Bubbleology 101

A New Diver's Guide to Understanding and Avoiding DCS

By John Francis

You know that bubbles are trouble, and that they come from nitrogen. But if you're like most divers, decompression theory—the nuts and bolts of bubble making—is an intimidating mystery. Just what does "supersaturation" mean? What the heck is a "tissue compartment" anyway?

Tired of scuba bullies kicking verbal sand in your face? For that matter, are you tired of your dive computer—that other bully—giving you preemptive orders for no apparent reason?

Or maybe you'd just feel better knowing what's really going on inside your body. As it happens, decompression theory is not as confusing as you might think. In fact, you just need to have ridden a subway once in your life. Or seen a subway in a movie. Or heard it described. It's that easy—trust me.

Let's start with the basics:

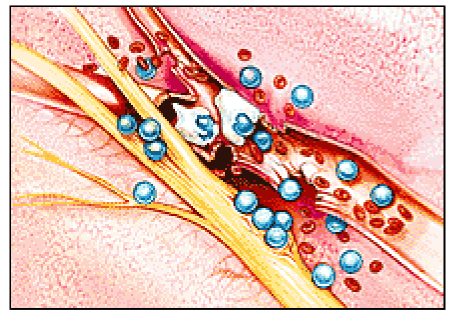

Illustration by Suzanne E. M. Edmonds

How does decompression sickness cause pain, paralysis and even death? As nitrogen bubbles clump together or expand in response to decreasing pressure, they can press on nerves and tear tiny blood vessels. Inside blood vessels, bubbles can slow down the flow of blood, which hurts tissues dependent on that blood supply. Another theory holds that white blood cells attack the bubble as a foreign invader, making it an even bigger obstruction to blood flow.

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How Nitrogen Dissolves in Your Tissues

You know already that nitrogen enters your body with the air you breathe and passes through your lungs into your bloodstream, where it is carried all over your body and deposited in your tissues.

Gas molecules are not attracted to one another. In fact, they try to push each other apart—the pushing is called gas pressure. So, in escaping one another, molecules of nitrogen disperse among your blood cells, pass through the walls of your blood vessels and, in a sense, head for the lonely, empty spaces inside your various tissues. When the nitrogen molecules are dispersed and mixed with the other molecules of your body like this, the nitrogen is called dissolved and is harmless. Only when the nitrogen molecules (and other gas molecules) are forced to associate do they form those troublesome groupings called bubbles.

Imagine a grouping of securities traders entering a subway car. Together, they are competitive and obnoxious—yelling "Debenture!" and "Yo Mama!" at one another. But if there are empty seats, they will quickly lunge for them ("Lookout, lady!") and disappear into their laptops.

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What Is Saturation?

When nitrogen or other gas molecules have filled all the available spaces in your tissues, the tissues are called saturated. (The subway car is filled when all the seats are occupied and all the standing room is taken.)

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Why Saturation Depends on Depth and Dive Time

More depth means the nitrogen (and other breathing gas) comes into your body under more pressure. More pressure means, essentially, more molecules of nitrogen crowding into the available space. They try, however, to go to where there is less crowding—less pressure. They will continue pushing into your tissues until the mutual antagonism between them—the gas pressure—in the tissues equals the pressure of the breathing gas coming in. At that point, crowding is the same everywhere, nitrogen molecules have no incentive to move and you stop absorbing more of them.

How many people can crowd into a subway car? Depends on how many want to get on—and on how hard they push.

But this doesn't happen instantly. It takes time as well as pressure to reach saturation. How many people can crowd into a subway car also depends on how long the doors stay open.

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What Happens When You Go Deeper

After enough time at, say, 60 feet, your tissues will become saturated for that depth and no more gas will enter them. But if you then descend to 90 feet, the increased pressure will drive in more gas until a new level of saturation is reached.

You thought the subway car was full until you reached a station with a big crowd wanting to board. The seat next to the smelly psychotic suddenly looks attractive. Strap-hangers double up. Somehow, there's always room for a few more passengers.

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What Happens When You Ascend

If you return from 90 feet to 60 feet, the pressure of incoming breathing gas is less than the pressure in your tissues, which are now called "supersaturated" (a six-bit word for "overcrowded" or "overpressured"). Nitrogen now wants to leave those tissues, via your bloodstream and lungs, and join the lower-pressure (less crowded) gas you exhale. Of course, leaving causes the pressure in your tissues to drop. Nitrogen will continue to leave your tissues until the pressures again equalize and a new level of saturation is reached.

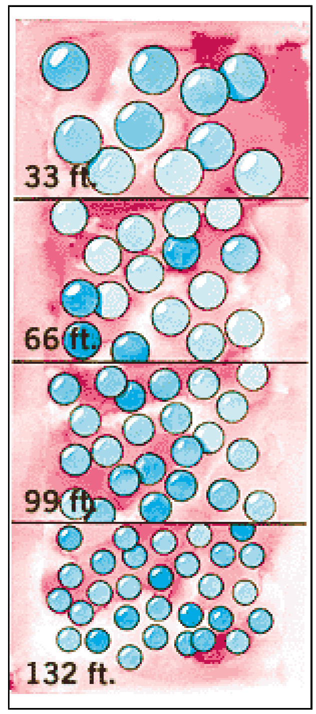

Illustration by Suzanne E. M. Edmonds

Tissue saturation varies with depth, and the deeper you go, the more nitrogen you absorb. Tissues that are saturated with gas at 66 feet can actually absorb even more nitrogen at 99 feet. If saturated at 99 feet, they can absorb more at 132 feet,

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Tissues Are Not Created Equal

Clear so far? It would be if all the parts of your body absorbed and released gas at the same rate. But they don't. Some take longer to reach saturation than others.

It has been known (or, at least, theorized) for a long time that thousands of different organs and parts of organs in your body reach their fill of nitrogen at thousands of different rates—ranging between instantaneous and glacial. Imagine that some subway cars have more doors and bigger doors than others—that, in fact, each car is different.

and so on.

The theory's not proven, but scientists like it because it explains why longer bottom times usually cause more bubbles and bubbles in different places: more areas of tissue have had time to reach their limits of dissolved gas.

It also explains why some tissues can be overfilled and release gas while others are still absorbing it. For example, you go to the bottom and stay there until a "fast" tissue completely saturates. A neighboring "slow" tissue, however, is still just beginning to fill. If you now ascend only a short distance, the reduced pressure lets gas escape from the saturated tissue, while the mostly empty tissue can go on filling.

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Tissues May Affect One Another

More theory: It seems reasonable to suppose that if a full tissue is next to a nearly empty tissue, nitrogen might pass directly from the full to the empty tissue. If the subway cars have connecting doors, some of the people in the full car will pass through to the empty one.

At any rate, that would explain why slow tissues can continue to take on nitrogen even during your surface interval: They are absorbing it directly from faster, already-filled tissues nearby.

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Why Bubbles Form

Remember that when you ascend after reaching saturation, the pressure keeping nitrogen dissolved in your tissues drops and the nitrogen wants to get out of your body. Basically, if the pressure drops faster than your body can process the exiting nitrogen, it clumps into bubbles.

If too many passengers want to leave the subway car at one stop, they crowd together and can't fit through the doorway in time. When enough of them miss their stops, they'll become a mob and wedge the doors or smash the windows to get out.

Why Bubbles Don't Form When They Should

Bubbles don't form easily. For one thing, tissues seem to be able to tolerate a certain amount of overfilling (supersaturation) before bubbles form. That's called the tissue's M value (M for maximum). And once again, tissues differ wildly from one another. In general, fast tissues seem to have higher M values—they tolerate more overfilling of dissolved nitrogen before bubbles form than do slow tissues.

That's why you can have a bottom time of 30 minutes at 90 feet by the U.S. Navy tables, yet ascend to the surface without making a deco stop. Your fastest tissues became full (saturated) in 30 minutes at 90 feet, but thanks to the tissue's tolerance for supersaturation, a controlled ascent rate gives enough decompression. But longer bottom times will fill less forgiving tissues, making deco stops necessary.

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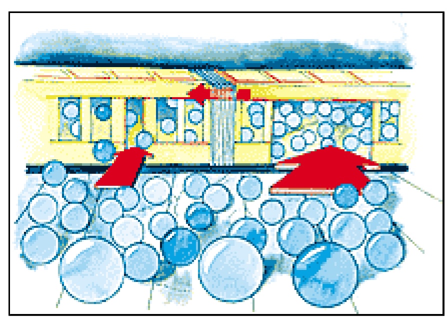

Illustration by Suzanne E. M. Edmonds

Different tissues absorb different amounts of nitrogen and at different rates. Think of these so-called "tissue groups" as subway cars of different sizes, capacity and with different sized doors. A slow tissue that absorbs and

What About "Silent Bubbles"?

releases gas slowly (a subway car with a small door) takes on nitrogen slower than a fast tissue (a subway car with a wide door); it also releases nitrogen more slowly.

It seems that gas molecules are more likely to clump around a nucleus of other gas molecules—a microbubble or a "silent" bubble. Apparently, nitrogen can remain dissolved despite being supersaturated, until some of these microbubbles arrive on the scene. The nitrogen molecules then join the microbubbles, which grow into real, DCS-sized bubbles.

Think of it this way: Those disgruntled, trapped subway passengers probably won't do anything until the alpha male among the securities traders says, "We gotta break a window." Then they become a mob.

We say "apparently" because this is another theory, first proposed by A. R. Behnke in 1942. He called them "silent" bubbles because they seemed to pass through your system without causing DCS symptoms.

The microbubbles themselves seem to be real enough. Modern Doppler ultrasound sensing allows us to "see" (actually, hear) them in veins, where blood is returning from tissues to the lungs. And, unfortunately, they are very common. They may be present on most dives, but as long as they are on the venous side of your circulation, they will probably be filtered out by your lungs and do no harm.

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Why Do Bubbles Cause Pain, Paralysis and Even Death?

Again, no one knows for sure, but here are the theories.

- Bubbles may do mechanical damage. Bubbles tend to grow by attracting nitrogen from solution and by clumping together. They can press on nerves and tear tiny blood vessels. Inside blood vessels, bubbles slow down the flow of blood, which hurts the tissues dependent on that blood supply. (A guy crowds into the subway car with a self-inflatable life raft, which, by some accident ...)
- Bubbles may do chemical damage. The nitrogen in the bubble is chemically inert, but the bubble itself may be seen by your body as a foreign invader. If that happens, white blood cells attack it and clotting cells stick to it, making it an even bigger obstruction to blood flow. Meanwhile, alarm bells activate all sorts of other chemicals in the immune system, all of which have side effects. (The crowd jostles the fire alarm, the subway train screeches to a halt, firefighters break in with axes ...)

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So, What Do We Know?

That bubbles are bad. Otherwise, not much for sure. Most of what is "known" about decompression is really theory. The actual mechanisms by which bubbles form, move about and cause harm are unproven.

Some animal experiments have been done, but animals are not human divers. Human studies are limited because of expense and the obvious danger to the subjects. Most of them have been done on military divers, who probably don't represent the general diving population in fitness, skill and dive profile.

And divers differ considerably in their innate susceptibility to DCS. Some don't get bent when they "should," others do get bent when they "shouldn't."

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The Bottom Line: Practical Advice

- Ascend slowly (especially during the last 60 feet) and don't miss stops. A slow, steady ascent is like a slow, steady discharge of passengers from the subway car—no anger, everyone stays calm.
- For the same reason, don't cut short surface intervals.
- Don't dive tables and computers to the limit. Because they give you specific numbers, they create a false sense of exactitude. It's not really a line between green and yellow, it's a zone.
- Factor in what the tables and computers don't know: your age, fitness, hydration level and how warm and rested you are.

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DCS Basics: Silent Bubbles And Sawtooth Profiles

A sawtooth profile (with several large ascents and descents) is more likely to result in DCS than a single descent to the same maximum depth for the same total bottom time followed by a single ascent. Why?

One theory blames "silent" bubbles, also called microbubbles and seed bubbles. On the first ascent, nitrogen comes out of circulation as microbubbles and travels through veins to the lungs. They are trapped in the alveoli and begin to be breathed out. But if you descend again, pressure redissolves the nitrogen you haven't yet breathed out. It escapes the "bubble trap" of your lungs and resumes circulating with your blood, but now on the arterial side where it moves out to your muscles, joints and spinal cord—the sites where DCS occurs.

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DCS Basics: How Compartments Might Connect

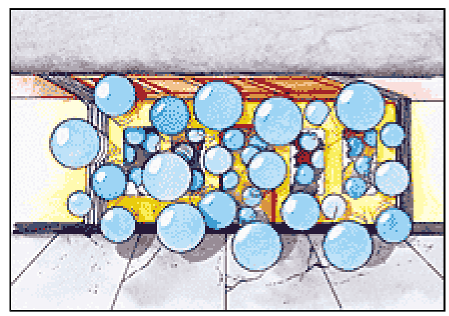

Illustration by Suzanne E. M. Edmonds

When pressure on a saturated tissue drops too rapidly, nitrogen bubbles are like angry subway passengers trapped inside the car—eager to get out quickly. As bubbles clump together, they become like an angry mob that's willing to wedge the doors and break the windows to escape.

Researchers have proposed several models to explain how gas might move between those mythical compartments, and between the compartments and your bloodstream. Each results in a unique algorithm or set of tables.

- **Haldane.** A "parallel" model: Each compartment fills and empties independently and directly from the bloodstream (each subway car is separate from the others). U.S. Navy tables are based on this model.
- **Series.** There's the "series" model where all compartments are imagined to be connected in a row and gas enters only at one end (a subway train with doors in only one car, but the cars are connected with doors of various sizes). Canada's DCIEM tables are based on this model.
- **EL.** The initials stand for Exponential—Linear which assumes parallel tissues that ongas at an exponential (declining) rate, but offgas at a linear (constant) and fairly slow rate. And, though it may be a coincidence, a full subway car doesn't discharge as quickly as it fills because exiting passengers have to disentangle from the others and fight through the crowd. Entering passengers just have to push inside the doorway.
- **Slab.** This model assumes just one tissue that's exposed to nitrogen on only one side (like one long subway car with a door at only one end). The British Sub-Aqua Club tables are based on this model.

Reality is probably a mix, like a train where most, but not all cars are connected and most, but not all have their own doors of various sizes and where rates of entering and leaving cars depend on lots of factors. But you might need a supercomputer to calculate tables on that model.

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DCS Basics: What About Tissue Compartments?

They're a more dignified name for those hypothetical subway cars. They don't exist either, but they help explain a theory.

John Haldane invented the idea of tissue compartments, along with the first decompression tables, in 1908. Haldane said, in effect, "We don't know anything. So let's imagine that there are five kinds of tissue. Let's give each one a different time to become filled, crank 'em through our theory, make tables, and see if divers get bent." It was messy, but that's science, folks.

The new tables worked, so the idea of tissue compartments was here to stay. It's only a metaphor, and the number of compartments is arbitrary. But it's no more illogical than a teacher dividing 100 students into five groups (A, B, C, D, F), two groups (Pass, Fail) or 10 groups (90-100, 80-89, 70-79, etc.). It's a simplification you can work with, which gives results you can use in planning.

The fill rates Haldane assigned to his compartments were just as arbitrary. He gave compartments "half times" of 5, 10, 20, 40 and 75 minutes on the theory that the absorption rate of a compartment slows as it fills at an exponential rate.

Here comes just a little math. An "exponential" rate means the five-minute compartment fills halfway in five minutes. The half that's still empty fills halfway in the second five minutes, for a total of 3/4 full after 10 minutes. Half of the remaining quarter fills in the third five minutes, for a total of 7/8 full after 15 minutes. And so on, ad infinitum, though six half-times is considered close enough to completely full—98.44 percent full, to be exact.

Meanwhile, the 10-minute compartment is taking 10 minutes to fill halfway, 20 minutes to reach 3/4 full, and so on. When the five-minute compartment is fully saturated in 30 minutes, the 40-minute compartment is less than half full and the 75-minute compartment is just getting started.

Haldane's idea of half-times, and most of the specific half-times he suggested, are still with us. Recent modelers (and computers to do the math) have given us more compartments with odd-looking half-times, like the Bühlmann ZHL-12 algorithm with half-times of 4, 7.94, 12.2, 18.5, 26.5 and so on up to 635 minutes.

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True or False? Test Your DCS Knowledge

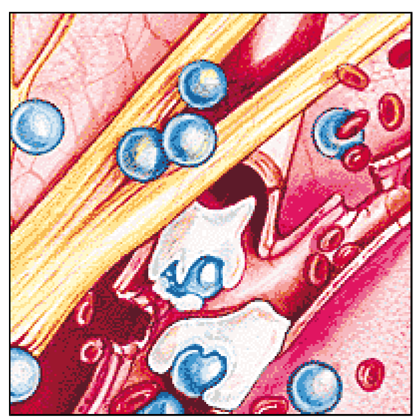

Illustration by Suzanne E. M. Edmonds

T or F: If you're ascending, you're offgassing.

False. On the deeper parts of most ascents, you will be offgassing from some tissues but still absorbing gas in other tissues. Some tissues absorb and release gas quickly (blood, nerves) and others absorb and release slowly (joints, bone). The slow tissues can still be absorbing gas during most of your ascent.

T or F: A slower ascent rate always means less risk of DCS.

False. Many divers are told, "Ascend at 30 feet per minute. Period." But if you've been deep for a short time, you will still be taking on more nitrogen than you lose for the first part of your ascent. Therefore, you might be better off ascending faster for the first part of the ascent, say at 60 feet per minute to 60 feet, then slowing down to 30 feet per minute. It all depends on how deep you've gone and how long you've been there.

This is one reason why some computers now prescribe variable ascent rates. It's also why most decompression stops are shallow, not deep.

T or F: When you return to the surface, you will be offgassing from all tissues.

False. "Slow" tissues can be still absorbing gas directly from nearby "fast" tissues that have become more filled.

T or F: Decompression stops are not part of recreational diving.

False. In fact, it is recommended that divers make two decompression stops on every recreational dive. One is the so-called "safety stop," a minimum of three to five minutes at about 15 feet. Some of the more candid instructors are now calling it a "precautionary decompression stop."

Consider this: When the traditional decompression tables, which do not prescribe a "safety stop" as such, call for one decompression stop it's at 10 feet (U.S. Navy, DCIEM, French Navy) or 20 feet (British Sub-Aqua Club), for several minutes or more, depending on bottom times. Hmmm. Wonder where the idea for the "safety stop"came from?

Some dive computers even calculate the duration of a variable safety stop like a decompression stop, extending it for "violations" like a too-rapid ascent.

And a mandatory slow ascent rate is, in effect, a "rolling" decompression stop, both in its intended purpose (to permit decompression) and in the sense that it prohibits a free ascent to the surface without increased risk of DCS. Recreational diving is often defined as that which allows an immediate ascent to the surface at any time without risk, but in fact there is no such dive.

T, F or Depends: Diving by computer is safer than diving by tables.

Depends. Which computer, and which table? They differ considerably. Even assuming the same algorithm for both, tables offer a safety factor when you round up the depths and times. Computers give you more bottom time—and more risk. They encourage you to dive right to the limit of the algorithm, but the limit is not a line, it's a gray zone.

What can be said for dive computers is that they don't make math mistakes. You're less likely to miss a decompression stop through miscalculation.

T or F: If a table or computer is based on more tissue compartments, it is safer.

False. A lot more important than the number of compartments is what the algorithm does with them—how each is weighted, for example. As an example, the British Sub-Aqua Club tables are based on the "slab" model which assumes just one compartment, yet they are not obviously less safe than others.

Then, too, many of the slow-tissue compartments are not very relevant for recreational diving. For example, a 635-minute compartment will saturate only after two-and-a-half days of bottom time. (Slower compartments do become more important after many days of deep, repetitive diving.)

T or F: Bubbles occur in your body only when the outside pressure on it decreases.

False. In fact, bubbles happen naturally and frequently, regardless of ambient pressure changes. If you can "crack" your knuckles, you are actually popping bubbles in your joints.

Bubbles are most likely wherever two solid surfaces separated by liquid (like blood and other bodily fluids) are moved apart or rubbed together. Turbulence results in the liquid, which causes local spots of low pressure. That's where bubbles form. The process is called tribonucleation. And that's why those natural bubbles happen so often in joints.

T or F: You offgas at the same rate as you ongas.

False. Haldane thought so, but recent research has shown that offgassing is much slower. One reason is that bubbles tend to impede offgassing. They slow down blood flow, and they "capture" nitrogen, which must redissolve out of the bubble before it can pass through the lungs.

T or F: Your dive computer measures your nitrogen loading.

False. That should be an easy one, though it is surprising how many divers think their computer is actually keeping track of their personal body. In fact, the computer is only reporting what a hypothetical human—whose age, hydration and fitness level are different from yours—might be experiencing. It's making a "guesstimate."

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