Density, impaired ventilation and dynamic airway compression

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For our purposes there are 2 key factors that contribute to the development of dynamic airway compression and therefore impaired ventilation of the lungs during a dive: gas density and flow rate of gas through the airways. As both rise, dynamic airway compression becomes more likely and once it occurs, you won't be able to increase your ventilation any more. If you think about it, that means that as gas density rises the amount of work you can achieve falls (because work requires increased ventilation with higher gas flow through the airways in order to get rid of the CO_2 produced by the work).

The Wet Mules have learned to pay attention to both sides of this equation by minimizing gas density and trying very hard not to work in the deeper portions of their dives. This is a winning formula, which has enabled them to do the dives they do. But they are still coming close to the combinations of work and gas density that promote dynamic airway compression, and because they are very introspective and make videos of themselves, they notice it and we (the watchers) can notice the warning signs (the grunting or coughing at the end of expiration). So why do they not get into the same terminal spiral that Dave Shaw did? It will be because of the fact that because the gas is less dense, the dynamic airway compression is happening at higher flow rates (remember the relationship I described above) and they are still in a zone where stopping / resting / lowering activity can make a difference. Put another way, the gas density is still low enough that they can generate enough flow through the airways to ventilate off their resting CO_2 production and maybe a bit more, so resting works. David on the other hand was so deep with such dense gas that he may have been doomed from the moment he arrived there.... once his CO_2 started to rise and drove him to try to increase flow, he was unable to get it high enough even to eliminate his resting CO_2 production, so resting or doing little would not work. Hope you can see what I am getting at.

David was also wearing a back mounted counter-lung, and if you have a negative static lung load the risk is almost certainly increased.

So, in respect of Harry's question.... why are rebreather divers who use nitrox between 40 and 50m not getting into trouble with dynamic airway compression, especially when working hard. I think the answer is that they probably do. However, like Harry's dives, this is still at a gas density where resting can probably make a difference. So when divers notice themselves getting short of breath they slow down or rest which in most situations works. But they are probably not far from big problems if the gas got any denser or they tried to work any harder. I think "deep air diving" on a rebreather is not a smart move, and even between 40 and 50m divers using nitrox in a rebreather should be **very** work-shy. I'm sure there will be unexplained rebreather deaths in these intermediate depths where dynamic airway compression, respiratory limitation and CO_2 toxicity are major factors.

Finally, I have not even touched on the fact that you don't need dynamic airway compression and limitation of ventilation to get into significant CO_2 problems (independent of scrubber failure), because of disturbance of normal respiratory control. But this post is getting too long so that can be a topic for another day. It is covered in that presentation that the OP linked to.

Dynamic airway compression happens because the pressure inside non-rigid segments of the airway falls below the pressure inside the chest during an expiration. The airway will then collapse and flow will be limited. This even occurs when breathing air with healthy lungs at 1 ATA during a forced exhalation (the spirometry tests that we all will have done) but it does not matter in this setting because flow limitation only occurs at extremely high flow rates; high enough that we don't even notice it and can exercise as hard as we like... we'll always be able to breathe enough to get rid of the CO_2 we produce.

At depth the increased density of the gas contributes to a faster drop in pressure as gas passes along the airway, and so airway collapse occurs with less expiratory effort, and at lower flow rates, thus limiting ventilation much more significantly. Now to the point.... If the exhalation begins with the airways already subjected to a negative pressure (negative static lung load) then collapse will likely occur even more quickly and at even lower flow rates. A slight positive static lung load has the opposite effect of **helping to splint the airway open and prevent collapse** as Harry implies. This is almost certainly why studies with heavily exercising divers have demonstrated a slight positive static lung load to be better tolerated from a respiratory point of view than a negative static lung load. Note the emphasis on "slight". A small positive lung load does not impair alveolar emptying. But I am sure you are right to imply that a very large positive static lung load would impair ventilation and be less well tolerated. As you suggest, there is a sweet spot for all of these things.

If you were designing a rebreather with the principal goal of supporting a diver routinely undertaking heavy exercise (e.g. attack swimming in the horizontal attitude) then you might think seriously about using a front mounted counterlung or at least some arrangement with a slight positive rather than negative static load in most postures. But for 99.9% of technical diving applications I would not be wringing my hands over whether my lungs were OTS or back mounted based on concerns about breathing.

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1. Hydrostatic imbalance, that is, whether you have a negative or positive static lung load. Simply put, when you are connected to a rebreather the pressure in your airways is the same as the pressure in the counterlung. If the counterlung is deeper than your lungs (e.g. front mounted in a horizontal diver), then the pressure in your airways will be greater than the pressure of the water (and tissues) surrounding them. If the counterlung is shallower than your lungs (e.g. back mounted in a horizontal diver) then the pressure in your airways will be less than the pressure of the water (and tissues) surrounding them. What is the significance of this?

Forget what you are wearing on your back for a second. A significant part of this thread has been dedicated to discussing expiratory flow limitation. To paraphrase what has gone before (see earlier posts) during expiration as gas passes out along the airway the pressure in the airway drops due to friction. If your lungs are providing extra effort to exhale quickly (e.g. when you are working and trying increase breathing) then the pressure inside the chest generated by your respiratory muscles pushes on the outside of the airways and can cause them to collapse if it exceeds the falling pressure inside the airways. When breathing air at 1 ATA this happens, but only at incredibly high gas flow rates through the airway... so we don't really notice it and can still exercise (and breathe) hard. However, when diving with a dense gas the pressure drop inside the airway happens more quickly, and the airway collapse described above will happen at much lower flow rates. It follows that our ability to ventilate the lungs (and therefore work) is reduced. The greater the density, the less ventilation (and work) we can perform before ventilation is limited. Because CO_2 elimination is entirely dependent on lung ventilation, it is possible to get into situations where it is difficult to ventilate enough to keep the CO_2 normal, but this would usually only occur when breathing very dense gas.

In this context, the significance of hydrostatic imbalance / static lung load is that a negative static load (see above) further increases the risk of airway collapse during exhalation. However, you would still likely need to be working hard with a pretty dense gas for your ventilation to be limited below what you require to keep CO_2 normal. Coughing or grunting at the end of exhalation may be a sign that this is happening, though coughing is a fairly non-specific event on a rebreather. Other things can cause coughing.

2. Work of breathing in the rebreather. This is the work required to move gas around the loop, and is tested by connecting the unit up to a test device (such as an ANSTI machine) and measuring the work required to move a pre-determined amount of gas around the loop under a set of standard conditions. Hydrostatic imbalance is just one of many things that potentially effect this, and the work of breathing of the unit *per se* is not a big player in determining whether you experience the expiratory flow limitation I have described above.

Work of breathing is, however, a BIG player in putting a diver at risk of retaining CO_2: NOT because of expiratory flow limitation, but rather because when the work of breathing is high, some divers respond to rising CO_2 by not trying hard to increasing ventilation in order to lower it again. Put another way, the brain subconsciously chooses to let the CO_2 rise rather than perform the extra work to ventilate it off. We sometimes refer to such divers are called CO_2 retainers. I can discuss this in more detail if people are interested, but the point I am trying to make here is that work of breathing is important (very), but not so much as a determinant of expiratory flow limitation.... that is mainly related to flow rates and gas density... and it may be worsened by a negative static lung load.

Now, if you have been following this so far and don't want to risk getting confused, then stop reading here.

It is possible that these two processes could be linked in precipitating a CO_2 crisis in the following way. Let's say we have a diver who tends to retain CO_2 (a CO_2 retainer) breathing on a CCR with a high work of breathing at a fairly deep depth with a dense gas. Remember that the reason they retain CO_2 is that they don't try hard to breathe it off, so the CO_2 level in the blood rises. They actually feel comfortable breathing at a low rate as their CO_2 rises (and I reiterate that this is why their CO_2 rises). However, even a CO_2 retainer will eventually respond to very high levels of CO_2, and there is some evidence that it is these divers who are at high risk of developing severe symptoms of CO_2 toxicity in a precipitous way. In other words, they transition from comfortable to very uncomfortable very quickly. Thus, our CO_2 retaining diver increases their breathing effort from not much to very high over a short space of time, and now, with a CO_2 level already very high, they suddenly encounter expiratory flow limitation because they are trying so hard to breathe. This is the sort of scenario where the diver might not be able to get out of trouble simply by sitting and resting. I hope you can see what I am getting at.

Simon M