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Decompression Science: Critical Gas Exchange

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Abstract

There are two broad classes of decompression algorithm: gas content models and bubble models. Based on their compelling theoretical attraction bubble models enjoyed a long period of popularity among technical divers in the early 2000s, largely in the absence of supportive data. More recently several comparative studies have demonstrated increased numbers of venous gas emboli after decompression dives planned using bubble models, and one study demonstrated a greater incidence of decompression sickness (DCS). It seems that protection of faster tissues early in the ascent by imposing deeper decompression stops (a key characteristic of the bubble model approach) is not as effective at controlling bubble formation as hypothesized. Indeed, it may fail because of continued uptake of inert gas by slower tissues during deep stops, causing these tissues to subsequently become more supersaturated later in the ascent. There is a general sense that bubble models may over-emphasize deep stops, and divers using the gradient factor approach to manipulating a gas content model may choose to de-emphasize deep stops. The optimal approach to decompression from deep bounce dives is, however, unknown. Another area of controversy is whether inert gas switches (from helium to nitrogen-based diluent) should be employed during decompression from deep rebreather dives. The efficacy of such switches in accelerating decompression has recently been questioned, and given the potential for such switches to (albeit rarely) contribute to inner ear DCS, and the lack of a financial imperative to save helium in a rebreather system, opinion seems to be swinging toward staying on helium based diluent throughout decompression in rebreather diving.

Keywords: diving, rebreather, decompression, deep stops, bubble model, gas content model

Introduction

Few issues in diving are as contentious and vexed as the debate around what constitutes the optimal approach to decompression.

This paper is a brief and superficial summary of current debate about the relative merits of decompression algorithms based on gas content models and bubble models. This is a simple account that concentrates on the basic philosophical differences between these different approaches to decompression and avoids discussion of the specific mathematics and modelling techniques. Basic (Doolette and Mitchell 2013) and more advanced (Doolette and Mitchell 2011) accounts of these latter subjects are available. The paper also briefly addresses the controversy around whether to perform diluent gas switches during decompression from deep bounce dives using rebreathers.

The Process of Decompression, and Decompression Modelling

During the descent and bottom phases of a compressed gas dive, the pressure of inspired inert gas (e.g., nitrogen in air diving) is increased, and this gas is absorbed into blood and then carried to tissues. Over time, the tissue inert gas pressure trends toward equilibration with the inspired pressure as gas diffuses from blood into the tissue. The rate at which equilibration occurs is faster for some tissues than others;

equilibration tends to occur more quickly in tissues with high blood flow and/or low solubility for the inert gas, and vice versa. Rapidly equilibrating tissues are often referred to as "fast tissues" and tissues which equilibrate more slowly are referred to as "slow tissues." If there comes a point where tissue inert gas pressure does equilibrate with the inspired pressure the tissue is said to be "saturated."

As ambient pressure falls during ascent the inspired inert gas pressure also falls and, once inspired gas pressure falls below the pressure of gas dissolved in a tissue, a pressure gradient becomes established for inert gas to move out of tissues into the blood, and thence to be carried to the lungs and exhaled. However, depending on the rate of ascent and whether the tissue is 'fast' or 'slow' there will likely come a point during the ascent where the sum of dissolved gas pressures in the tissue exceeds the ambient pressure. At this point the tissue is said to be "supersaturated." This is significant because once supersaturation occurs bubbles may form in the tissues themselves or in the blood passing through the tissue microcirculation. The latter bubbles subsequently pass into the veins where they can be detected using either Doppler technology or echocardiographic imaging when they arrive in the right heart. Depending on their size, number and distribution (and other factors), formation of these bubbles may result in the development of symptoms of decompression sickness (DCS).

Not surprisingly (given the preceding discussion) strategies to prevent DCS focus substantially on controlling tissue inert gas supersaturation. Implicit in this approach is the mathematical approximation of inert gas uptake and elimination by a range of hypothetical tissues during a dive, and the tracking of inert gas pressures in those tissues relative to the ambient pressure particularly during the ascent. Using the relevant calculations, control of tissue supersaturation can then be achieved by slowing the ascent rate or imposing stops in the ascent to allow time for inert gas to diffuse out of tissue before supersaturation exceeds some predetermined acceptable threshold. The biggest difference between the approaches to decompression planning discussed below is their respective "views" on acceptable degrees of supersaturation in the various tissues over the course of the ascent.

Gas content models

The so-called gas content models, such as those proposed by Haldane and later by Buhlmann, were the first widely used and largely successful decompression strategies. The underlying decompression philosophy was an aim to establish the largest tissue supersaturation that could be tolerated without producing DCS because this would maximize the gradient for tissue outgassing and therefore (in theory) maximize inert gas elimination. In this approach, a series of supersaturation limits were calculated based initially on animal experiments by Haldane, but later modified many times based on a mix of theoretical and empirical adjustments. Arguably the most famous of these sets of limits were the ZH-L16 ascent rules for 16 hypothetical tissues promulgated by AA Buhlmann. These have formed the basis for many decompression strategies still in use today.

In decompression diving, it is an inevitable result of the underlying philosophy (see above) that gas content models allow an initially large excursion toward the surface before imposing the first decompression stop. This frequently results in relatively large supersaturations in faster tissues early in the ascent because these tissues have often equilibrated (or nearly so) with the pressure of inspired inert gas during the period at the bottom. However, these supersaturations are relatively short-lived because the fast tissues eliminate inert gas quickly. This characteristic of gas content models becomes relevant as this narrative further unfolds.

Since gas content models were the archetypal approach to decompression there was little else to compare them with in the early days. Most evolution of the approach involved tinkering with the supersaturation thresholds, but the underlying philosophy of maximizing supersaturation without producing symptoms persisted. It was, of course, clear from the start that these approaches to decompression were not invariably successful. Cases of DCS still occurred even when divers adhered rigidly to the decompression procedure prescribed by their decompression table. Moreover, the advent of Doppler technology demonstrated that bubbles formed in tissue capillary beds appeared in the venous blood very commonly after surfacing from dives. Although it was clear that this could be tolerated in most cases (because the divers did not have symptoms of DCS), it was a confronting finding for many who had assumed that adhering to the supersaturation thresholds prescribed by gas content models actually prevented bubble formation. The combination of the frequent formation of bubbles and sporadic occurrence of DCS despite adherence to decompression procedures prescribed by bubble models provided fertile ground for the emergence of alternative philosophical approaches to decompression.

Bubble models

The most important of these alternative philosophies is the so-called bubble model approach to decompression. The fundamental philosophical difference to a gas content model is the belief that the initial large ascents permitted by the latter (which, as described above, result in significant supersaturation of fast tissues) are a strategic error which initiate the formation of bubbles that may later go on to produce symptoms. The bubble model approach holds that smaller supersaturations during the ascent will permit control of bubble formation within predictable parameters of number and size, and that this will reduce risk of DCS. The mathematical approach employed in bubble models is described elsewhere (Doolette and Mitchell 2011; 2013) and will not be explored here. However, it should be obvious that in order to impose smaller supersaturations during ascent a decompression algorithm will impose decompression stops earlier in the ascent to reduce supersaturation in the faster tissues. This approach has resulted in bubble model decompressions becoming synonymous with the term "deep stops."

The obvious theoretical attraction of the bubble model approach to decompression saw these models become very popular if not ubiquitous among technical divers in the early 1990s. Several proprietary bubble models (the Variable Permeability Model – VPM; and the Reduced Gradient Bubble Model – RGBM) emerged and were adapted into decompression computers for both scuba air and technical divers. Such was the faith in the "bubble control concept" that some early bubble model decompressions were conspicuously shorter than gas content model ascents despite the imposition of deeper stops. The underlying assumption was that prevention of initiation of bubble formation early in the ascent allowed shorter stops later in the ascent. There was some empirical reversal of this assumption (and adjustment of bubble model algorithms) in response to DCS cases, but the perception that bubble model decompressions were safer and more efficient nevertheless persisted.

It is relevant to mention that even among divers who continued to employ gas content model supersaturation limits in their dive planning there was an almost ubiquitous trend to using methods that made the prescribed ascents look more like bubble model decompressions. The use of the so-called "gradient factors" method is the most conspicuous example of this. In this method, the diver chooses a fraction of the allowed Buhlmann supersaturation limits that will be tolerated early in the ascent and at the point of surfacing. The diver can choose fractions that are less than or that exceed the Buhlmann limits, but arguably the most common application during the period of strong belief in bubble models has been to use the gradient factor method to emphasize deep stops in the decompression profile. If, for example, the diver accepts only 20% of the allowable Buhlmann limit early, the ascent will proceed until the most supersaturated tissue reaches 20% of the allowable supersaturation and a decompression stop will be undertaken at that depth. It should be obvious that this stop will occur at a deeper depth than had the diver accepted 100% of the normal Buhlmann supersaturation limit, and this approach therefore results in deeper stops as is the case with bubble models (although clearly the underlying mathematics are very different). As mentioned, the diver also chooses a fraction of the allowable Buhlmann supersaturation that will be tolerated at the point of surfacing. If the diver chooses a fraction lower than 100%, then the final shallow decompression stops will be longer in order to allow the slower tissues to eliminate more inert gas than would normally be required by Buhlmann prior to surfacing. The algorithm interpolates a line between the two chosen "gradient factors" which essentially specifies a re-defined range of allowable fractions of the Buhlmann limits that will be followed throughout the ascent.

Human Data

It is fascinating to reflect on the fact that the widespread perception of bubble model superiority for decompression diving was unsupported by any data from human studies (or animal studies for that matter). Indeed, the mass gravitation to the use of bubble model approaches to decompression among technical divers was substantially based on theoretic attraction and word-of-mouth promotion. The fact that many thousands of technical dives are undertaken using bubble models is often mistaken for or indeed, incorrectly portrayed as evidence of superiority of the models. In fact, while such observations demonstrate that bubble model decompressions do work in the majority of dives, they do not constitute evidence of superiority in comparison to other approaches to decompression.

On that background it is equally fascinating that the small number of relevant human studies that have emerged in recent times have challenged the bubble model approach. The first relevant study was published by Blatteau et al. (2005) who compared venous bubble grades in divers following decompressions (from 165-200 ft [50-60 m] dives) performed according to protocols prescribed by their standard gas content model or several experimental "deep stops" models. They found higher bubble grades following several of the deep stops decompression profiles. In a more recent study of technical diving decompressions using a bubble model, the authors recorded very high venous bubble grades following almost every dive (Ljubkovic et al. 2010). This was not a comparative study but the finding of consistently high bubble grades after decompressions prescribed by a model whose stated goal is to control bubble formation was surprising and somewhat ironic. While these studies are interesting, the relevant outcome measure was venous bubble grades as opposed to clinical DCS, so the conclusions that can be drawn are limited.

The most important relevant human data comes from the US Navy Experimental Diving Unit (Doolette et al. 2011). At the height of bubble model popularity among technical divers in the mid to late 2000s the USN were contemplating shifting the emphasis of their dive planning tools from gas content models to bubble models. They designed a trial designed to isolate the effect of distribution of stop time (either emphasizing deep stops or shallow stops) in dives that were otherwise identical (same depth and bottom time, and length of decompression). The dives were all air dives to 170 fsw (52 msw) for 30 min bottom time, conducted in water at 86°F (30°C) with no thermal protection and with the divers exercising at 115 watts during the bottom time. Air was breathed throughout the decompression. The decompression profiles were generated by a gas content model (VVal-18, shallow stops) and a bubble model (BVM-3, deep stops). These models are USN-designed algorithms whose details are beyond the scope of this discussion, but both produce decompression profiles with characteristics that are typical of the underlying decompression gas content and bubble model philosophies respectively. Although an uncommon approach in decompression diving, air was used throughout the decompression in order to prolong the decompression and thereby to help unmask any significant influence of redistribution of stop time on outcomes. The profiles are shown in Figure 1. The primary outcome was the incidence of DCS diagnosed by the duty diving medical officer following the dives. Venous bubble grades were also measured after diving as a secondary outcome measure.

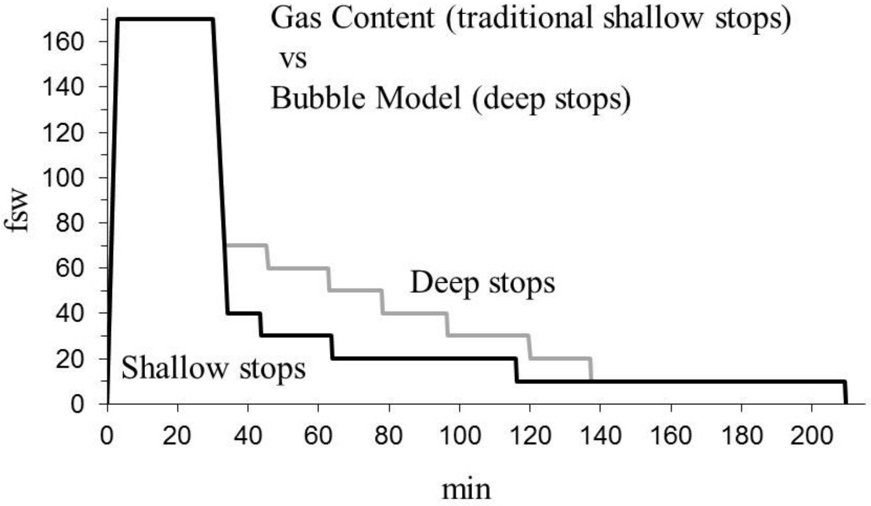

Figure 1. Dive profiles in the NEDU deep stops study.

In accordance with the approved protocol the study was stopped when the incidence of DCS became significantly different between the two groups on a sequential analysis. At that point there had been three cases of DCS in 192 dives (1.6%) on the shallow stops profile and 10 cases in 198 dives (5.1%) on the deep stops profile. The secondary analysis also showed that the deep stops profile was associated with a higher proportion of divers exhibiting high venous bubble grades. On this basis, the USN has declined to widely adopt bubble model decompression for its own purposes.

The result begs the obvious question "why did the deep stops fail"? Analyses of the supersaturation (expressed as an integral of supersaturation magnitude and time) across the range of hypothetical tissues (from fast to slow) at all stages of the ascent demonstrate that the NEDU deep stops profile did result in less supersaturation of the fast tissues early, which is the property of a bubble model hypothesized to control bubble formation. But the analyses also reveal that this comes at the price of more supersaturation of the slow tissues later in the ascent because of continued inert gas uptake into these tissues during the deeper stops. The poorer clinical outcomes and higher bubble counts in the deep stops arm of the study suggest that the assumption that reducing supersaturation in fast tissues early in an ascent will control bubble formation and result in less DCS may be flawed; indeed, the study results indicate that supersaturation of slower tissues later in the ascent is a more important determinant of bubble formation and risk of DCS.

The NEDU deep stops study has generated an immense amount of debate within the technical diving community. The most common criticism centers around the superficial observation that the NEDU deep stops profile "does not look like" profiles that would be generated by bubble models (such as VPM) typically used by technical divers. Specifically, a typical VPM profile would have been shorter, and would have included a very short series of even deeper stops. However, in reality, the NEDU deep stops profile is not significantly different from a VPM profile where the latter model is applied with sufficient conservatism to produce a profile of identical length to the NEDU dives. Moreover, this argument ignores the fact that the apparently disadvantageous supersaturation pattern (decreased supersaturation in fast tissues early and increased supersaturation of slow tissues later) is highly likely to be replicated in any dive where a finite amount of decompression stop time is distributed deeper rather than shallower. Indeed, analysis of decompression profiles for real world technical rebreather dives prescribed by commonly used bubble and gas content models reveals the same apparently disadvantageous pattern of supersaturation distribution repeating itself, even when bubble model profiles are compared to gas content models modified by gradient factors to introduce some deep stop characteristics. Thus on the basis of currently available data and contrary to previous widely held belief, there is no reason to believe that bubble model/deep stop decompression is more efficient than decompression prescribed by a gas content model when dives of equal length are compared. Indeed, one would be compelled to draw the opposite conclusion.

Unfortunately, the NEDU study does not define optimal decompression and nor does it provide a basis for definitive advice to technical divers on this issue. Perhaps the best that can be said is that the concept of using bubble model decompressions to improve decompression efficiency has been 'oversold' to the technical diving community and that the current best evidence suggests that approaches which de-emphasize deep stops to some poorly defined extent are preferable. Many technical divers who use the gradient factor approach to decompression planning (see earlier) are responding to this scenario by increasing the 'gradient factor low' and are thus accepting a higher fraction of the allowable Buhlmann supersaturation limit in determining the depth of their first decompression stop. There is, however, no objective basis for a recommendation on how far such "backing-off" from deep stops should go. The knowledge we seek on "optimal decompression" remains an elusive goal.

Diluent Switches During Decompression from Rebreather Dives

Another decompression controversy independent of the above discussion about decompression models but relevant to scientific dives with rebreathers relates to the use of gas switches during decompression from deep mixed gas dives. Specifically, in open-circuit diving it has been common practice to switch from trimix to air and/or progressively richer nitrox mixes during decompression, and ultimately, to breathe 100% oxygen during the final shallow stop. There are several goals underpinning this practice. First, the elimination of helium from the breathing mix saves on the cost of this expensive gas. Second, the progressive increase in the inspired fraction of oxygen hastens the elimination of all inert gases. Third, it is perceived that substituting nitrogen for helium in the inspired gas will (independent of increasing the inspired oxygen fraction) accelerate elimination of helium because helium will diffuse out of tissues into blood faster than the nitrogen will diffuse from the blood into tissues. This favorable "counterdiffusion" process would have the effect of causing at least a transient enhancement of gas elimination from tissues. The practice of gas switching has also found its way into rebreather diving in the form of diluent switches during decompression (for example, a switch from trimix diluent to air diluent at an appropriate depth).

The first two of the above goals are clearly legitimate. The third is more controversial. It has long been assumed, mainly on theoretical grounds, that helium to nitrogen switches during decompression will reduce supersaturation in most tissues (Lambertsen and Idicula 1975). The related controversy arises in part from the long standing recognition that such switches may occasionally be associated with the onset of inner ear DCS. Because of its unique anatomy, the inner ear is perhaps the only organ in which a helium to nitrogen switch can produce an unfavorable gas counterdiffusion process. The mechanism was recently summarized by Mitchell and Doolette (2015) as follows:

"The perilymph and endolymph are non-perfused compartments that take up and eliminate inert gas through the perfused membranous labyrinth. After a period of heliox breathing, the perilymph, in particular, accumulates a substantial reservoir of helium. Following a switch to nitrox breathing, owing to a higher diffusivity of helium than of nitrogen, diffusion of helium from the perilymph and endolymph to the membranous labyrinth exceeds the diffusion of nitrogen in the opposite direction. At the same time, owing to higher solubility of nitrogen than of helium in blood, delivery of nitrogen to the membranous labyrinth in the arterial blood exceeds the removal of helium in the venous outflow. Together these could cause a transient supersaturation of the membranous labyrinth without decompression."

The risk of such events is low (Doolette and Gerth 2014) but it has nevertheless caught the attention of the technical diving world. In addition, there is some doubt over whether gas switches really do accelerate inert gas elimination in tissues other than the inner ear and therefore over whether there is any advantage in doing them from a decompression point of view. In a recent study, Doolette et al. (2015) were unable to demonstrate any difference in helium and nitrogen kinetics in brain or skeletal muscle, and this could be interpreted to imply that a gas switch would not of itself materially alter inert gas pressures in these tissues at least.

It is therefore concluded that while gas switches will undoubtedly continue to be employed by open-circuit divers to save on the huge cost of helium, there is little compelling reason (and perhaps some small risk) in doing them during rebreather dives where very little helium is used, even if a helium diluent is employed throughout the dive.

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QUESTIONS AND DISCUSSION

LIZ KINTZING: How did Buhlmann come up with his supersaturation limit?

SIMON MITCHELL: Initially with mathematics. Then by testing and empirical modification after use in the field.

DAVE CONLIN: When you are moving on these shallower stops with supersaturated slow tissues your individual pressure gradients between sequential stops is much greater so one would expect greater bubble formation as a consequence of that too; is that correct?

SIMON MITCHELL: These are actually smaller supersaturations. This scale is actually smaller than the other one. It is important to integrate supersaturation with time because when fast tissue become supersaturated they do not stay supersaturated for long. But with slower tissues you can see you have got big integrals of time and supersaturation. The area under the curve is much greater, which is part of the point you are getting at.

SIMON TALBOT: It is the tissue perfusion relationship, the off-gassing much faster in the fast tissues.

SIMON MITCHELL: Correct. That is why they are fast tissues; because they perfuse better. Fast tissues are fast tissues mainly because of perfusion. There are other factors like the solubility of the gas in the tissue compared to the solubility in blood, but they are fast tissues mainly because they get more blood flow.

BRETT SEYMOUR: On the flip side, how can people look at a study like this and say that it was flawed? You mentioned earlier the people who do not prescribe to it do not understand it.

SIMON MITCHELL: I am coming to that.

JEFF GODFREY: Can you see if there was a difference in the ratio between type 1 and type 2 DCS?

SIMON MITCHELL: Good question. The answer is there were not enough cases to be sure, but, no. Both profiles resulted in a mix of cases. And so what you are thinking is that with greater supersaturation of the slow tissues you might have got more type 1. There were type 2 in both of these definitely, and in roughly the same proportions, but the numbers were very small.

DAVE PENCE: Has anyone looked at what further decompression would have been required to protect both the slow and the fast tissues?

SIMON MITCHELL: No, but you could do that. You could play around with this and come up with a better profile. But, I guess what David would say if he was here is, well, actually, as a military unit, we are actually really happy with the results of the shallow stops profile. We ran hard-working dives on air with no oxygen acceleration of decompression, with thermal stress and we got three cases of DCS in 200 dives. That is pretty good. And I think, actually, it probably is. These were very provocative dives. Do not make any mistake about that. It was a provocative profile.

KARL HUGGINS: So the standard profile was derived from the VVAL-18?

SIMON MITCHELL: Yes.

KARL HUGGINS: So if you ran through the VVAL-18 the initial deeper stops before you reached the ceiling, did anyone look at how much additional decompression would be required?

SIMON MITCHELL: No, they did not. One of the questions that often arises is "would it be better if you did deep stops and extended your shallow stops in order to compensate for those deep stops"? You could do that, but based on these data, I do not think that there is any advantage in it. There is no evidence of an advantage from protecting the fast tissues early. It makes intuitive sense, but in practice, it is not being borne out. But that is part of the reason I am saying these are incomplete data. That work could be done.

DAVE PENCE: As a guy who may be doing a provocative profile in a tribal village in New Guinea with no chamber anywhere near, three out of 200 dives is not necessarily a happy outcome. So, again, is there a way to use the dissolved gas models and do the deeper stops and simply suffer the extended decompression that would be even more protective?

SIMON MITCHELL: Again, I think that what we are seeing here is that there is no evidence for protection from deep stops. What I would do in that situation is just extend my shallow stops on oxygen. Can we leave discussion of optimal decompression until the end because some of these are things that I am going to put some perspective on?

RICHARD PYLE: I have a lot I would like to comment on related to all of this, but I think it makes sense to let you finish and then we can come back to the conversation.

SIMON MITCHELL: We are well aware of your leadership role in the deep stops revolution. You are a scientist, Richard. It is evidence, data.

RICHARD PYLE: That is one of the words I want to quibble with you on, but go ahead.

JEFF BOZANIC: Just trying to understand what you are presenting with the models here. Would the gradient factor selection vary based on the dive profile in terms of depth and times? In other words, you have presented a gradient factor here of 40/74 as an example to give us a set of curves that look similar to the shallow NEDU studies. From a practical standpoint, would you vary gradient factors based on the dive profile you are looking at to achieve similar results? Or can you select a similar gradient factor that would be generally applicable to a broad range of dives?

SIMON MITCHELL: More the latter than the former. Because the beauty, if you will, of gradient factors is that by choosing your gradient factor low, you can manipulate the emphasis that your decompression places on deep stops. If you choose 10, it will do lots of deep stops. It will look just like a bubble model.

JEFF BOZANIC: It seems like you would want to choose a gradient factor of 70.

SIMON MITCHELL: That is the problem. We do not know what optimal decompression is. We think we know what it is not, but we do not know what it is. And natural caution would suggest, given that lots of people are religiously adhering to a deep stop approach, backing off from deep stops to some poorly-defined extent is probably a good idea. But how far you should back off is unclear. We do not know where the optimal is.

JESSICA KELLER: So when you were at Bikini and you are using a 40 or 50 low gradient factor, how different is your profile time-wise compared to the other people who are using 50?

SIMON MITCHELL: It did not make a lot of difference at Bikini, I have to say. You start to see the differences, bigger differences, in deeper, longer dives. We were diving mainly to 40-50 m (130-165 ft). There is a little bit of a difference. And we had one guy who was doing ratio deco. I have never seen anything quite like it. The Saratoga flight deck is at 23 m (75 ft). His first stop seemed about 1.5 m (5 ft) above the flight deck. He would just hover there. You might as well just continue diving. It was strange. And he was the only guy who got bent, I might add.

PHIL SHORT: My apologies to Rich, but what are your thoughts on instead of a bubble model that is putting deep stops in, putting Pyle stops in?

RICHARD PYLE: First of all, I curse on you for mentioning Pyle stops. I hate that term. Can I take a moment here?

SIMON MITCHELL: I am going to say one thing before you do. "Pyle stops" are a different thing to a bubble model.

RICHARD PYLE: That is what I want to get to. First of all, excellent visual representations. I think your explanation of the intermediate and fast tissues was the best I have seen shown. We thought through all of this 15 years ago when we were working on this. And I have never seen it visually represented. That is really good.

SIMON MITCHELL: There is something bad coming here.

RICHARD PYLE: No. I actually want to say I agree with almost everything. The first quibble I have is what Phil was just alluding to. This sort of equation, equality of bubble models in deep stops. And those, having been involved in this, are very, very different things. You used deep stops, but really what you were talking about was bubble models. So whenever you said X about deep stops -- let me just clarify the difference between the two. Bubble models are theoretical, conceptual, mathematical representations of what ought to be; whereas, deep stops emerged empirically from what people actually did. And the fundamental difference is what Karl and Dave were alluding to. Deep stops are an ad hoc addition to an ascent profile, which were actually modeled after shallow water safety stops. If you think of your ceiling as effectively going straight to the surface without a safety stop with a fully saturated dive, the idea of a deep stop was to add, essentially, I call them deep safety stops. Will Smith has called them Pyle stops, and I curse him, even though he is dead, for it. In any case, the important distinction is that the way we used to calculate them with desktop software and currently do them with real-time decompression computing is that they do not terminate the dive at the same time. They actually end up extending the total duration of the time. So the question is are you getting the benefit of them because you are doing an extra hour and it does increase the --

SIMON MITCHELL: We do not know --

RICHARD PYLE: Forget the benefit.

SIMON MITCHELL: Let us not assume.

RICHARD PYLE: Let us assume there is no benefit. But let us say that even if there were a benefit, you still would not know if that benefit was a consequence of the initial deep stops or a consequence of the long stops. It is a very complicated thing to tease apart. The main point I wanted to make is to distinguish the terminology. What I believe people who use the term "deep stops" to mean, it is the bubble model people who conflated them. Because they say, our models have deep stops; therefore, deep stops equal bubble models. I do not buy it, and David Yount was a dear friend of mine. I have never used a bubble model. I would never use a bubble model. Whenever you hear me talk about deep stops, I just wanted to clarify that distinction.

SIMON MITCHELL: I have no objection to anything you have just said. Nobody has addressed your methods.

RICHARD PYLE: Right, and that brings me to the second point, and that is my slight quibble with the difference between the word "data" and the word "evidence." Data is basically a subset of evidence in the broader scheme of things. And I agree with you that there is absolutely no data to support my method or any other ad hoc deep stop method. What we have now is data to show that a bubble model approach to things may be inferior in some cases. You had said on one of your earlier slides we may have some data against deep stops. We do not. We have no data against deep stops.

SIMON MITCHELL: That's your definition of deep stops. Just remember how the technical diving community uses that term which is usually in relation to bubble models.

RICHARD PYLE: I have not been paying attention to what the community is doing. I only know what I do. I wanted to sort of clarify that there is really no data. The NEDU study was beautiful and elegant and I talked to Wayne Gerth about this quite a bit right when he published it, and he and I both agreed that that is a beautiful test of the, sort of, bubble model approach which gives you the shape of the profile. But we both agree that it is not a test for what, at least at the time, which was 10 years ago, most technical divers were doing. It was an air profile that had big, long intermediate stops.

SIMON MITCHELL: But the patterns are the same.

RICHARD PYLE: No, they are not, actually.

SIMON MITCHELL: Yes, they are.

RICHARD PYLE: I have graphs that shows they are the same. I can show you that when you add the deep stops the way you add a two-minute here, a two-minute here, and pretty soon you are caught up in your ceiling, it is very different. If you plot the area between the two curves of the decompression profile, that area of discrepancy is much smaller with a deep stop approach than it is with the approach that Wayne used.

SIMON MITCHELL: By deep stop approach, you mean your approach? Sure.

RICHARD PYLE: That is my point. Maybe the Internet crowd that I have not been paying attention to has been rebranding the term deep stop.

SIMON MITCHELL: They are, I am afraid.

RICHARD PYLE: Then in that case we have a terminology complication.

SIMON MITCHELL: That is right. We do.

RICHARD PYLE: Maybe for clarity of conversation for at least this audience, it would be helpful --

SIMON MITCHELL: Pyle stops.

RICHARD PYLE: Anyway, I just wanted to make it clear that I agree with almost everything you say. I do not like bubble models for the reasons that you came up with. But I wanted the room to understand that when they hear me talking about deep stops, I am talking about something that is fundamentally different from what apparently the Internet community is talking about.

SIMON MITCHELL: I am not going to challenge any of that. It is fine. It is a different thing. It is not as widespread in the community as it used to be. Thank you, Rich.

JOHN BRIGHT: Maybe an addendum or a corollary to the third question there, what are the implications for bailout gas mix planning if the resulting switch from a helium-rich to a helium-poor mix could manifest a bubble in the inner ear.

SIMON MITCHELL: That is a really good question. Off the top of my head I would say that when you are in a bailout situation, you would accept a small risk of an adverse outcome if logistically it would be hard to carry the optimal form of bailout.

JOHN BRIGHT: Hundreds of cubic feet?

SIMON MITCHELL: Yes, exactly, of a particular gas just because you are worried about isobaric counterdiffusion. I am not sure that the risk/benefit equation would favor doing that.

JEFF BOZANIC: A question that comes to my mind in looking at your second point, gradient factors are used, what should we use. In the absence of other factors, environmental or physiological, what kind of a safety stop, and I am calling it a safety stop on purpose, should we be adding to the mandatory decompression stops that the model called for in order to provide a buffer?

SIMON MITCHELL: In other words, should we all be doing what Richard does?

JEFF BOZANIC: Essentially.

RICHARD PYLE: Not quite. How much should we not run to our ceilings.

JEFF BOZANIC: In other words, I run to my ceiling. I am done with my deco. My computer says I am clear. I am warm. I am comfortable. Nobody is panicking on the boat. Just as a buffer because there is no other factors demanding that I get out of the water right now.

SIMON MITCHELL: It is something a lot of divers do. One of the points I would make is that in using gradient factors and, for example, in choosing a high gradient factor of 70, you are already imposing quite a lot of buffer on there. You could say, well, I will routinely choose 65. Or you could leave at this time at 70 and make a discretionary decision.

JEFF BOZANIC: My point is that you do not want to violate a model when you are on decompression dives. You are better off to choose 80, but then add to it because there are times where you need to get out of the water sooner.

SIMON MITCHELL: That is a fair comment and a good question.