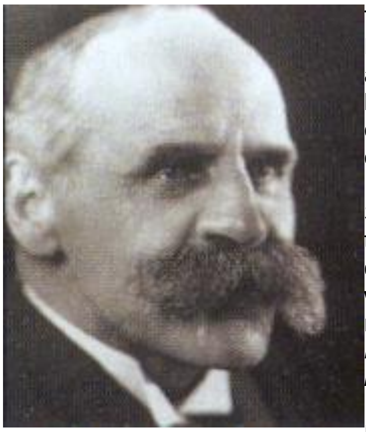
Decompression theory for goats

part one.
Full screen

We divers all have a sneaking suspicion that we ought to know more about decompression theory than treating tables as gospel or just watching the computer and being hopeful that the people who make it knew what they were doing.
Well I did so I read the books rather than doing my own research.



The first real work on the subject was Dr. John Scott Haldane who got a British Navy budget to try and make divers last longer. They were expensive to train and expensive to retire when the MO said they were unfit for further service. He knew the basics, that nitrogen dissolved in the diver's blood and when they came up it undissolved and it hurt and sometimes they fell over and had to be carried off to sick bay.

So in 1905 Haldane started a series of experiments in a compression chamber that today would have the animal rights people up in arms. However in those days Haldane escaped vilification as a serial goat bender and worked back from what he saw to the underlying conditions below and laid the foundations for modern decompression medicine.
Boycott AE, Damant GCC, Haldane JS. The prevention of compressed-air illness. Journal of Hygiene. Cambridge 1908

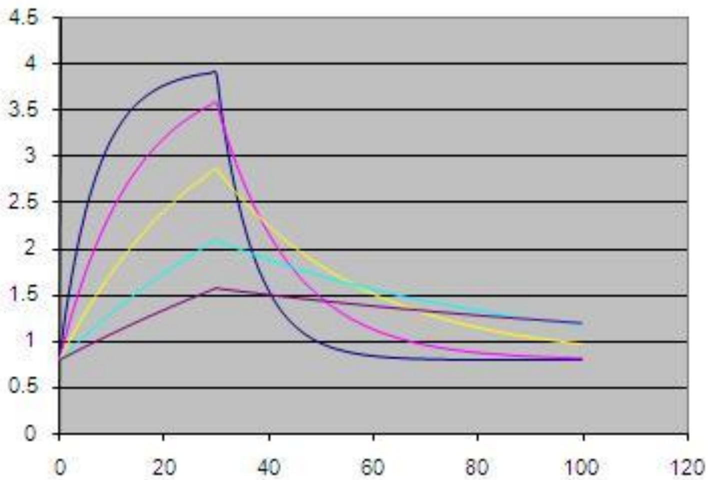
Haldane's model of nitrogen and people says that for any bit of your body there is a rate that nitrogen, or any other inert gas, builds up. He had Henry's law that says that the amount of gas that *will* dissolve is proportional to the partial pressure of that gas applied and Haldane needed to put time to that. In essence he discovered that the gas dissolves at a rate that is proportional to the difference from the final value of the current value. So if we know the level we are moving towards is 10 units and we are at 8 units the rate is based on the difference 2 units so it is twice as fast as if we were at 9 units (difference 1) but only half that if we were at 6 (difference 4). Usefully the rate of undissolving works the same way more difference equates to a faster change.

This is an exponential and is mathematically easy to model but Haldane soon realised that what may work for a liquid in a jar, which has a simple constant called a half time, does not work for a goat. The simple liquid has a number that represents the period of time it takes for the dissolved gas to move half way to the final value so if the half-time is 10 minutes and the initial difference is 12 units then after 10 minutes the difference has dropped to 6 units, after 20 minutes it is down to 3 units and after half an hour it is only 1.5 units. You will notice that it keeps getting closer but never gets there.

Haldane's best trick was to realise that he did not need to model every bit of a goat and know its half times. He just needed to have representative numbers that were near enough so that their effects overlapped. These are called *Compartments*.

Haldane's other discovery was that once the partial pressure of dissolved nitrogen was double the absolute pressure it started to spontaneously undissolve and you got bubbles. Now *double* is considered a bit simplistic these days but it was a lot better than nothing. Haldane's table kept divers below the critical 'double' and stopped the British Navy routinely bending divers and reduced the Admiralty's bills.

OK? Well let's bend a goat on a 40 meter dive.

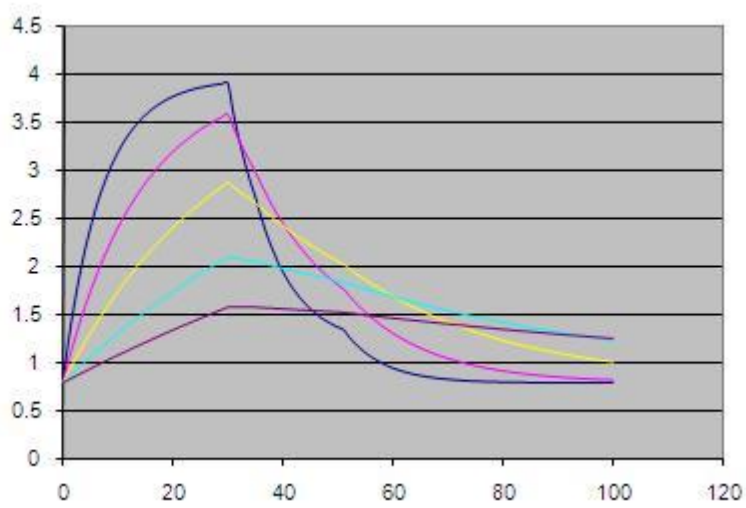


The graph represents the nitrogen tension in the five Haldane compartments vertically in bar with the time in minutes horizontally.
Surface ppN_2 is 0.79 bar so that is where all our graphs start. At 40 meters it is 3.95 bar so that is where they are heading some fast and the others more slowly although none will get there. Our goat needs to worry about compartments with a tension (like partial pressure but for dissolved gases) of 2bar or more on surfacing (double the absolute pressure).

The problem with compartments is that

blood is fast, that is it has a short half time and takes on enough Nitrogen to be a problem long before bone has accumulated enough to care about but conversely after a long dive the nitrogen in the bone takes a long time to dribble out so the blood may be decompressed but you still need to stay down. Haldane used five half times in his model and his first dive tables were based on the idea of adding up the nitrogen dissolved and subsequently undissolved in half times of 5, 10, 20, 40 and 75 mins. Look at the graph. They start at 0.79 bar, that is the nitrogen in normal pressure air, and the target is 3.95 bar which is the nitrogen in air at 40 meters. You can see the 5 minute compartment (blue line) shoots up and get very close. The 10 minute compartment (purple) goes slower and never gets above 3.6 in the half hour under pressure. The 75 minute compartment (cyan) only gets to 1.6. After half an hour the outside pressure reverts to 1 bar and the poor old goat decompresses like a freshly opened can of coke. Notice that the 5 minute compartment is virtually clear by 70 minutes but by 100 minutes the compartment with the most nitrogen is the 75.

Now if the bend limit was 2bar (double the absolute pressure) this was one badly bent goat when he stepped out of the chamber.



Not much good that one. Goat for supper again. Right get me another goat and we'll give this one a couple of deco stops.

The compartment with the most nitrogen after 30 minutes is the 5 minute one (blue) with 3.9 bar so if we are not to let the absolute pressure go to less than half the tissue tension we'd better stop him at 10 meters, 2 bar. We'll keep him there for five minutes, i.e. thirty five minutes into his dive.

Look at the graph. The 5 minute compartment rushes down towards 1.58 bar being the ppN2 in air at 2 bar but the 75 minute compartment is unchanged as 1.56 is just where it is so it has virtually no reason to change.

I'm sorry but the kinks at 35 minutes are a bit hard to see but our worst nitrogen level at the end of the stop is now 2.97 bar so we can afford to take our goat to a level that is half that i.e. 1.5 bar so let's give him a 5 meter stop where the absolute pressure is 1.5 bar and he can stay here till it is safe to surface.

To surface the max ppN_2 must be less than 2 bar which happens at 52 minutes when the 20 minute compartment finally falls below the limit.

Time to knock off for the afternoon and take our remaining goat down the pub for a beer but he is still decompressing. Watch my graphs. After 100 minutes from the start of his dive he still has 1.125 bar of nitrogen in his 75 minute compartment. Remind this goat not to fly.

Decompression theory for goats

part two.

OK. In part one we looked at the general idea and the history of decompression planning but now we need to move on a bit.
When I first thought about deco theory I wondered how much gas is actually involved and search as I might I could not find anybody quoting it. <sigh> However a dig in the usual sources (The old Rubber book) turned up the molar fraction solubility for nitrogen in water that leads me believe that at 0.79bar ppN2 (on the surface) we have about 0.72 grams of dissolved nitrogen in a 70Kg person. So a good exposure to breathing air at 25 meters will give us 2.5gms of nitrogen which is 3.2 surface litres.

Admittedly quite a bit of our bodies are not going to get the full exposure but the blood and the immediate soft tissues it bathes are going to get their share. I have watched a tiny bubble in an intravenous drip run up the hose into my arm with serious trepidation thinking about the size of the average blood vessel so this deco stuff needs taking seriously.

After Haldane's work, nearly a century ago, many other people have proposed changes to his compartment model and also other models but one of the most reputable is probably a Swiss gentleman, Professor Albert A Bühlmann, Dr. med. who worked for thirty years at Zürich University.

Over a period of many years the team at Geneva studied the biology and physics of diving and improved the Haldane model. They, and others, made several significant adjustments:

Firstly The simple rule for bubble formation at 'double' the anticipated ppInertGas for that depth is too simplistic. Haldane used more complex formulations on his later models but Bühlmann produced a simple formula published in his book ***Tauchmedizin***. (Yes it is in German. I did say he was Swiss.)

minimum safe pressure = (ppInert Gas - a_i) * b_i

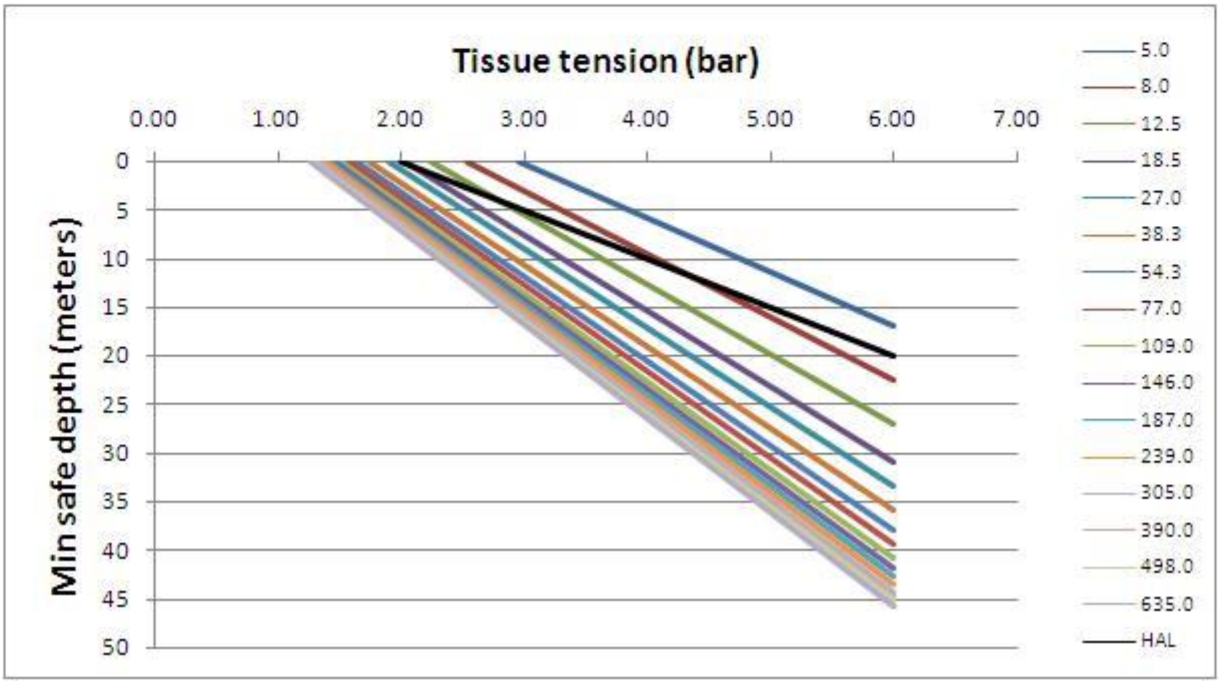
where there are seperate **a** and **b** values for each compartment.

Here are the numbers for Nitrogen:

time (mins)	5.0	8.0	12.5	18.5	27.0	38.3	54.3	77.0	109.0	146.0	187.0	239.0	305.0	390.0	498.0	635.0
a value	1.1696	1.0000	0.8618	0.7562	0.6667	0.5600	0.4947	0.4500	0.4187	0.3798	0.3497	0.3223	0.2850	0.2737	0.2523	0.232
b value	0.5578	0.6514	0.7222	0.7825	0.8126	0.8434	0.8693	0.8910	0.9092	0.9222	0.9319	0.9403	0.9477	0.9544	0.9602	0.965

Now what does this do to us? Well firstly remember that the compartments are mythical creatures. You can't look on an X-ray and see the 27 minute compartment nestled behind your spleen. You can't actually say that a certain organ of your body is in an X minute compartment as the actual interactions are more complex than that. Blood tends to the fast end and bone to the slow but the whole point about compartment is that when you model them the total effect is a good approximation of what is going on. Bühlmann introduces more compartments so he can both run to higher periods and also get more overlap so a tissue that if you tested it in isolation and got a 15 minute half-time would be adequately covered by the values derived for the 12.5 and the 18.5 compartments.

Let us calculate some safe depths (based on the pressures) for different tissue loadings:



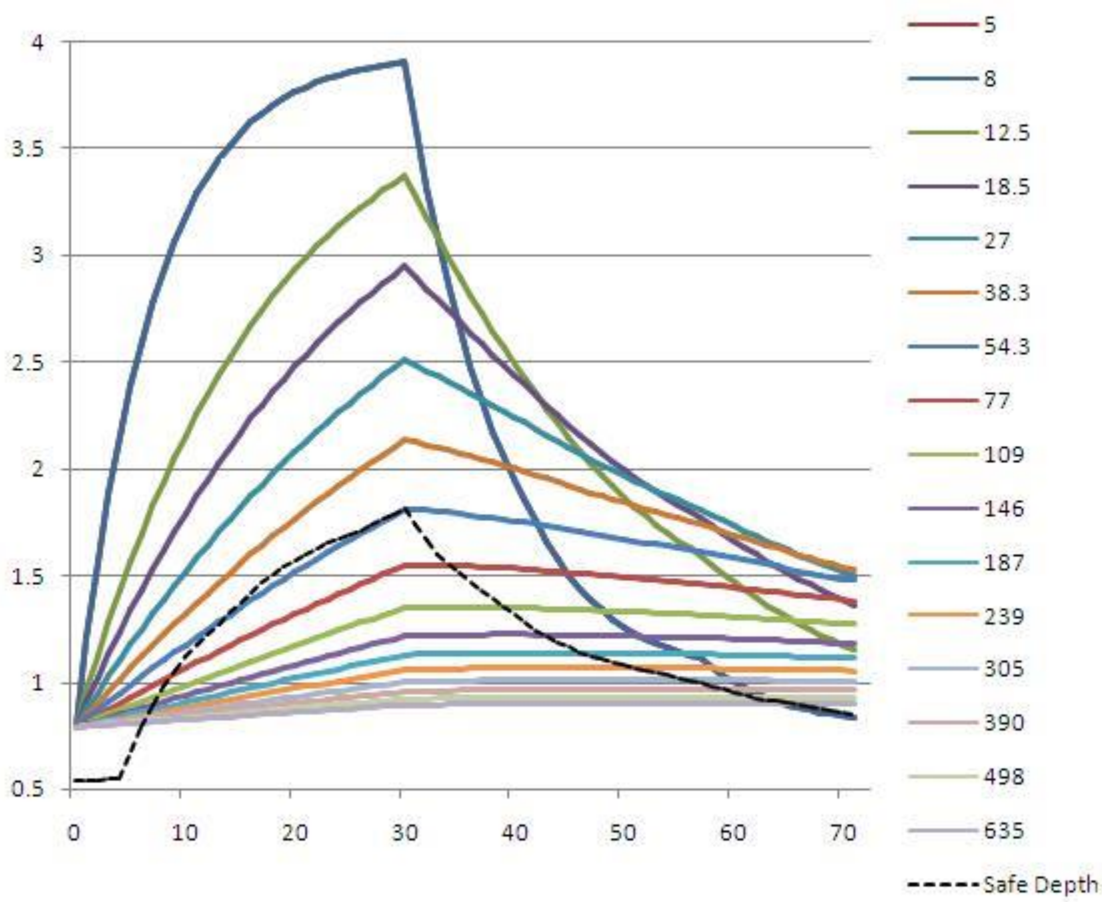
Now what is this graph? Along the top we have the inert gas tension in the compartment from 1 to 6 bar and the vertical scale is the safe depth for that tissue in meters. Remember we take each inert gas individually but diving Air to 40 meters gives you 5*0.79 = 3.95 bar of Nitrogen to cope with.

The black line represents the original Haldane 'double' law so at one end you could surface with 2 bar of inert gas (say diving air 19m forever ie: 69% Nitrogen at 2.9bar = 2bar) and at 6bar you are to stop at 20meters (3bar).

The other lines represent the Bühlmann limits for the compartments starting with 5 minute compartment in blue at the top right through to the 635 minute compartment in grey at the bottom.

Now at first sight the slowest compartment keeps you deepest so why worry about the others? Well remember the graphs for the compartments in part 1. For a reasonable duration dive although the shorter time compartments rushed up to their saturation values the slower ones never made it. We have to model all the compartments for inert gas in and out and then when it comes to stops we choose the compartment that keeps us deepest to set our first stop and wait there until all the compartments permit us to move to the stop depth above.

OK let's get a goat and go diving.
Let's do 40 meters for 30 minutes again because we already know what the compartments look like.
Remember we aren't changing the rules for gassing on and gassing off, just changing how we calculate the 'safe' limits.



Right. Similar graph but, naturally, more compartments.

Again the five minute compartment rushes up to nearly get to the 3.95 bar target while the new 635 minute compartment barely moves. The spread sheet that is drawing my graph here is also using the Bühlmann **a** and **b** constants to calculate a minimum safe depth for each compartment and then selects the maximum (deepest) value. This is plotted in bar as the broken black line. You can see the bumps in it as the different compartments take over as who is deepest. Don't forget this is bar absolute while the others are just Nitrogen loading in the tissues. At 30 minutes this stands at 8.12 meters from the 12.5 minute compartment so, rounding to sensible units, we need a 9 meter stop.

After four minutes at 1.9 bar absolute pressure the minimum safe depth has dropped to 5.53 meters so we can go for a 6 meter stop at 35 minutes run time. This time the controlling compartment is the 18.5 minute one but only by 15 centimetres.

Now in the sea I would stop at 6 meters as otherwise I am in the swell and I tend towards seasickness but a goat in a chamber doesn't have these problems so we can go to a 3 meter stop at 41 minutes run time when 18.5 minute compartment allows us.

Finally, at 57 minutes run time, the 38.3 minute compartment is the last to pass 1 bar so zero depth and we are allowed to surface our goat.

OK so what can we say is different from the early Haldane model we started with?

Well actually a lot of what Bühlmann is doing here is based on Haldane's later work so Dr. H deserves more credit than I'm handing out. The first thing you see is a longer profile overall and less obviously a much longer profile for longer, deeper dives as the use of compartments of over 10 hours become the dominant factors. The derivation of different 'safe' limit constants for different compartments is non-intuitive but the compression chambers in use by Zürich university produced good numbers and millions of dives on Bühlmann tables and Bühlmann based dive computers seem to bear it out.

Probably many people would disagree but I tend to see most later models as tweaks on Bühlmann and the parallel work by Robert D. Workman for the US Navy. If you come up with a wonderful theory that gets people out of the water faster they get bent. The advances are in leaving them longer.

OK? You want to leave them longer?

Well the decompression theory is OK, it's just the wretched divers don't come in a standard model so we can work things out. They come in all sorts of shapes and sizes and have a nasty habit of having slightly different chemical makeups and certainly don't all stay at the same temperature.

All this adds up to messing our nice clean mathematical model about. We can get it right for most of them most of the time but they don't seem to like that. What do we do to keep them happy?

This is called adding conservatism. It is a way of going beyond the model to make things safer in case we don't fit the model that particular day.
A popular system was to plan the dive for a bit deeper than it really was or plan for a gas mixture with a bit more nitrogen in it than it really had but I believe there are better ways.

Dr. Richard Pyle is an Ichthyologist and I'd rather let him explain his deep stops thinking himself but in brief he studies fish and has probably done more deep diving than most UK clubs have in total for all their members. He picked up the fact that even diving reputable tables it was the dives where his care for his specimens caused him to make extra, deeper stops that left him feeling a lot better aprés dive so he derived a protocol to do them normally.

These are really deep stops, stops near the bottom of the ascent and not an obvious intuitive step when the object of decompression seems to be to get out from the pressure so you are off-gassing as soon as possible.

What is happening here? Well look at my graphs. On the ascent the lines on the graph are steep so the 'safe depth' value is changing fast. This is the point where you want to be wary and stay well away from the bent/not bent line so a slow ascent and deep stops helps the gas get out without actually costing you much in your total dive time. OK the longer compartments will still be on gassing but let's get up to the shallow stops without generating any bubbles. The older tables zoomed up and then compensated with longer stops at shallow and are often termed 'bend and mend'.

When we finally arrive at the shallow stops the graphs are no longer steep but nice and flat. As our goat started his ascent the 'safe depth' was coming down towards him at nearly 30cms a minute but when he is clearing his 3 meter stop the rate of change is a mere 3cms a minute. If you want to do extra time to be safe you need to do it at the deep end of the scale where it will bite you and it is less imperative shallow.

We now put the 'feeling a bit rough' sensation that comes from diving close to the bent/not bent limits down as 'sub-clinical' bent and with deep stops and padding the shallow ones and breathing richer nitroxs we seem to avoid it.

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by Nigel Hewitt