles to be combined in order to calibrate a mathematical function (risk function). This is then used to construct a decompression model to either compute a risk for a specific profile or to compute tables to a specified level of risks. The goal of the generated mathematical model is to provide a tool to permit a rational choice between risk and time in the water. This type of analysis has been done and presented in tabular form for the US Navy, Royal Navy and DCIEM tables by Weathersby et al. It allows a useful analysis of the effect of decompression time on the risk of developing DCI.

For instance, look at the following dive profiles. A dive to 36 msw (120 ft) for 15 minutes carries a 1.8% risk of DCI. The same dive, but with a bottom time of 30 minutes and a 14 minute stop at 3 to 5 msw as required by the table, carries a risk of 0.9%, half that of the shorter dive! There would indeed seem to be some advantage accrued in the staged decompression process! Looking more closely, we see that, by putting this data into the computer and analysing it with a 3rd generation Haldanian algorithm, the effect of the staged stop has been to reduce the inert gas loadings in the fast tissue compartments, the brain and cardiovascular system. Both dives are allowed in the US Navy tables.

The safety stop as currently practised may go some way in reducing the risk of DCI to the diver, but the practice of spending 5 minutes at 3 m was introduced to slow the ascent, thereby decreasing the risk of DCI secondary to pulmonary barotrauma. Using the same algorithm but this time looking at the safety stop, we see a similar beneficial effect in terms of fast tissue inert gas loadings. There is the belief that time spent off gassing in the shallows before surfacing will decrease bubbling and hence the risk of DCI. Intuitively this would follow from analysis of the p(DCI) as predicted by likelihood analysis, which indicates that, up to a point, staged decompression diving is inherently safer than no-stop diving. But can formal decompression after every dive, even when not required by whatever algorithm is used to control the dive, reduce the risk of DCI for the recreational diver? The evidence for a benefit to the recreational diver is less clear than is the evidence for a benefit in staged decompression diving.

Pilmanis in 1975 looked at bubble counts following a 30 m (100 ft) dive for 25 minutes. His small study clearly showed a reduction in bubble count if time was spent off-gassing at depth.

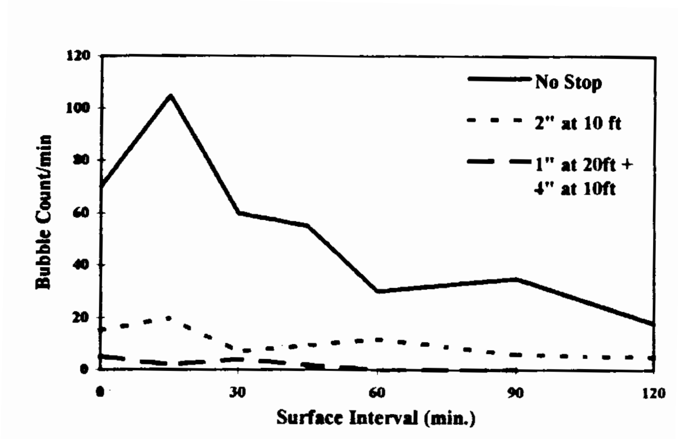

Figure 2. Bubble counts after no-stop dives and those with stops.

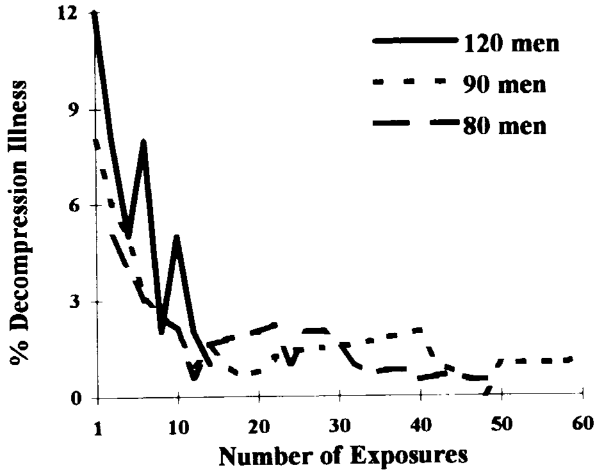

Figure 3. Adaptation in caisson workers.

What we may conclude is that time spent performing a safety stop does reduce bubble counts after the dive. What we do not know is if this reduction in bubble count equates with a reduced risk of DCI. It is likely that a reduced doppler bubble count will have little effect on the incidence of DCI. This apparent dichotomy between bubbles being clearly the cause of DCI and not premonitory is due to the nature of doppler detection. The bubbles that are detected have left the body tissues and are in the venous system on their way to the lungs to be filtered and removed. It is the evolution of bubbles in the tissues, particularly the nerve tissue, that causes DCI. The relationship between venous bubbles and tissue bubbles, if any, is waiting for some eager beaver to determine.

Kindwall has shown that N_2 elimination between the depths of 5 and 15 m, exceeds that at the surface for some time following a dive to 30 msw (100 ft) for 40 minutes. Rates of off-gassing were measured at 30, 15, 5 and 0 msw. Combining the data from this study and that by Pilmanis, the only reasonable conclusion is that off gassing is more effective in the absence of bubbling.

Thalmann reported similar results at 9 msw in 1983. A more recent trial, this time from the UK, demonstrated a reduction in the incidence of DCI by 40% when the safety stop was transferred from 3 msw to 6 msw. Perhaps what we can conclude is that a safety stop will not be effective in reducing the risk of DCI if substantial bubbling has occurred before reaching the stop. Deeper stops may thus be beneficial, and shallow stops may well do nothing more than slow the ascent as originally intended.

It has long been recognised that frequent exposure to pressure reduces the risk of DCI, thus suggesting that some type of acclimatisation does occur that is in some way partially protective.

Figure 3 shows the reduction in DCI, "adaptation", in caisson workers with increasing exposure to pressure. During the first 10 exposures the incidence of DCI in these caisson workers is seen to fall dramatically, an effect that is maintained as pressure exposure continues. After 10 days without pressure exposure the incidence returned to the initial level so adaptation, if it does truly exist, is short lived. Similar effects were seen during the construction of the Hong Kong tunnel project. Data from recreational diving however shows an increase in cases of DCI rather than a decrease with repetitive multi-day diving.

I have hypothesised that for tables to become safer, more decompression time at depth is required than provided in existing tables. A comparison of DCI incidence for the 1974 and 1986 French Tables provides some insights into this hypothesis. With 57,000 recorded dive profiles for the 1974 table, an overall incidence of DCI of 0.22% was seen. This database was used to empirically develop the 1986 tables. These tables effectively increased the decompression time by some 30-40% and, on reviewing the data from 32,000 dives, an overall incidence of DCI of 0.1% was seen. The effects of this empirical increase in decompression time are demonstrated, but there is a point at which increases in decompression time render recreational diving a pointless activity. Perhaps though, this data further supports my original hypothesis that staged decompression after every dive, even if no decompression debt is owed, will reduce our risk of DCI.

The new US Navy tables due to be released soon have incorporated a lot of this theory into their construction. They are based on a mathematical model which used statistical techniques to optimise its fit to a database of some 2,300 plus dives This new model computes the actual expected risk of DCI and has a p(DCI) of 2.3% for no-decompression dives within the range 18-

33 m (60-110 fsw). This risk has been applied to the new no-decompression limits, and the same level of risk has been used for decompression dives up to a total decompression time of 20 minutes. Longer dives have been allowed to ramp up to 5% when the total decompression time reaches 60 minutes. The old 12 hour clean rule has gone, and on some dives it will take up to 33 hours to be clean.

These new tables are no longer considered to be safe or unsafe by the US Navy, rather, they simply have a greater or lesser chance of causing DCI. Additionally, they give information about the level of risk at various times during a dive. This is an exciting approach to the way we conduct our diving, and reinforces the point that diving is merely a risk acceptance activity.

In conclusion, I believe that our thinking regarding how we dive needs to change if we are to reduce further the incidence of DCI in recreational diving. The holy grail of no-stop diving may not be such a laudable goal after all, and the data suggests that staged decompression after every dive will substantially reduce a divers risk of DCI. Further, studies suggest that these stops need to be made before significant bubbling has occurred if a benefit is to be realised. Spending, say, 1 minute at 18 msw, 2 to 3 minutes at 10 msw and 5 to 10 minutes at 5 msw after each dive should significantly reduce risk. An increase in risk is seen as dives get deeper, but this effect is not nearly as great as with time. DCI can be expected to occur occasionally, even in relatively unprovocative exposures. Thus it should not be regarded as an accident. It is expected to happen occasionally, and it does not always represent a loss of control as is implied by the use of the term “accident”.

But can we trust recreational divers to discipline their diving to this extent so that we will see a decrease in those presenting for treatment of DCI? Realistically I think not, as current studies show an alarming number of divers who are unable to manage even their air supply, with those that make the statistics probably representing only the tip of the iceberg. However, I do hold out hope for those who have a genuine interest in reducing the risk of DCI in their dive practice, mainly us older, once bolder types.

I believe that the evidence is overwhelming for staged decompression even following a dive profile that, according to some algorithm, incurs no decompression debt. The objective of our procedures after all is to REDUCE the probability of DCI to an ACCEPTABLE minimum, and I believe we have the tools at our disposal to enable us to do this within a predicted probability of risk.

Key Words

DCI, risk, tables.

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A list of references consulted is available from Dr Gordon.

POST DIVING ALTITUDE EXPOSURE

Ian Millar

The Alfred Hospital experience

During the 68 month period 1 November 1987 to 30 June 1993, the Alfred Hospital, Melbourne, Hyperbaric Unit treated a total of 401 cases diagnosed as suffering decompression illness (DCI). Of these, 44 had involved post diving altitude exposure. Only one of these was associated with medical retrieval; cases where air ambulance transport occurred but did not aggravate DCI were not included in the 44. This series provides illustrations for many of the dilemmas associated with determining safe limits for altitude exposure after diving and after treatment for DCI.

Review of available case records revealed the following:

All but 5 were recreational divers.

Note that several patients appear twice. DCI was initially provoked by altitude exposure after diving and subsequently relapsed with further altitude exposure post treatment

ASYMPTOMATIC BEFORE EXPOSURE

Twenty one cases were asymptomatic prior to their altitude exposure ranging from 300 to 800 m above sea level (ASL).