Freedive Wire

FREEDIVING SCIENCE

THE DETAILS OF CO2 TRANSPORT AND CO2 TOLERANCE FOR FREEDIVERS

MARCH 10, 2019 | JAAP | LEAVE A COMMENT

CO_2 tolerance is complicated, hence this post is complicated. Hopefully it is less complicated to read than it was to write. Just in case it gives you a headache, here are the highlights:

- *CO_2 is transported in three ways: bound to hemoglobin, as bicarbonate ion, and dissolved in the blood stream.*
- *Red blood cells are crucial for generating bicarbonate ion, and for facilitating CO_2 bound to hemoglobin.*
- *Only dissolved CO_2 can diffuse to the central chemoreceptors.*
- *Physical CO_2 tolerance may be governed by blood volume and quality, which is commonly overlooked in CO_2 tolerance training.*
- *Endurance athletes commonly have the highest CO_2 tolerance and storage (in comparison to short and mid distance sprinters).*
- *Mental CO_2 tolerance focuses on desensitization of the central chemoreceptors.*

Influencing your breathing rate to an extreme extent means either hyperventilating or holding your breath. If you hyperventilate your skin can start to tingle. If you hold your breath you can get contractions and tunnel vision.

Oh, and did I mention you can pass out from both?

So how do freedivers, who hold their breath as a leisurely past-time activity, deal with the buildup of CO_2? What happens in their body that enables them to tolerate more CO_2?
CO_2 is produced by the energy factories in your bodies' cells, the mitochondria, as a result of aerobic metabolism. The CO_2 diffuses out of the cell and must then be transported to the lungs where you can breathe it out. There are a few different ways that CO_2 is transported, and thus temporarily stored.

The following three paragraphs lean heavily on this article, and references therein.

In the red blood cells: CO_2 bound to hemoglobin

CO_2 can bind to hemoglobin in the red blood cells. Hemoglobin with bound CO_2 is called carbamino-hemoglobin. There is no competition between O_2 and CO_2 bound to hemoglobin (unlike O_2 and CO, which do compete).

Interestingly, CO_2 binds easily to hemoglobin that has already released its oxygen. This makes hemoglobin a very effective transporter of CO_2 from cells that require O_2 and produce CO_2. The effect exists the other way around too, once the hemoglobin encounters oxygen in our lung tissue it releases its CO_2 and binds to O_2 again, repeating the cycle. This effect is called the Haldane effect.

With help from red blood cells: CO_2 as bicarbonate

Water can combine with CO_2 to form carbonic acid: H_2CO_3. This H_2CO_3 easily dissociates into HCO_3^- (carbonic acid) and H^+. In blood plasma this reaction is very slow, but our red blood cells carry an enzyme called carbonic anhydrase that speeds up the reaction. So the CO_2 that moves into a red blood cell and is not bound to hemoglobin is converted by carbonic anhydrase into carbonic acid.

The H^+ stays within the red blood cell and the HCO_3^- moves into the blood plasma. HCO_3^- is slightly basic, and our blood is protected from intense acidity thanks to the red blood cell's buffering capacity.

Once the HCO_3^- is in the blood plasma it keeps our blood from becoming too acidic by acting as a buffer for H^+ generated within other tissues such as the muscles.

CO_2 dissolved in blood

As opposed to O_2, CO_2 dissolves readily in the blood plasma. In the blood plasma, CO_2 can be dissolved as a gas and can be transported to the lungs where some of it is expelled. Because CO_2 is so easy to dissolve in blood, the concentration of dissolved CO_2 actually does not change much when blood is transported through the lung tissue. During normal breathing, only about 15% of dissolved CO_2 is removed in the lungs.

CO2 is transported in three ways: bound to Hb, as bicarbonate, and dissolved as a gas. The dissolved can cross the blood brain barrier and end up in the cerebrospinal fluid, where the central chemoreceptors may trigger contractions. The initial systemic increase of CO2 may help induce the dive reflex.

Relative abundances

Most of the CO_2 in the body is stored as bicarbonate ion. In arterial blood this is up to 90%. However, it is important to realize that this is not all expelled in the lungs. In veinous blood, only 60% of the CO_2 is contained in bicarbonate ion. This doesn't mean that there is less CO_2 in veinous blood than in arterial blood. On the contrary! it means that a significant portion of the CO_2 that is expelled in the lungs is actually bound in hemoglobin and transported as dissolved CO_2.

'Physical' tolerance to CO_2

CO_2 tolerance is not just a mental game. At Freedive Wire we have been digging into the mechanisms of CO_2 tolerance and contractions for quite some time.

In an article we published on Freedive Wire in September 2018, Luca speculated that it is the dissolved CO_2 that ends up triggering contractions. Long story short, neither HCO_3^- nor H^+ can be transported to the central chemoreceptors, but dissolved CO_2 can.

Is the real trick to better CO_2 tolerance to limit the amount of dissolved CO_2? If so, CO_2 tolerance might best be trained by increasing blood volume and quality. After all, more red blood cells will allow more CO_2 to bind to hemoglobin and more blood plasma means a bigger volume to dissolve HCO_3^- in.

Perhaps it is not a coincidence that endurance athletes, who generally have a higher concentration of red blood cells, also have the highest CO_2 storage capabilities. Elite freedivers commonly have a high amount of red blood cells too, as a result of partly desaturating the blood of oxygen on a regular basis.

Unfortunately, divers that only get in the water every now and then won't be able to reap the benefits of high(er) counts of red blood cells and blood volume without specific training.

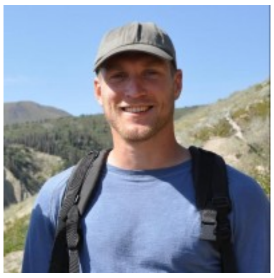
Don't despair though: 35 minutes of exercise (cardio and/or power) 3 times per week already has a positive effect on blood volume and quality. Add 20 minutes of sauna to that after the session and the effect will be even larger.

'Mental' tolerance to CO_2

Another aspect of CO_2 tolerance is desensitization. After a few breath holds, your body might have come to expect a high CO_2 concentration and the alarm bells won't jingle quite as fast. If you expose yourself to high CO_2 concentrations regularly for a long period, you might be able to postpone those alarm bells on every dive.

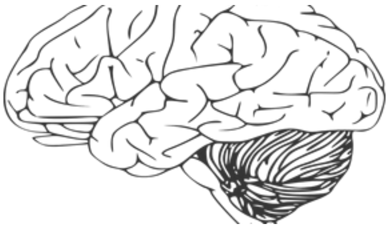
On land, freedivers mostly train this type of tolerance is with CO_2 tables. Using CO_2 or tables or even just slow breathing you are able to expose yourself to high CO_2 concentrations for as long as you want, and you don't even have to move while doing it. A study from 2000 further confirmed that slow breathing and yoga independently increased CO_2 tolerance during hypoxia and hypercapnia. Other methods that increase our 'mental' tolerance to CO_2 are Buteyko breathing and the use of training masks.

How do you approach CO_2 tolerance? Let us know in the comments!

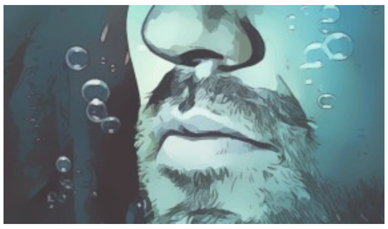


Jaap

Jaap is a geologist by trade and a freediver by passion. Jaap wrote the book Longer and Deeper in 2018. His book teaches how to train for freediving and spearfishing on land.



Chemoreceptors: the puppet masters in freediving?



The inevitable contractions when you hold your breath

Minimizing freediving risk part 1: shallow water blackout