DECOMPRESSION AND THE DEEP STOP WORKSHOP PROCEEDINGS

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OVERVIEW
DECOMPRESSION AND THE DEEP STOP WORKSHOP

Theoretical and practical solutions as to how to ascend or decompress after scuba diving have been considered since Haldane some 100 years ago, and yet decompression sickness (DCS) still occurs.

The traditional "Haldanian" approach to planning decompression has been to limit supersaturation (the difference between tissue inert gas tension and ambient pressure) according to empirically derived rules that purportedly maximize gradients for inert gas washout and therefore provide a low risk of DCS.

The use of Doppler to monitor the central venous circulation, however, shows this approach still frequently results in bubble formation. Other more recent decompression theories have relied on so-called "bubble models," which focus on prevention of such bubble formation. To do this, the algorithms limit supersaturation more aggressively and typically result in the imposition of deeper decompression stops. These have been used quite successfully for many years by technical divers for deep diving.

In recent years, the utilization of a deep stop by recreational scuba divers at depths less than 130 fsw (41 m) also has been proposed. This is now appearing in dive computers using "bubble models" such as Varying Permeability or the Reduced Gradient Bubble Model or the Half the Depth Model. Some training agencies have also incorporated deep stops into their training regimens.

However, there is debate as to when to stop, for how long and how often in regard to whether such a deep stop does limit bubble growth or ameliorate the risk of DCS.

This workshop has brought together the most active international individuals with practical human data, animal research and theoretical concepts to help clarify the role of "deep stops" in contemporary recreational scuba and technical diving, and to point out what we know as well as indicate future research needs.

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ABSTRACTS

EARLY OBSERVATIONS ON THE EFFECT OF "DEEP" DECOMPRESSION UPON DOPPLER ULTRASONIC BUBBLE SIGNALS FOLLOWING 210/50 AND 170/30 DIVES

Tom Neuman

The problem of whether "deep" decompression stops add significantly to the safety of a given decompression profile is a difficult one. Ultimately of course, this is a question that must be addressed empirically. However, any studies involving decompression sickness are fraught with a variety of problems. Control groups, blinding and the selection of an appropriate endpoint are some of the difficulties confronting any group attempting to address these issues.

In the middle 1970s the U.S. Navy had specific operational objectives that required a number of dry chamber dives to 210 FSW for 50 minutes on air and to 132 FSW for 30 minutes, using a normoxic nitrogen/oxygen mixture. At that time, we were able to make some unique observations concerning the decompression profiles used for those dives.

The original intent of these experiments was to validate the reliability of Doppler ultrasonic bubble detection methods; however, we were also able to make observations relating to the effect of "deeper" decompression stops upon bubble scores. For these dive profiles there was a significant reduction in bubble score associated with a short "deeper" stop, independent of overall decompression time. It is, however, premature for these results to be extrapolated across the continuum of diving exposures or across the range of decompression algorithms that currently are used to calculate decompression tables. These results may be solely a consequence of the use of the model that generated the decompression profiles used in these dives.

LANL DEEP STOP DATA BANK AND DUAL PHASE BUBBLE MODEL FOR PROFILE ANALYSIS AND RISK

Bruce Wienke, Timothy R. O'Leary

Linking model and data, we detail the LANL reduced gradient bubble model (RGBM), dynamical principles and correlation with data in the LANL Data Bank. Table, profile and meter risks are obtained from likelihood analysis and quoted for air, nitrox, helitrox no-decompression time limits, repetitive dive tables and selected mixed-gas and repetitive profiles. Applications include the Bennett and Marroni 2.5-minute recreational deep stop, early Duke experiments with helium and deep air switches, NEDU deep stop tests, French Navy deep stop profiles, EXPLORER decompression meter algorithm, NAUI Tables, University of Wisconsin Seafood Diver Tables, comparative NAUI, PADI, Oceanic NDLs and repetitive dives, comparative nitrogen and helium mixed-gas risks, USS *Perry* deep rebreather (RB) exploration dive, world record open-circuit (OC) dive, and WKPP extreme cave exploration profiles.

The algorithm enjoys extensive and utilitarian application in mixed-gas diving, both in recreational and technical sectors, and forms the bases for released tables and decompression meters used by scientific, commercial and research divers. The LANL Data Bank is described, and the methods used to deduce risk are detailed. Risk functions for dissolved gas and bubbles are summarized. Parameters that can be used to estimate profile risk are tallied. To fit data, a modified Levenberg-Marquardt routine is employed with *L2* error norm. Appendices sketch numerical methods, and list reports from field testing for (real) mixed-gas diving. A Monte Carlo sampling scheme for fast numerical analysis of the data is also useful, as coupled variance reduction technique and additional check on the canonical approach to estimating risk. Supercomputing resources are used. This work attempts a (needed) correlation between global mixed-gas diving, specific (bubble) model, and (deep stop) data. The whole issue of deep stops and staging is one of timing, with questions of time and depth at deep stops possibly addressed optimally within consistent model and ranging data frameworks.

TECHNICAL DIVING OVERVIEW

Simon J. Mitchell

There is no universally agreed definition of technical diving, but it is characterized by decompression diving, the utilization of gases other than air, and equipment configurations other than single-cylinder open-circuit scuba in order to visit deeper depths or extend underwater duration or both. The adoption of these techniques, which in the past have been more commonly associated with occupational or military diving, has been driven largely by wreck and cave divers wishing to explore deeper wrecks and deeper and /or longer caves respectively.

The operating depth and duration of single-cylinder scuba air is limited by the small amount of gas that is carried, and the unfavorable characteristics of air as a deep diving gas, including its high density and high nitrogen and oxygen fractions, which at sufficient depth predispose to narcosis and oxygen toxicity respectively. Technical divers utilize complex multiple open-circuit cylinder configurations or rebreather devices to extend duration. Helium is lighter and non-narcotic, and is substituted partly or wholly for nitrogen in deep diving gases. The oxygen fraction is also tailored to the depth being visited. Multiple gas mixes with progressively increasing oxygen fractions are frequently utilized during decompression to optimize inert gas elimination.

Using these methods, recreational technical diving exponents have extended "bounce dive" depths and durations well beyond limits adopted by the more conservative occupational and military groups. Technical divers have visited depths exceeding 300m and open-ocean wrecks as deep as 200m. Caves as deep as 280m have been dived, and a cave system 90m deep and 11 kilometers long was recently traversed over seven hours of bottom time, followed by 15 hours of decompression. Although these examples represent current boundaries established by cutting-edge exponents, there is a vastly greater number of participants who are "routinely" diving to depths between 60 and 100m.

Although there are no definitive figures, limited data and anecdotes shared by diving physicians and divers seem to indicate that technical diving is hazardous. There is reason to believe that fatality rates are much higher than for scuba air divers, particularly among rebreather users. Moreover, there are numerous episodes of "unexpected" decompression sickness associated with these dives, and this has given impetus to improvement of decompression algorithms for deep "bounce" diving.

Reference

1. Mitchell S. Technical Diving. In: Moon RE, Piantadosi EM (eds). Dr. Peter Bennett, Symposium Proceedings. Durham, NC: Divers Alert Network, 2007:55-70.

A DECADE OF DEEP STOP TRAINING WITH THE REDUCED GRADIENT BUBBLE MODEL

Timothy O'Leary

Linking a dual phase decompression model to mixed-gas training operations, I will recount and detail protocols and diver training data from 1998 to the present. The diver data and training protocols described will be selected helium based dives and variable mixes with both open-circuit and closed-circuit in the 150 fsw to 300 fsw zones, along with repetitive profiles as used in the technical diver programs. The algorithm and published groupless, no-fuss NAUI mixed-gas decompression tables with repetitive dive protocols have seen extensive application in the technical diving sectors from a wide array of mixed gas instructors and divers in a variety of countries and is currently extending to dive meters in the training field.

A PRACTICAL LOOK AT DECOMPRESSION SURVIVAL ON DIVES DEEPER THAN 100 METER AND USE OF INTUITIVE DECOMPRESSIONS

Tom Mount

This presentation will address the practical decompression procedures used by some "technical divers" and how they evolved. It will describe use of a multimodel approach such as advocated by J.P. Impert and will reflect this to combinations with VPM-RGBM and gradient factors.

The process of decompression may be compared to a giant circle, where practice produces consequence, learning, and management of technique interact, creating the foundation of "intuitive decompression."

We will also address some modifications to decompression models used by deep trimix divers. The overall process is to use a model but use it in a manner stated by R.W. Hamilton as a "what works-works" approach. Within this, most of us favor deep stops or very slow ascents, which contradicts the thoughts of many researchers and agrees with others. Yet this process is hard to define. We will endeavour to do so.

The paper will also address what the author believes to be the most ideal decompression strategy when using a CCR. This leads us away from the concept of getting off helium. It maintains the same gas for the duration of CCR decompression as the inert gas volume mixed is reduced due to the constant PO_2.

At the end of the presentation an understanding of the apparent "what works decompression process" should be evident. Although subjective, as was the "subjective" feeling of nitrox dives vs. air dives long ago, it does seem to provide better post-dive health.

WORLD RECORD CAVE DIVE, DEEP STOPS WITHIN THE WOODVILLE KARST PLAIN PROJECT

Jarrod Jablonski

During the late 1980s a nonprofit exploration group known as the Woodville Karst Plain Project (WKPP) began steadily expanding the length of their deep cave immersions. By the mid 1990s these divers were experiencing bottom times of about six hours at a depth of 300 feet. During this period and in the years to come, the team would focus considerable energy toward safely reducing total decompression time.

This process was primarily a response to the sense that conventional Bühlmann algorithms were not structured with the most favorable arrangement of decompression stop times. Over approximately 7,500 dives spanning nearly 20 years, these divers aggressively experimented with a range of decompression profiles, working to support immersions that have reached nearly 30 hours. The divers utilize a similar decompression time for all dives in excess of six hours' bottom time, where dives average approximately 280 feet. To date, 10 hours is the longest bottom time obtained, resulting in a decompression of 17 hours.

THE APPLICATION OF 'DEEP STOPS' IN ANDI'S TECHNICAL DIVER TRAINING AND EXPEDITIONS

Ed Betts

Introduction

The validity and efficacy of the RGBM is an unresolved topic. To some, it is controversial. After much discussion and investigation, ANDI performed its own trials on two expeditions and recorded all data for our own use. Although no specific case studies and conclusions were offered by others, we decided to conduct our own trials. ANDI has since implemented the use of this methodology by means of the ANDI-Gap software program.

Data collection

The original "field tests" consisted of four series of dives that were performed by groups consisting of 12 males and two females with age variations of 23 to 61. The dive planning was completed using the Gap software in RGBM mode and the individual tables were printed including bailout options. Depths ranged from 24m to 156m, with bottom times at the deepest depths of 20 to 29 minutes. Several dives made at the shallowest depths exceeded 150 minutes of BT. In 2003, ANDI has trained a team of commercial divers using surface-supplied equipment from pre-mixed gas racks. ANDI methodology was used on their project, the Rio-Andirion Bridge, Europe's largest. Several thousand dives were completed.

Current usage

ANDI has four-plus years of use throughout our network. With training conducted in more than 60 countries by our trainers and instructors in many different languages we require that ANDI-Gap is the only algorithm permitted. We are not scientists, mathematicians or research physiologists. We are engineers, instructors and working divers who are often the test subjects for our own methods. We currently offer students free use of the software and require instructors to purchase it. We have recorded more than 2,500 free downloads of the trial program from our website.

Results of the dives

Regarding the efficacy of the deep stop method we can only say "what works ... works." I am not the expert here. My position is that decompression is still an art and not yet a science. We are all still learning and especially so at the more extreme exposures. Despite conflicting comments from some colleagues, our experience using this method is as follows.

No incidences of DCI occurred during the expeditions, and all divers reported no sub-clinical symptoms. We have not had one single case ever reported to ANDI of DCI during any training program, nor, any reports of DCI experienced by ANDI-certified divers using this method.

Conclusions

Until contrary data can be offered, it is ANDI's decision to continue to recommend the use of this diving methodology and training procedure.

DEEP STOPS: AWARENESS AND CURRENT PRACTICE IN THE TECHNICAL DIVING COMMUNITY

Drew Richardson, Karl Shreeves

The practice of making deep stops began with tech diving more than 10 years ago, with Richard Pyle, Ph.D., primarily credited with raising the question and creating awareness. Decompression models such as the Reduced Gradient Bubble Model (RGBM) and others have also come to the fore with recommendations that it is beneficial to begin decompressing deeper than mandated by conventional Haldanian-type models.

Anecdotally, the approach to deep stops in tech diving includes using deep models like RGBM, adding deep stops to conventional Haldanian-type model predictions and not making deep stops, but there have been no data that reveal which practices are present to what extent. The authors initiated a survey of individuals certified as technical and technical trimix divers, instructors and instructor trainers to determine an indication of the present state of deep stop awareness and practice in the technical diving community. This paper discusses the findings from the survey.

Joseph Dituri, Kirk Parsley, Harry T. Whelan

The opinions expressed herein are possessed solely by the authors and do not necessarily reflect those of any organization with which the authors may be affiliated.

Background

Conventional commercial and U.S. Navy deep "bounce" diving is generally limited to 300 feet and requires the support of large surface platforms and a minimum of 13 divers. The breathing media generally used is HeO_2, and the diving apparatus is the MK-21 or Superlight 17 style hard hats. This method requires recompression chambers, storage racks and equipment in excess of 50,000 lbs. on site.

Methods

Using trimix rebreathers and portable recompression chambers in lieu of the above mentioned method, deeper dives are being achieved with greater safety.

Results

Incorporating new knowledge of decompression tables and algorithms would allow the depth limit for "bounce" dives to be increased to as much as 600 feet. The use of constant partial pressure of oxygen rebreathers and dive computers can increase safety and decrease required decompression time. The incorporation of inflatable chambers and rebreathers would also reduce the required footprint and weight of a team as well as vessel required.

Conclusion

With this proposed – less expensive – system, a team of 12 divers can deploy more rapidly, with 80% less equipment burden, while greatly exceeding the current diving model's capabilities.

DEEP STOPS AND THEIR EFFICACY IN DECOMPRESSION: U.S. NAVY RESEARCH

Wayne A. Gerth, David J. Doolette, Keith A. Gault

Introduction

Classical decompression algorithms limit hypothetical tissue gas contents and prescribe decompressions that advance rapidly to shallow stops where most of the total stop time (TST) is scheduled. Recent bubble-based algorithms limit calculated bubble profusion and size and prescribe decompressions with TST skewed toward deeper stops. Navy Experimental Diving Unit (NEDU) has completed a controlled comparative study of these approaches.

Methods

Divers wearing swimsuits and T-shirts, breathing surface-supplied air via full face masks, and immersed in 86 °F water in the NEDU Ocean Simulation Facility wetpot were compressed at 60 fsw/minute to 170 fsw. They performed 115-watt cycle ergometer work during an ensuing 27.2 minutes at bottom and were decompressed at 30 fsw/minute with stops prescribed by one of two schedules, each with 174 min TST.

Schedule 1, with stops at (fsw/minute) 40/9, 30/20, 20/52 and 10/93, was prescribed by the man-tested, deterministic gas content, VVAL18 Thalmann Algorithm. Schedule 2, with stops at 70/12, 60/17, 50/15, 40/18, 30/23, 20/17 and 10/72, was the optimum distribution of TST according to the man-dive calibrated, probabilistic BVM(3) bubble model.

Decompression sickness (DCS) incidence with these schedules was compared under the sequential stopping rules of reject-high if DCS risk > 7% or reject-low if DCS risk < 3% with 95% confidence.

Results

The trial was terminated after midpoint interim analysis. Neither schedule was rejected, but DCS incidence in Schedule 2 (deep stops, 11 DCS/198 dives) was significantly higher than in Schedule 1 (3/192, p=0.030, one-sided Fisher Exact).

On review, one Schedule 2 DCS was excluded, but the result remained significant (p=0.047). Most DCS was mild, late onset, Type I, but two Schedule 2 cases involved rapidly progressing CNS manifestations.

Conclusions

The deep stops schedule had a greater risk of DCS than the matched conventional schedule. Slower gas washout or continued gas uptake offset benefits of reduced bubble growth at deep stops.

DEEP STOPS DURING DECOMPRESSION FROM 50 TO 100 MSW DIDN'T REDUCE BUBBLE FORMATION IN MAN

Jean-Eric Blatteau, Michel Hugon, Bernard Gardette

Background

The French Navy uses the MN90 decompression table for air dives as deep as 60 msw and the MN78 decompression table for trimix dives (60-80 msw). The resulting incidence of decompression sickness (DCS) for deep air dives (45-60msw) is one case per 3,000 dives (with 89% of neurologic DCS). We hypothesized that introduction of deep stops could reduce fast tissue bubble formation and neurological DCS risk in deep air diving. We also expected that adding deep stops could reduce bubble formation and decompression stress for trimix diving (80-100msw).

Methods

We incorporated deep stops (DS) into a series of six experimental ascent profiles (EAPs) developed with decompression software built on a Haldanian model. Deep stops for air dives (EAP 1-4) were introduced at about one-half the absolute depth and about one-third for trimix dives (EAP 5 & 6).

EAPs were tested in the wet compartment of a hyperbaric chamber. For EAPs 1-5, eight subjects dove to 50, 60 or 80 msw and ascended according to the French Navy standard tables or an EAP. Precordial bubbles were monitored with pulsed Doppler at 30-minute intervals after surfacing. The signal of bubbles was graded according to the Spencer scale before being converted into Kissman Integrated Severity Score (KISS). EAP1: 60 msw /20 minutes, first DS at 27 msw, decompression times (DT) 59 minutes vs. 48 minutes (MN90); EAP2: 60 msw/20 minutes, first DS at 27 msw, (pure O_2 6-0 msw) DT 42 minutes vs. 48 minutes (MN90); EAP3: repetitive dive to 50 msw/15 minutes with a three-hour surface interval, first DS at 18 msw, DT 31 minutes vs. 46 minutes (MN90); EAP4: 60 msw /15 minutes, only one DS of two minutes at 25 msw, DT 31 minutes vs. 29 minutes (MN90); EAP5: 80 msw/15 minutes with trimix O218%-He41%-N241% (80-12 msw) and pure O_2 (12-0msw), first DS at 24 msw, DT 74 minutes vs. 66 minutes (MN78). For EAP6, 12 subjects dove to 100 msw and ascended only according to the EAP, which was not compared to another table. EAP6: 100 msw/15 minutes with trimix O215%-He45%-N240% (100-30 msw), nitrox 40% (30-6msw) and pure O2 (6-0 msw), first DS at 33msw, DT 121 minutes.

Results

We found no significant differences in bubble scores KISS between standard tables (MN90 or MN78) and EAPs 1,2,4 or 5. Nevertheless EAP3 produced an increased level of prolonged bubbling for all eight divers [mean KISS: 20 (EAP3) vs. 8.6 (MN90), p=0.03], as well an important tiredness for five divers that improved with one hour of normobaric O_2 breathing. One diver suffered joint pain DCS after EAP2 while exhibiting Spencer grade 3 bubbles at rest

60 minutes after surfacing. His symptoms improved with hyperbaric oxygen, but MRI showed a bone infarction of humeral diaphysis. EAP6 produced Spencer grade 4 bubbles 60 minutes after surfacing for two divers, without symptoms of DCS; fortunately, bubbling was reduced after 30 minutes of normobaric O_2 breathing.

Conclusion

The utility of deep stops in human decompression has yet to be demonstrated for deep air dives as deep as 60 msw and trimix dives as deep as 100 msw with mixed gas including $N_2 \geq 40\%$.

BUBBLE DETECTION AND DCS RELEVANCE

Neal Pollock

Decompression studies traditionally rely upon symptoms of decompression sickness (DCS) as an endpoint. An observation made in the early 1960s that Doppler ultrasound could detect decompression-induced bubbles moving in the bloodstream expanded the possibilities for evaluation. The development of a series of semi-quantitative grading scales followed.

The 0-IV Spencer scale remains the most popular (0 = no bubble signals; I = occasional bubble signal; great majority of cardiac cycles signal-free; II = many but less than half of the cardiac cycles contain bubble signals; III = all cardiac cycles contain bubble signals, but not obscuring signals of cardiac motion; and IV = bubble signals sounding continuously throughout systole and diastole and obscuring normal cardiac signals).

The Kisman-Masurel scale is more sophisticated, with signals separately scored on the frequency, percentage/duration and amplitude of bubble activity before these parameter scores are combined to produce a single 0-IV grade. Kisman-Masurel scores can easily be converted to Spencer grades, but the reverse conversion is not possible.

Ultrasonic monitoring can be used to provide a secondary measure of decompression stress if symptoms are to remain an endpoint. Alternatively, ultrasonic monitoring may be used as a primary endpoint measure of decompression stress if the endpoint of symptoms is not appropriate for ethical or practical reasons. For the latter case, in particular, it is important to consider the limitations of bubble data.

Most critical is that the role that bubbles play in the development of symptomatic DCS is not clear. Part of the problem is that current technology makes it easy to study only intravascular bubbles. We know very little about the development of bubbles in extravascular tissues. Intravascular bubbles are associated with DCS, but DCS can develop in the absence of observed bubbles. Higher intravascular bubble grades (Spencer III or IV) are more strongly correlated with DCS than lower grades, but still at modest levels.

A recent study of 1,726 air dives and 1,508 heliox dives showed extremely poor positive predictive value for Spencer grade III-IV intravascular bubbles. The greatest strength of the bubble data was in the negative predictive value – the absence of DCS symptoms – associated with Spencer grade 0-II bubble scores.

There are additional practical challenges in interpreting ultrasonic data. The marked variance in sampling protocols (inter-measure interval and total sampling duration) may affect the validity of the data. The presence of intravascular bubbles has been reported to peak at 60 minutes post-dive, but this can vary as a function of the dive profile and breathing gas.

Differences in test procedures may also affect the comparability. This can include instrumentation, monitoring site selection, case sampling (rest or rest and various movement cases), and recording/review procedures.

Variability in technician training and experience are also potentially problematic, more so when scoring sessions are not recorded and confirmed.

Finally, self-selection within subject pools can be an issue, notably for more extreme exposures. It is possible that such groups will be disproportionately populated with bubble-resistant individuals, making it difficult to extrapolate the results from such groups to the wider population.

The above points are made not to discredit ultrasonic bubble monitoring but to remind the community that protocols should be carefully thought out and that the results of such monitoring must be critically and conservatively evaluated.

THE OPTIMAL PATH

Richard D. Vann, L.E. Howle, R.G. Dunford, Petar Denoble

The optimal path is the decompression profile that has the lowest possible probability of decompression sickness (DCS) for a given depth, bottom time and ascent time. The optimal path also applies to venous gas emboli (VGE). Understanding optimal paths for VGE will be important if arterialized VGE are proven responsible for cerebral DCS.

Optimal paths were estimated using probabilistic decompression models calibrated to 841 nitrogen-oxygen dive trials that were conducted in 1985 at the U.S. Navy Experimental Diving Unit. Doppler VGE data were also available for these trials. To model VGE probabilistically, we defined a binary variable called "High Bubble Grade (HBG)" with a value of 0 for Spencer Grades of 0-2 and a value of 1 for Grades 3-4.

To validate the model predictions, we estimated the DCS and HBG probabilities for the deep stops trials conducted by the Navy for 30-minute dives to 170 fsw. The DCS model predicted the observed DCS incidences relatively well, but the HBG model was unsatisfactory.

The first decompression stop for the optimal DCS profile was deeper than for the U.S. Navy schedule used from 1957-2008.

THE EFFECT OF DEEPER STOPS ON BUBBLE FORMATION IS DEPENDENT ON LENGTH OF BOTTOM TIME

Christian R. Gutvik, D. Glavas, A. Møllerløkken, Z. Dujic, Alf O. Brubakk

Background

Deep decompression stops compared to more conventional shallower stops have recently been introduced. Most findings and theoretical work on excess gas phase / bubble models suggest an apparent advantage of using deeper stops. However, some reports indicate that the incidence or risk of decompression sickness may actually increase following such procedures.

Materials and Methods

As a part of the validation of the Copernicus decompression model, a series of experimental dives were performed on recreational divers in Split, Croatia. A total of 11 dive procedures with seven to eight divers in each group were tested in water. The protocol included two series of deep/short dives (54 msw / 20 minutes and 45 msw / 16 minutes) and two series of shallow/long dives (24 msw / 70 minutes and 24 msw / 40 minutes). The four dive protocols followed two to three different decompression procedures with both deep and shallow stop regimes. The dives were evaluated using ultrasonic bubble detection.

At UHMS 2007 we presented a hypothesis based on animal experiments and a theoretical concept of stabilized bubble nuclei that the benefit of deep stops primarily applies for long bottom times. The present human data were analyzed to test this hypothesis.

Results

On the 24 msw / 70 minute dive, the experimental deep stop procedure seems to produce fewer bubbles than the Bühlmann shallow stop procedure. On the 45 msw / 16 minute dive, the VPM deep stop procedure gave more bubbles than the experimental shallow stop procedure. Simulation results from the Copernicus model with the implemented nuclei dynamics give the same results.

Conclusions

Although not statistically significant, the results point in the same direction as the previously presented hypothesis and fit well with the Copernicus bubble model. Our suggestion is that deep stops are primarily recommended on longer dives; however, more studies specifically designed to test this are advised.

INTERNATIONAL DAN DEEP STOP RESEARCH FOR RECREATIONAL DIVING

Peter B. Bennett

The predominant signs and symptoms of decompression sickness (DCS) in recreational divers are pain (23.9%), numbness (22.0%) and weakness (7.2%) and are of a neurological nature indicative of spinal cord involvement rather than joint pain. The incidence of DCS has changed little over the past decades (0.04-0.07%). Review of the history of ascent profiles shows that the 1906 Haldane 2:1 staged ascent was far superior to the Hill linear ascent. Yet today we are still making linear ascents, plus only a shallow stop at three to five meters for three to five minutes.

Since the U.K. and U.S. Navy divers experienced mostly joint pain DCS, they considered the problem was in the joints with their poor blood supply, which saturated or took up gas very slowly. Haldane's (1906) model of the body had five compartments (or exponentials) representing very full blood supply as in the brain and spinal cord at five minutes, 10 minutes, 20 minutes, with 40 minutes, 80 minutes and 120 minutes (representing poorer blood supply like the joints).

But the recreational diver's problem is in the fast tissue spinal cord, with 12.5 minutes half time, not the slow joint 120 minutes. It is proposed, therefore, that we now ascend far too rapidly and cause bubbles to form deep.

Working with Italian divers in the Mediterranean and an IDAN team of physicians and scientists, we hypothesized that introduction of a deep stop at half the depth would reduce the deep bubble formation and decompression risk in the spinal cord. A total of 181 dives were made to 25 m (82 fsw) by 22 volunteers with eight different ascent protocols. Ascents of three, 10 or 18 m/minute (10, 33 or 60 fsw/minute) were combined with no stops, or a shallow stop at 6 m (20 fsw), or a deep stop at 15 m (50 fsw) and a shallow stop at 6 m (20 fsw).

Bubbles were detected by Doppler over the heart after reaching the surface. These experiments indeed showed the highest gas loads were in the fast compartments (five and 10 minutes), not the slow. More importantly, the lowest bubble scores were with an ascent rate of 10 m/minute (33 fsw/minute), not three m/minute (10 fsw/minute).

Stops were best for five minutes at 15 m (50 fsw) and 6 m (20 fsw). More recent additional research has shown, in fact, that the best stop time for the deep stop is two and one-half minutes at half the depth. The one-minute stop recommended by some training agencies is too short. We therefore recommend a deep stop at half the depth of two and one-half minutes followed by the customary 6 m (20 fsw) for three to five minutes. While the direct correlation with signs and symptoms of DCS has not yet been made, this still does constitute a definite decrease in decompression stress.

THE USE OF DEEP STOPS IN RECREATIONAL DIVING : DAN EUROPE AND IDAN – OVERVIEW OF EARLIER STUDIES AND RECENT OBSERVATIONS

Alessandro Marroni, Frans J. Cronjé

Decompression illness (DCI) affects some 1,500 divers every year. Although DCI is relatively rare, two-thirds of these divers develop neurological manifestations. To study the factors associated with DCI, and to make diving even safer for recreational divers, DAN Europe, in collaboration with International DAN, performed a series of experiments since 1995. This presentation summarizes the highlights of these investigations.

Between 1995 and 1999, DAN Europe conducted an observational study and collected and analyzed 2,105 fully monitored, unrestricted recreational dives. The dives ranged from 5 to 65 meters sea water (MSW) and involved 575 volunteer research divers. The largest number of dives – 33.15% – were made in the 20- to 30-meter depth range. All the divers were Doppler-monitored at fixed intervals post-dive.

The presence of venous gas emboli (VGE) was graded as LBG (low bubble grades – occasional bubbles), HBG (high bubble grades – frequent to continuous bubbles); and HBG+ (very high bubble grades – continuous bubble showers).

VGE were detected in 37.4% of the monitored dives; LBG were observed in 25.4%; HBG in 12%; and HBG+ in 2.4% of the dives. Only 15% of the repetitive dives were bubble-free; LBG were detected in 18% of the repetitive dives and HBG/HBG+ were recorded in 67% of the repetitive dives.

Careful analysis of these dives suggested that post-dive high bubble grades were directly related to three key factors (TKF): gas-loading of fast to medium half time (HT) tissue compartments (TC) as per Bühlmann ZH-L8 ADT model; computed venous partial pressure of nitrogen (PvenN_2) in excess of 1,100 mbar; and leading TC nitrogen partial pressures (PltN_2) exceeding 80% of the allowed M-value.

Based on these results, a project was started to confirm the validity of the TKFs in controlling bubble grades. Three experimental square dive profiles were selected:

(1) a single dive to 20 m for 60 minutes;
(2) a single dive to 40 m for 10 minutes: and
(3) a series of three repetitive dives to 30 m for 16 minutes with 75-minute surface intervals.

The dives were made according to the original ZH-L8 ADT model and repeated with a modified algorithm designed to stay within the TKF limits. This implied a gradual reduction of the leading TC M-value, inversely proportional to the TC HT (proportional M-value reduction concept – PMRC), extended to include the 80 min HT TC and reaching correction factor 1 for the 160-minute HT TC (i.e., no change).

To achieve these partial pressures and gradients, extra deep stops had to be introduced during the ascent. These drastically reduced post-dive precordial Doppler-detected venous gas emboli (PPDDVGE) in a sample of 14 volunteer divers performing 210 dives and serving as their own controls. The study showed that the pressure gradient (i.e., Delta-P) imposed on the leading TC, irrespective of the rate of ascent, appeared to be the critical factor for bubble production in this series of experimental dives.

Given the experience with the extra deep stops, and in order to establish practical recommendations relevant to typical recreational divers, the next phase of the study considered the effect of adding deep stops of varying durations at half-the-depth of the dive – half depth deep stops (HDDS). These were evaluated during experimental repetitive diving to 25 MSW. The results are presented elsewhere at this workshop.

The final part of the experiment examined the effect of HDDS, in addition to the standard "Safety Stop," during single and repetitive recreational dives, from 18 to 40 MSW. Eight volunteer divers performed 24 different no-decompression dives between 18 and 40 MSW, with or without HDDS. Six of the profiles involved repetitive dives, designed according to the current USN Diving Tables, with three-hour 30-minute surface intervals. The depth patterns were chosen to reflect the normal habits of most recreational divers (18+18, 21+21, 25+25, 27+21, 30+2, 40+24 MSW respectively).

The introduction of an HDDS generally reduced PPDDVGE, with an overall decrease of high bubble grades compared to the same dives without HDDS. The data suggest that the inclusion of an HDDS on dives between 25 and 30 MSW, with bottom times of 25 minutes or less (i.e., the typical dive profiles performed by recreational divers) reduces decompression stress as measured by PPDDVGE.

The value of HDDS in reducing PPDDVGE was not as evident for shallower (18-21 MSW) and deeper dives (40 MSW), when brought to the limit of the respective no-D bottom time according to USN Dive Tables, and showed conflicting results. Further investigation is now being planned to unravel the apparent ambiguity of HDDS at these depths.

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