Ins and Outs of Mixed Gas Counterdiffusion

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Isobaric counterdiffusion (ICD) is a hefty word describing a real gas transport mechanism in the blood and tissues of divers using helium and nitrogen. It's not just some theoretical concoction, and it has important impacts for tech diving. It was observed in the laboratory by Kunkle and Strauss in bubble experiments, is a basic physical law, was first studied by Lambertsen and Idicula in divers, has been extensively reported in medical and physiology journals, and is accepted by the deco science community worldwide.

But let's start at the beginning. What is isobaric counterdiffusion (ICD)? Isobaric means equal ambient pressure. Counterdiffusion means two (or more) gases diffusing in opposite directions. For divers, the two gases are nitrogen and helium. And, that is where concern focuses–inert gases, and not metabolic gases like oxygen, carbon dioxide, water vapor, or trace gases in the atmosphere. Thus, ICD in diving underscores two inert gases moving in opposite directions under equal ambient pressure in tissues and blood. What's important are relative speeds for counterdiffusion. Lighter gases diffuse faster than heavier gases. In the case of helium and nitrogen, blood with helium and surrounding nitrogen-loaded tissue will result in greater total gas loading because helium will diffuse into tissue and blood faster than nitrogen diffuses out, resulting in higher total inert gas tensions. Blood with nitrogen and surrounding helium-loaded tissues will produce the opposite effect because helium will outgas faster than nitrogen ingasses, and total inert gas tensions will be lower.

Perhaps a better term would be isobaric countertransport, because diffusion is only one of a number of different movement mechanisms. Historically, both terms have been used. Countertransport processes are a concern in mixed gas diving because differing gas solubilities and diffusion coefficients provide a means for multiple inert gases to move in opposite directions under driving gradients. While ambient pressure remains constant, such counterdiffusion currents can temporarily induce high tissue gas supersaturation levels, with greater susceptibility to bubble formation and DCS.

In general, problems can be avoided when diving by employing light-to-heavy (breathing) gas mixture switches, and by using more slowly diffusing gases than the breathing mixture inside enclosure suits (drysuits). Such procedure promotes isobaric desaturation, as termed in the lore. The opposite, switching from heavy to light gas mixtures and using more rapidly diffusing gases than the breathing mixture inside exposure suits, promotes isobaric saturation and enhanced susceptibility to bubble formation. More simply, the former procedure reduces gas loading, while the latter increases gas loading. The effects of gas switching can be dramatic, as is well known. For instance, a dive to 130 fsw (40 msw) for 120 minutes on 80/20 heliox with a switch to 80/20 nitrox at 60 fsw (18 msw) requires 45 minutes of decompression time, while 210 minutes are required without the switch (Keller and Buhlmann in famous mixed gas tests in 1965). Yet, skin lesions and vestibular dysfunctionality have developed in divers breathing nitrogen while immersed in helium (test chambers and exposure suits). And nitrogen-to-helium breathing mixture switches are seldom recommended for diving, particularly diving for extended periods of time.

In the case of exposure suits filled with light gases while breathing heavier gases, the skin lesions resulting are a surface effect, and the symptomology is termed "subcutaneous ICD." Bubbles resulting from heavy-to-light breathing gas switches is called "deep-tissue ICD," obviously not a surface skin phenomenon. The bottom line (if you don't want to read further) is simple. Don't fill your exposure suits with a lighter gas than you are breathing and avoid heavy-to-light gas switches on a deco line. In both cases, bubble risk tracks with exposure time.

But what, you say, about detox switches during decompression from deco nitrox to trimix or heliox back gas? We all know it's been done since time immemorial, and it is still done. For most of tech diving in the 200 fsw to 300 fsw (60 msw-90 msw) range, for periods of time not exceeding 60 minutes or so, short detox switches of nitrox to heliox or trimix are not high risk, so long as cumulative detox times stay below 30 minutes roughly.

But, the statements above are still true–switching from nitrox back to trimix

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Ins and Outs of ICD (cont'd.)

incurs risk versus other alternatives that can be used. And for very deep dives in the 500 fsw (150 msw) range and beyond (like the dives Mark Ellyat clocked), isobaric switches of nitrox back to trimix are not a good idea. In fact, because of the depths and pressures, increased ingassing gradients for one or other gases lead to isobaric slam, as we have coined the word. Slam is mitigated by making isobaric gradients as small as possible within the deco plan. Slam also shows up on deep dives as inner ear vertigo with fluid shifts (bad!). Or simply, ICD problems increase with depth as ingassing gradients for one or the other gases increase. Avoid this by careful selection of switch mixes, minimization of nitrogen, and washout with oxygen in the shallow zone. Or, not trying to be a smart alec, use a rebreather instead of open circuit scuba with stage bottles.

Another important consideration is nitrogen level. Nitrogen is not your friend for diving, with risk of DCS increasing with nitrogen fraction across multifaceted diving. We come back to all of this in discussing Ellyat's record open circuit dive. It turns out that most of this is an efficient deco strategy too within dual phase bubble models.

Details of ICD obviously cannot be recounted here in gory detail, but the rudiments, time scales, and mechanistics can be found in *Technical Diving In Depth*, *Reduced Gradient Bubble Model In Depth,* and *Basic Decompression Theory And Application*. But, don't go out and buy a copy; just borrow it from one of your diving buddies if you are interested. Also, released NAUI RGBM Tec Tables embody all discussed herein, but with a more simplistic approach to training. Minimization of intermediate and deco stage bottles for open circuit training is a NAUI RGBM Tec Table mainline.

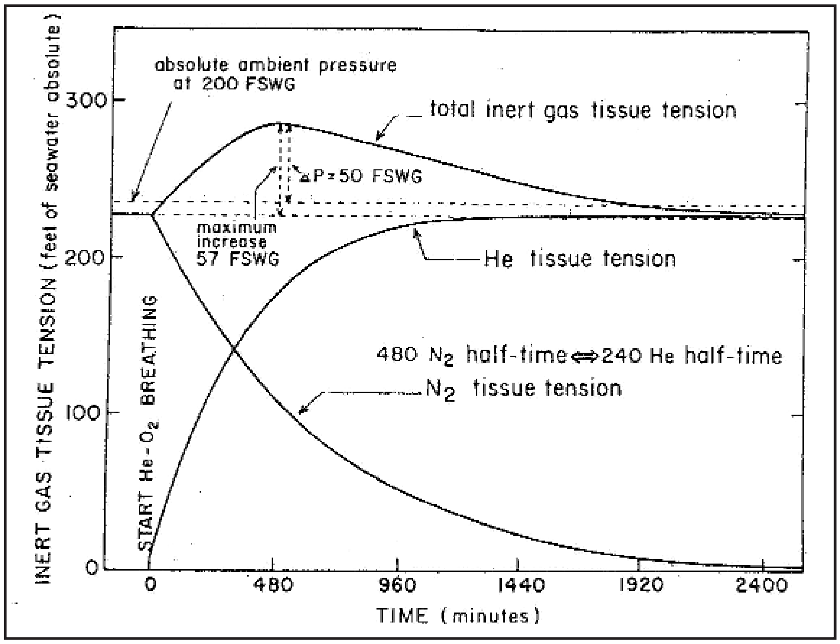

Figure 1

A closer look at the isobaric countertransport phenomenon is interesting. Particularly interesting is the isobaric saturation scenario depicted. Figure 1 tracks gas supersaturation following nitrogen-to-helium switching due to the isobaric counterdiffusion of both gases. For helium-to-nitrogen switching (hopeful case for technical and commercial divers), a state of isobaric desaturation would ensue due to isobaric counterdiffusion. Depicted in Figure 1 is a comparative representation of the time courses of changes in helium, nitrogen, and sum of the two, tissue tensions for 480-minute nitrogen tissue compartments and 240-minute helium tissue compartments. The depth is 200 fsw (61 msw) with abrupt change from normoxic nitrox to normoxic heliox. Note the buildup in time of total inert gas tension, with a maxima after some 400 minutes. With faster tissue compartments, this maxima builds more quickly–on time scales of the slowest tissues involved. Actually the curves remain the same as shown, but axis time scales are shortened by the ratio of the fast tissue halftime, τ, divided by 240 for the helium compartment, $\tau/240$, and similarly for the nitrox compartment, tissue halftime, τ, divided by 480, that is, $\tau/480$. This is quite obviously not a good scenario for the mixed gas diver. If the gases were flip-flopped, a minima would develop, identical in shape to an inverted Figure 1. For faster tissue compartments, usually the case in deco (non-saturation) diving, effects seen in Figure 1 occur much more rapidly, like in the 10 minutes to 50 minutes time frame.

Mark Ellyat (UK) has made a number of dives beyond the 500 fsw (152 msw) mark. A recent dive to 1040 fsw (317 msw) on open circuit trimix is a record and a spectacular accomplishment. Hats off, Mark. Here's a straw man of his switch schedule:

1040 fsw (317 msw)/1 minute on 5/76 trimix

295 fsw (90 msw)/4 minutes on 14/56 trimix

138 fsw (42 msw)/10 minutes on 27/43 trimix

69 fsw (21 msw)/19 minutes on 50/23 trimix

Dive Profile	
surface breathed nitrogen = 0.79 helium = 0.00 down switches = 4	trimix = 0.76 helium 0.19 nitrogen up switches = 5
switch 1 depth = 0.0 fsw helium = 0.00 nitrogen = 0.79	switch 5 depth = 295.0 fsw helium = 0.56 nitrogen = 0.30
speed = 60.0 fsw/min way time = 0.0 min	speed = -30.0 fsw/min way time = 0.0 min
switch 2 depth = 10.0 fsw helium = 0.56 nitrogen = 0.30	switch 6 depth = 138.0 fsw helium = 0.43 nitrogen = 0.30
speed = 120.0 fsw/min way time = 0.0 min	speed = -30.0 fsw/min way time = 0.0 min
switch 3 depth = 400.0 fsw helium = 0.76 nitrogen = 0.19	switch 7 depth = 69.0 fsw helium = 0.23 nitrogen = 0.27
speed = 90.0 fsw/min way time = 0.0 min	speed = -30.0 fsw/min way time = 0.0 min
switch 4 depth = 1049.0 fsw helium = 0.76 nitrogen = 0.19	switch 8 depth = 30.0 fsw helium = 0.20 nitrogen = 0.00
speed = -30.0 fsw/min way time = 1.0 min	speed = -30.0 fsw/min way time = 0.0 min
	switch 9 depth = 20.0 fsw helium = 0.00 nitrogen = 0.00
	speed = -30.0 fsw/min way time = 0.0 min

Decompression Schedule	
bottom depth = 1049.0 fsw	deco plus surfacing time = 400.5 min
pp02 = 1.6 atm	cum CNS% = 1.86 cum OTU = 409.7 min
OTU/CNS = 2.0 min/0.02 %	cum gas consumption = 2071. ft^3
bottom time = 11.6 min	dive time = 412.1 min

Table 1

30 fsw (9 msw)/24 minutes on 80/20 heliox

20 fsw (6 msw)/25 minutes on pure O2

with a total run time in the 420 minutes range. Stops are made every 10 fsw or so beginning near 750 fsw. With rapid descent, a straw man RGBM schedule is shown in Table 1. As far as ICD (and HPNS because of the extreme depth), Ellyat's straw man schedule exhibits a number of interesting features.

Dives exceeding 400 fsw (122 msw) require high helium, low nitrogen. On the way up, oxygen is increased in roughly the same proportion as helium is decreased, while keeping nitrogen fairly constant and in the 15%-25% range (the lower the better for deco, but higher than 10% to address high pressure nervous syndrome [HPNS] concerns). Oxygen toxicity management falls in an oxygen partial pressure equal to 1.2 ata region. Pure oxygen is employed at 20 fsw (6 msw). Note, there are NO isobaric switches to nitrox anywhere. No EAN50 at 70 fsw (21 msw). At 30 fsw (9 msw), 80/20 heliox (no nitrogen) is the switch mix. Rather than EAN50 at 70 fsw (21 msw), heliox 50/50 would be a better choice. Also HPNS and rapid descents can be a problem on trimix below 600 fsw (183 msw), just like heliox below 400 fsw (122 msw). Though 10% nitrogen is popular for mitigating HPNS, it's not foolproof, and nitrogen thus is above 10%. Bottom line here is that ingassing gradients for nitrogen have been minimized by avoiding isobaric switches, and the transitions from richer-to-leaner helium mixes are also smoother. No slams.

Remind you of a rebreather in some ways? Yeh, guess it does.

Safe and happy tech diving.

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