TECHNICAL DIVING INDIA

The Oxygen Window - A Triple Summary

The "Oxygen Window" is one of those concepts that are heavily discussed in technical diving, yet often misunderstood. One of the main reasons for this misunderstanding might be that there are several definitions of the Oxygen Window, which are somewhat related, but nevertheless quite different, and focusing on either off-gasing rate, bubble formation risk, or both. This article attempts to summarize and simplify 3 definitions, based on a variety of different sources, especially including the excellent "*Deco for Divers*", by Mark Powell, and the very thorough "*Gas exchanges, Partial Pressure Gradients and the Oxygen Window*", by Johnny E. Brian.

I. Faster inert gas off-gassing through oxygen increase/inert gas decrease in breathing mix

• The quick explanation •

When diving air or nitrox, increasing the percentage of oxygen in the breathing gas during the ascent mathematically reduces the percentage of nitrogen. Reducing the percentage of nitrogen reduces the partial pressure of nitrogen in our blood, and therefore increases the nitrogen pressure gradient between our tissues, which got loaded with nitrogen during the dive, and our blood. The off-gassing rate being proportional to this pressure gradient, our tissues will off-gas faster.

• The more detailed explanation •

1 • During a dive, the pressurized nitrogen in the gas we breath diffuses into our tissues : the Nitrogen tissue tension increases.

2 • During the ascent, the ambient/breathing pressure decreases, and so does the partial pressure of nitrogen we breath.

3 • Bubble formation depends on the difference between the overall tissue tension and the ambient pressure: the smaller the difference, the less chance of bubbling (note the use of the word *chance*: there are numerous other factors at play in bubbling).

4 • Off-gassing depends on the pressure gradient of each individual gas, i.e. the difference between the tissue tension of this particular gas and its partial pressure in the breathing gas: the bigger the gradient, the faster the off-gassing.

5 • Ideally, we need a way to "disconnect" overall gas pressure from nitrogen partial pressure in order to get the best of both worlds: more nitrogen off-gassing without increasing bubbling risk.

6 • Increasing oxygen (without exceeding max PPO_2 values) while equally reducing nitrogen content in breathing gas does not affect the breathing/ambient pressure (and therefore does not increase the risk of bubbling).

7 • Increasing oxygen (without exceeding max PPO_2 values) and reducing nitrogen content in breathing gas increases the nitrogen pressure gradient between our tissues and our blood, therefore increasing the off-gassing rate.

II. Natural pressure drop between alveolar, arterial & venous systems: potential bubbling risk reduction

• The quick explanation •

Oxygen consumption in our tissues induces a 8-13% pressure drop between our arterial and venous blood. Since bubble formation depends, among other things, on the difference between ambient pressure and tissue/blood pressure during ascent, a lower venous pressure reduces this difference, and thus probably reduces the risk of bubble formation.

• The more detailed explanation •

1 • If the ventilation (gas supply), perfusion (blood supply) and gas exchanges in the lungs were 100% efficient, the gas pressure in the alveoli and in the arterial blood would be equal. Since nothing is perfect in this world, we have a slight pressure drop between the alveoli and the arterial blood (around 5-8 mmHg - *see figure II-a*).

2 • Only 80% of O_2 is converted to CO_2 in our tissues. Furthermore, CO_2 is 20 times more soluble in blood than O_2, and a higher solubility of a given gas results in lower partial pressure for a given amount of this gas when absorbed in tissues. As blood traverses tissues, the increase in CO_2 partial pressure is therefore much lower than the decrease in O_2 partial pressure.

3 • Consequently, venous blood has a lower overall pressure than the arterial blood or the alveolar air (*see figure II-a*).

4 • The total difference between inspired (or alveolar) gas pressure and the venous gas pressure is the oxygen window, which is mainly opened because O_2 is removed from arterial blood but only partially replaced by CO_2 in venous blood.

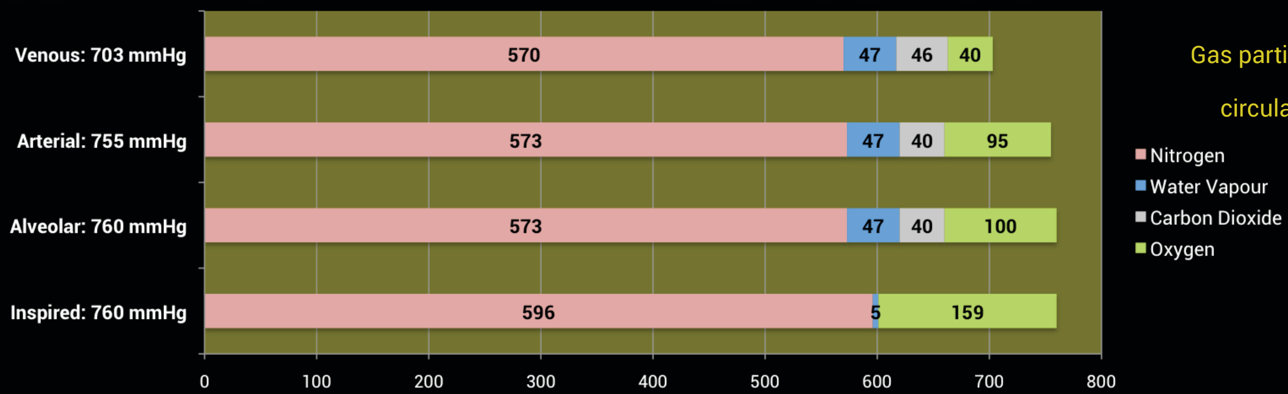

Figure II-a:
Gas partial pressures along the circulatory system

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5 • Each gas acts independently for the purpose of off-gassing but all gases act together when it comes to forming bubbles.

6 • Bubbles mostly form when Delta P > M-Value (Delta P = difference between tissue gas pressure and ambient gas pressure).

7 • During ascent, ambient pressure decreases: a lower venous gas pressure then implies a lower Delta P.

8 • According to point 6, a lower Delta P for a given M-Value means that bubble formation is less likely.

9 • This phenomenon happens naturally, regardless of the gas breathed, as long as it contains O_2 (and it definitely should).

III. Increased pressure drop between alveolar, arterial & venous systems through higher O_2 breathing: "widening the oxygen window" to try and reduce bubbling risk further

• The quick explanation •

This definition of the oxygen window is similar to the previous one, as it is based on the pressure drop between arterial and venous systems, which can reduce bubble formation risk. We can, however, increase this pressure drop by increasing the proportion of oxygen in the breathing gas, thus playing with the proportion of O_2 carried dissolved in the plasma vs. carried chemically-bound to haemoglobin. "Widening the oxygen window" by using hyperoxic mixes during decompression might reduce the risk of bubble formation further.

• The more detailed explanation •

1 • Inert gases like helium or nitrogen are transported in solution, i.e. dissolved in plasma and not carried by specific molecules.

2 • Oxygen and CO_2 are metabolic gases. They are mostly moved to and from our body cells using a specialized transport systems based on haemoglobin (after conversion to bicarbonate ions in red blood cells for CO_2).

3 • At atmospheric pressure, the total haemoglobin in our red cells is 97% saturated with O_2, and carries 98.5% of the O_2 in our body, while only 1.5% is directly dissolved in the plasma. Interesting note for later: O_2 chemically bound to haemoglobin does not exert partial pressure anymore: only O_2 in solution exerts partial pressure.

4 • A small oxygen partial pressure increase is sufficient to saturate the remaining 3% of our haemoglobin.

5 • Once our haemoglobin is saturated, the only way for our blood to absorb more O_2 is by dissolving it into plasma.

6 • Henry's Law states that the mass of a dissolved gas in a given volume of solvent at equilibrium is proportional to the partial pressure of the gas: in other words, once the haemoglobin reaches saturation, the amount of oxygen dissolved in our plasma will increase linearly while oxygen partial pressure increases.

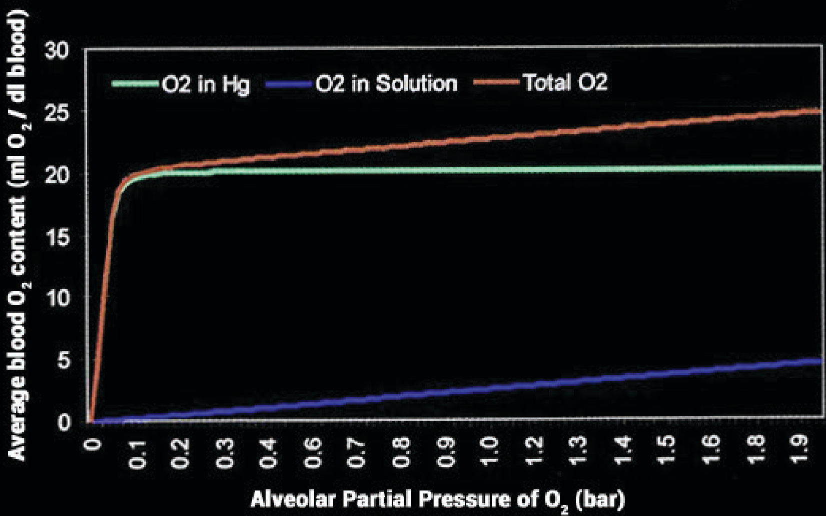

Figure III-a:
O2 blood content with increasing partial pressure
(Based on "Deco For Divers", by Mark Powell)

7 • This double O_2 transport mechanism can be summarized as follows: the amount of O_2 carried chemically-bound to haemoglobin will first increase sharply and then reach a plateau (saturation point), while the amount of O_2 carried dissolved in the plasma will slowly but linearly increase with the O_2 partial pressure. See figure III-a for a visual representation of the phenomenon.

8 • Tissues use oxygen: out of the 19.8 ml of oxygen per dl of blood usually contained in our arteries, 6 ml in average are used by our tissues, resulting in a 6 ml O_2 drop between the arterial and venous systems, and hence in the O2 partial pressure drop described in section II.

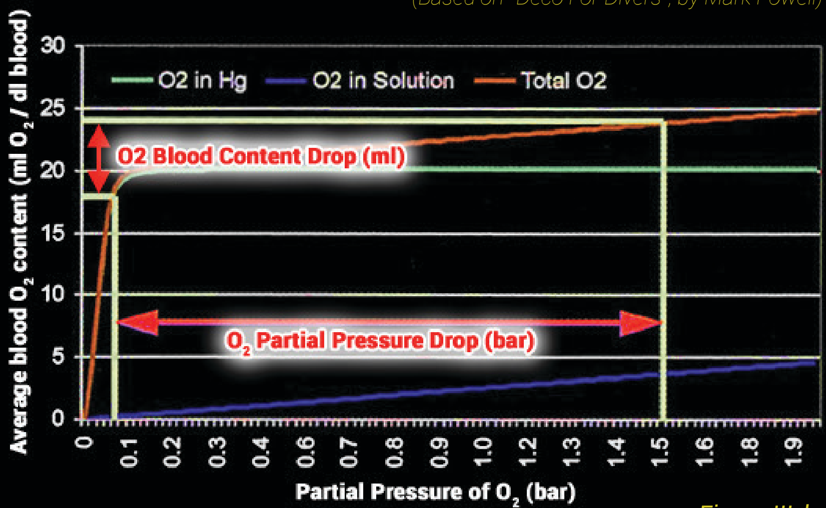

Figure III-b:
Varying O_2 Partial Pressure Drop for constant O_2 Blood content drop
(Based on "Deco For Divers", by Mark Powell)

9 • The shape of the graph means that in order to get a drop of 6 ml, the partial pressure drop will vary considerably depending on the starting partial pressure. In other words: breathing hyperoxic mixes, and thus increasing the partial pressure of oxygen, can be used to "widen the oxygen window", i.e. to achieve a greater oxygen partial pressure drop between arterial and venous systems, with the same amount of oxygen consumption by our tissues. See figure III-b for a visual representation of the phenomenon.

10 • For the geeks among you, let's put some figures on it : at 1.6 bar, pure O_2 creates an oxygen window of 1066 mmHg ; at 1.3 bar, the oxygen window is reduced to 844 mmHg ; and when breathing air at 1 bar, it is only open by around 55 mmHg. For the record, the maximum O_2 window (fully saturated venous haemoglobin) would be 1400 mmHg at around 3 bar of pure O_2.

11 • As stated earlier, a higher O_2 partial pressure drop does not influence nitrogen off-gassing, since off-gassing depends on partial pressure gradients of each individual gas - but it does reduce the total gas tension in our blood, and therefore the risk of bubble formation while ascending.

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Summary & Additional Considerations in the Real World

There are at least 3 ways of defining the oxygen window:

1. One that states that increasing the oxygen partial pressure in the breathing mix will accelerate off-gassing.
2. One that shows that the natural oxygen consumption in our body tends to reduce bubble formation risk even without gas change (but does not affect off-gassing rate).
3. One that suggests that this natural bubble formation risk reduction can be further optimized by “widening the oxygen window”, i.e. by breathing a higher oxygen partial pressure (but without affecting off-gassing rate either).

There is some debate about whether to use 100% O_2 or a mix like EAN80 for decompression. A lower mix could seem safer and more convenient, as it can be breathed deeper, and will be more forgiving of poor buoyancy control during shallower stops - but based on the 1st explanation, using 100% O_2 instead of a 80% mix would accelerate off-gassing more (while the venous pressure drop effect would not vary if we keep the same max. PPO_2 when calculating gas-switch depths). It's up to each team to decide upon their decompression strategy (though poor buoyancy control should not be an option when executing decompression dives).

Anyway you look at it, the bottom line is that the oxygen window can help us decompress more efficiently and/or more safely.

However, the oxygen window shouldn't be opened “too wide” or “too long” for 3 reasons:

1. If the partial pressure of O_2 goes above 1.6 during decompression, the risk of CNS O_2 toxicity increases.
2. If a diver breathes high partial pressures of O_2 for too long, even while staying below 1.6 bar of partial pressure, lung toxicity can become an issue, and the risk of CNS toxicity can increase as well. OTUs and CNS% need to be carefully monitored.
3. Oxygen acts as a vasoconstrictor, which for prolonged exposure would mean that the positive effects of the oxygen window might be nullified by a restriction of the blood flow, which slows down off-gassing.

Furthermore, some technical divers believe that in order for the various potential benefits of the oxygen window to kick in, one has to wait for the blood to circulate through the whole body, which can take up to 2 or 3 minutes, and therefore extend the gas switch stop. Most decompression software let users configure extended gas-switch stops, both for providing time to switch and for accommodating the O_2 window effect.

Conclusion & Warning

Switching to the highest possible hyperoxic mixes during decompression stops, while still respecting maximum O_2 partial pressures and oxygen exposure limits (both OTUs and CNS percentage limits), allows us to optimize decompression both in terms of off-gassing rate (shorter decompression) and bubble formation prevention (safer decompression).

Trying to understand the mechanics behind the oxygen window is good fun, at least for slightly geeky divers - but as is often the case with decompression theory, the physiological phenomena behind the various definitions of the oxygen window are complex, often misunderstood, and should not give a false feeling of safety when using hyperoxic mixes for deco. A big mistake would be to think that taking advantage of the oxygen window would somehow allow us to be more lenient, more complacent in our dive planning and execution, since the oxygen window is covering our back and providing extra safety by optimizing decompression.

It might actually be the opposite: in order to benefit from the various advantages of the oxygen window, one requires much more complex and careful dive planning (gas preparation, marking and switching procedures, as well as multi-gas deco planning) and execution (perfect buoyancy control to avoid opening the oxygen window too wide and toxing on high O_2 partial pressure, and necessity to introduce air breaks for long deco to avoid pulmonary toxicity).

The oxygen window is like a watchdog:
sure it can keep you safe, but it might and will bite you in the ass if you misuse it.

REFERENCES & FURTHER READING

- Deco for Divers, by Mark Powell, Aquapress, UK (First published 2008, 2nd edition 2014)
- Gas exchanges, Partial Pressure Gradients and the Oxygen Window, by Johnny E. Brian, University of Iowa
- The Isobaric (Oxygen Window) Principle of Decompression, by Albert R. Behnke, U.S. Navy (1967)
- PADI Tec Deep Diver Manual, Tec45, Chapter 5, PADI
- Decompression myths and mistakes: The Oxygen Window, V-Planner Documentation
- Dissolved and free phase gas dynamics, by Johnny E. Brian et al, University of Iowa College of Medicine
- Tauchmedizin, by A. A. Bühlmann, P. Nussberger & E.B. Völlm (1994)
- Explanation of the oxygen window, George Irvine, DIR Articles, frogkick.nl
- Deep into Deco, by Asser Salama, Best Publishing Company (2015)

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