COMING SOON TO A DIVE COMPUTER NEAR YOU

It's been twenty-five years now since dive computers came into general use. During that period of time a lot has changed, particularly in science and technology. Despite this, dive computers, at their core, have remained essentially unchanged. True, they now handle nitrox and trimix, and various "bells and whistles" have been added, but the algorithms underlying all dive computers currently marketed are still based on Haldane's model of independent parallel compartments, a model that has been around for one hundred years. ("No way!" you say. "What about bubble models?" Chill, we'll get to them.)

This wouldn't be a problem if Haldane's model worked really well. After all, sharks have survived essentially unchanged for eons and are considered, not as outmoded, but as a near-perfect design for their function and survival. Haldane's model isn't remotely in the same league. Its initial attractiveness was its relative simplicity. Suggestions for more realistic interconnected models were already around, and had been for some time, at the birth of the dive computer. But early dive computers were able to implement Haldane's model; a more complex model would have been too much for their memory and microprocessor capabilities.

Now, of course, we're in a completely different era where computing power and memory are concerned. And independent parallel compartments just don't stand up to scrutiny. A number of medical and physiological studies have examined the rates at which various substances, including gases, get distributed in and washed out from body tissues. The overall conclusion? The results were not consistent with Haldane's model, where the compartments were isolated from each other, but indicated that a more interconnected compartmental arrangement was likely to be involved.

Here's a "heads-up" on a new interconnected model, one that will most likely be part of your diving future[1]: Saul's ICM. Figure 1 illustrates the basics of, on the left, a Haldane-type model and, on the right, Saul's ICM. Arrows indicate where gases can enter and leave compartments, so the differences in connectivity between the two models can be seen from the figure. A little less obvious is what the compartments in the different models represent. Each of the compartments in Haldane's model represents tissue that may give rise to decompression illness. (That's why all its compartments are red – for danger). Tissues that don't suffer decompression injury play no part whatsoever in Haldane's simple model.

Although risks from all three compartments in a Haldane model are included in calculating the risk of decompression, in practice, the risk for any particular dive is mostly derived from the risk of only one compartment (the "controlling compartment"), with very little contribution from the other compartments. On the other hand, in Saul's ICM model, only the central "risk-bearing" compartment (red) represents tissue with a risk of decompression injury; the remaining compartments (green) represent "inactive" tissues (such as fatty tissue) where decompression injury does not occur. Instead, their role in the model is to function as receptacles or reservoirs for excess gas.

Initially, during compression, these tissues act like an overflow tank, increasing the amount of gas that can be absorbed without causing harm. But, as the dive continues and more and more gas is absorbed, remember that payback time will come. The dive will end and you will begin your ascent. The "overflow" gas has not disappeared. When you decompress, the risk-bearing compartment has to eliminate not only the gas already in it, but, in addition, the "payback" gas now returning from the other compartments.

(This, by the way, increases the importance of slow ascents and safety stops.) Of course, in very low-risk dives, relatively little gas would be absorbed during compression, resulting in low concentrations of gas both in the risk-bearing compartment and in the other compartments.

With a low concentration of gas in the reservoirs, the payback during decompression is very slow and, since the risk-bearing compartment is off-gassing it's own low concentration of gas at the same time, the risk of DCS is less than it would otherwise be. All this makes a certain amount of intuitive sense when you think about how the body functions as a whole. But intuition has limited usefulness. The real test is in how well the model itself functions. And it's becoming clear that this model is far superior to existing models in predicting the probability of decompression sickness.

What, exactly, do I mean by this? Obviously, models aren't psychic. Here's how the comparison works. In practice, models are represented by sets of equations. At its core, an equation is just a sequence of mathematical operations performed using numbers in one of two ways: as variables or as constants. In diving models, the variables would generally represent things like time, depth, whether or not the dive resulted in the "bends" – basically, things that vary with the data. Constants are numbers that form part of the equation itself – numbers that remain constant whatever data you input. Before you can use a model – which begins as, essentially, a theoretical framework – you have to adjust it to fit a sample of actual data of the type you hope to predict. This is called "calibration". During the process of calibrating a model on a sample set of data, things get a little weird: the variables actually remain constant (because the data sample doesn't change) while the constants vary (because you are trying out different values of your constants to see which bring your predictions closest to the sample data). When the best values for the constants have been determined, the model can then be made into a functioning algorithm.

One measure of predictive capability – the most elementary – would be how well a model fits the actual data that you used to calibrate it. But, in a sense, this is the least important measure. It bears some similarity to predicting the past. You already know what happened, and you construct your model in such a way that it agrees with what happened. Still, it does have some value – if you fail this measure, your model is toast – but it's no more than a starting point. The next step up is to see how well the model performs on a different set of data, but one that is still similar to the calibration data set. Now you're not predicting the past anymore. If you pass this test your theory has some consistency, albeit within a limited range. Most models that satisfy the first measure will satisfy this one too.

But for a measure of the real strength of a model, you need to see how well it performs in predicting the risk for a set of profiles that is completely outside the range of risk represented by the calibration profiles.

So how well do models calibrated using moderate-risk diving data fare when applied to a completely different set of dives where risk of decompression sickness is considerably higher? Let's go for an extreme case. US Navy researchers looked at decompression sickness rates from saturation dives in the real "don'teven- think-of-trying-this-at-home" range. They did this in trying to determine the risks entailed in direct ascents from a disabled submarine.

Because of the very high level of risk expected, they used mostly rats and pigs but were able to calculate how their animal results would apply to humans. The points show the expected risk of decompression sickness for each of three profiles: all were direct ascents from saturation on air at 33, 40 or 50 feet of seawater (fsw). Let's see how different models, each calibrated on lower risk diving data, fare in predicting the results actually found. The graph shows some rather striking differences. The models we compared were: a typical Haldanean model; the LE1, Saul's ICM, and Saul's ICBM (a bubbleversion of the Saul's ICM) models. The LE1 purports to add the effect of bubbles to what is otherwise a Haldanean model. Looking at

the graph, we see that Saul's ICM and ICBM models are well in line with the actual results (which rise rapidly with saturation depth), while both the bubble-based and non-bubblebased Haldanean models maintain approximately straight-line trajectories which very seriously underestimate the risks at greater depths. Adding bubbles to both interconnected and independent compartment models produces a relatively minor change in the predictions, while the effect of changing from an independent to an interconnected compartmental structure is huge.

What about comparing the models in the opposite, very low-risk direction, more typical of casual recreational diving? When we examine the incidence rate for about 10,000 dive profiles on air (from DAN's Project Dive Exploration [PDE] dataset), the interconnected models come closest to predicting the actual number of hits that occurred. These dives resulted in only 10 instances of decompression sickness. Doing some basic statistics on this, a model predicting anything between 5 and 18 hits would be reasonably on target. The LE1 model would predict 51 hits; a straight Haldanean model would predict 126 hits, the ICM would predict 10 hits and the ICBM would predict 11 hits. Again, the interconnected models outperform the others. So they are more accurate both with very high risk and with very low risk dives.

If you look only at the low-risk results, you may be inclined to yawn and wonder why you should care. So the existing models over-predict the number of hits – big deal. Doesn't that mean that they're more conservative than the interconnected models? And isn't that essentially a good thing, when it comes to staying safe? The answers are, respectively: "No" and "It depends."

Remember the very high risk comparisons we looked at earlier? The existing models grossly underestimated the risk there. That means they are unsafe for these high-risk profiles. That in itself doesn't matter too much, because you wouldn't dive those profiles anyhow. More troubling is that their predictions didn't follow the right pattern. This makes it likely that their predictions also seriously underestimate the risk in lesser, moderately high-risk profiles that you might consider diving. Is a more conservative model (which, as we have seen, does not necessarily describe current models) a good thing? Possibly, provided it's an accurate one.

The relative level of risk a diver is prepared to accept is a personal decision. But, without accurate information, you are not in a position to assess the true level of risk. Whether you want the safest option or whether you're willing to tolerate slightly higher risks, the key to getting what you want lies in accuracy. Saul's models can, as we have seen, provide much greater accuracy. (Obviously, this article could only provide a brief overview of the models and the research behind them. For complete details, and downloads of recent published journal articles, consult the author's website.)

I expect that Saul's models will be appearing in dive computers in the relatively near future and that they will eventually become the new standard for diving. Meanwhile, your best strategy is to continue to dive according to your dive computer, but be aware of its limitations. If it appears to conflict with something you may remember from dive tables or classes, take the safer option. And above all, never neglect your safety stops.

Figure 1

ABOUT THE AUTHORS

Saul Goldman, a physical chemist, is Professor Emeritus at the University of Guelph and has published about 100 papers in some of the most prestigious journals in the field (see

http://www.chemistry.uoguelph.ca/goldman/). Much of his research has dealt with liquids and solutions, particularly gases in liquids. He is also an avid diver who has logged almost 1000 dives. Since, like many physical chemists, he is somewhat “addicted” to equations, **Ethel Goldman** became involved to keep the material suitable for casual reading by nonphysical chemists and, in particular, to rigorously weed out equations and scientific jargon. When Saul insisted that equations were necessary, at least for background, Ethel “relented” but the only place you’ll find them is as background – literally.