

Dynamic control of breathing blend for professional diving

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Summary

In hyperbaric environments, like underwater, the body behaves differently in front the different gasses, normally by absorbing and storing inert gasses between tissues. In the event of a sudden decompression, like a diver ascending, these gasses can form bubbles, which can harm badly the diver. In order to avoid this peril, divers preform a series of stops to help the body get rid of these gases safely, decompression stops.

Taking base on the current technics of gas blending, this paper proposes an automatic dynamic regulation of these gasses, Oxygen/Nitrogen. By tuning the proportions of the mix according to the divers needs the accumulation of inert gasses is reduced, which leads to a big improvement of the waiting time the divers have to wait before exiting the water, in addition to their safety.

1. Introduction

The objective of this paper is the proposal of an alternative breathing mix procedure for professional diving, through a dynamic mixture of the breathing blend “enriched-air”, popularly called “Nitrox”, in order to reduce the waiting time of the diver has to do at the ascensions. Cutting down the total time any professional work would take, in contrast of the current methods used in the diving industry.

The target user of the proposed mix are the professional diving teams. As they are often exposed to the dangers of decompression, and the time their work takes is, in great part, dependant to the changing shift between workers. By reducing the exposure to inert gasses responsible of the decompression, through the proposed mix, the process will speed up, which makes the diver team more competitive.

As the proposed mixing system is an automatization of the process of the blending of the gasses, which is an add-on of the current gas blending systems, it can also present some features and information useful for the team (depth, time, emplaced time ascension, ...).

2. Decompression stops

As the diver starts to ascend the stored inert gasses start to exit the body, until the pressure difference, between the inner gasses and the environment, may cause bubbles to form. This limit is called the **ascension ceiling**. At this point the diver has to stop, before surpassing the ascension ceiling, and wait at that depth until the inner pressure is low enough to keep ascending to the new ascension limit, at a shallower depth, this stops are referred as **decompression stops**.

As the decompression get to the shallower depths, were the pressure decrement is smaller, the body last longer to dispose the inert gasses, as it can be seem at the **Fig 1**. The main objective of this work is the trimming of the time these stops take.

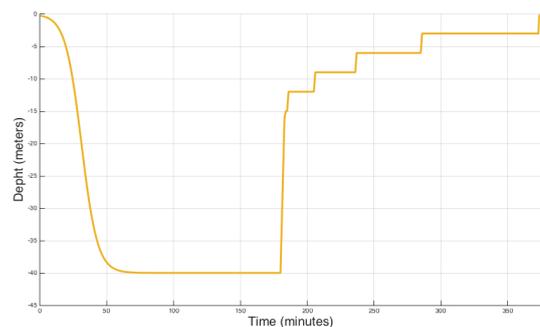


Fig 1. Dive profile using air

3. Breathing mixes

Being this project directly related to the manipulation of Breathing mixes, it may be helpful to understand what they are, and what is their propose.

The breathing mixes are just a mixture of gasses with the sole intention of being breathed. Since 1970 breathing gasses have been used in hyperbaric activities to reduce the proportion of inert gasses that air contains (78% Nitrogen, 21% Oxygen and others). The most common breathing gasses are the blends named “enriched-air”, which usually the inert gasses used in these blends are **Nitrogen** and **Helium** [1].

One may think that if the concentration of inert gasses in the body are the cause of the decompression problems, why is not used the Oxygen pure? This is true in part, as the smaller the proportion of inert gasses in a blend, the smaller the quantity gets accumulated by the body during a dive, what results in less time to wait at the ascension. However, as the proportion of inert gasses get lower the partial pressure of Oxygen rises, and at certain pressures Oxygen can become toxic [2], known as “Paul Bert effect” or **Oxygen toxicity**. In consequence, inert gasses are used as diluent for Oxygen. So depending on the proportions of the mix, the maximum depth limits changes.

The two main types of breathing blends, the Nitrogen variant (“**Nitrox**”) and the Helium (“**Heliox**”). Although Helium is a much faster gas than Nitrogen, making it much better decompression gas, it also cost 13 times more [3] than

Nitrogen. Making it uncommon to use. This is the main reason why the proposed mix is a variant of Nitrox, as it's the most common and cheaper breathing mix.

4. Proposed dynamic mix

The proposed method is a dynamic mix of the combination of two gasses, Oxygen and Nitrogen, intended to supply the diver with the maximum Oxygen possible at any depth, before Oxygen toxicity becomes a problem. So the diver is always breathing the minimal part of inert gas, reducing the accumulation of it and trimming ascension times. As opposite to the traditional approach, where the common praxis is to fix a proportion of Nitrogen, adequate for the maximum depth the diver will reach. Let me exemplify, if a professional diver team has to do a work at 40 meters underwater, they have to choose a Nitrox mix for that depth like Nitrox27 (27% Oxygen), which maximum depth is at 41.9 meters. If the same team chooses to perform the same work using the proposed dynamic mix, they don't need to bring any premade blends, because the algorithm tunes automatically the mix according to the depth where the diver is situated.

The different effects on the gasses under pressure, like Oxygen toxicity or the inert gas retention, is given by its partial pressure, which are defined at the **Dalton's law of partial pressures**, which states: "In a mixture of non-reacting gases, the total pressure exerted is equal to the sum of the partial pressures of the individual gases."

Mathematically expressed as:

$$P_t = \sum_{n=1}^n P_n$$

where:

$$P_n = C_n \cdot P_t \rightarrow 1 = \sum_{n=1}^n C_n$$

- P_t : Total pressure of the mixture.
- P_n : Partial pressure of gas, in mixture.
- C_n : Proportion of gas in mixture.

For example, if a person breaths air (21% Oxygen) at surface at a pressure of 1 atmosphere, the partial pressure of the oxygen is 0.21 ppO₂(P_n). If the same person gets underwater, breathing the same air, until the environment pressure rises to 5 atmospheres (P_t = 5 atmospheres), the partial pressure of oxygen is 1.05 ppO₂.

Being Oxygen toxicity the only real restriction, for any breathing blend, the main focus of the dynamic mix proposed is to proportionate the maximum Oxygen at any time to the diver, while maintaining a safe margin to the Oxygen toxicity partial pressure threshold, by the control of the proportions of inert gasses in the mix. The approach of the traditional methods is to fix a proportion of oxygen, adequate for the maximum depth the diver will reach. And stick to that breathing mix all the dive.

The solution proposed is an open loop control of the mix breathed, that fixes a partial pressure of oxygen and as the environmental pressure changes, directly proportional to the

depth, the proportion of Nitrogen compensates the pressure. It can be expressed as:

$$cn = 1 - \frac{ppO}{Pd}$$

- cn: Proportion Nitrogen.
- Pd: Pressure of of the water [bar].
- ppO: Partial pressure of Oxygen [bar].

As it can be easily seen in the graph (**Fig 2**), while the other mixes, air and Nitrox, remained static at their proportions. The proposed mix adopts the profile of the dive.

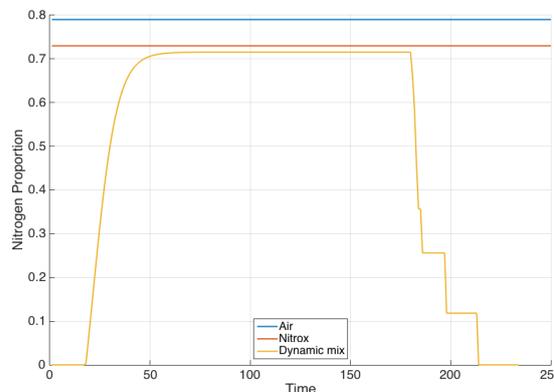


Fig 2. Proportion Nitrogen through a dive (40meters-230 min)

Unlike the current methods, the dynamic mix has virtually no depth limit. Giving the diver the opportunity, in an unforeseen case the possibility to exceed the planned limit and don't risk his or her health.

In some occasions, with the traditional methods, at the end of the last decompression stop, the last 3 meters, the team may opt to perform an **accelerated decompression**. What consist in supplying the diver Oxygen 100% to reduce even more the time the decompression takes. In the case of the proposed mix, this happens along all the ascension. The dynamical mix, will supply the diver the right Nitrogen proportion to the diver during the dive, and in addition, at the ascension it will perform as an accelerated decompression.

This concept is very similar to a type of high risk diving, for autonomous diving, were the diver carries different bottles of breathing mixes though the dive, and at each interval of depth he or she switches manually the mix breaded to adapt to his or her needs. This technique is called "Technical diving" or "Tech diving". The proposed breathing mix presented in this paper has inspired from this technique, with the big difference of being supplied from surface and there is no switching of breathing mixes nor the necessity of caring bottles around, as the mix is dynamically changing, being safer to user. What makes this proposal perfect for professional diving.

5. Oxygen toxicity

Oxygen toxicity is the real limit for any type of breathing blend. As there must be enough Oxygen, so the blend doesn't suffocate the user, and not as much to become toxic.

“Paul Bert effect” or Oxygen toxicity was not documented until 1878, by Paul Bert. The damage produced by this phenomenon can be separate in two types: **Central Nervous System (CNS)** and **Pulmonary** (or whole body).

To avoid the perils that the Paul Bert effect may produce, the communities and schools of diving has fixed maximum ranges of partial pressures for oxygen. Most of them have situated this limit for enriched-air diving at 1.4 bar. As it keeps the diver at a safe range and it also serve as margin of error, between the limit and the contingency pressure. The contingency oxygen partial pressure limit is 1.6 atm. But is strongly discourage to plan a dive whit this pressure in mind because there is no room for error.

The CNS has its effects on the central nervous system. The symptoms appear at relatively short times, around 1.6 ppO₂, the main manifestation is an epileptic-like convulsion that may occur without warning. Whereas “whole body” Oxygen toxicity is characterized by effecting the lungs, as they are the first organ in contact with the gas. The symptoms are much slower to appear, the damage is produced is permanent, decrease of the **lungs capacity** to absorb oxygen [4].

6. Law restrictions

Because the target user’s safety and health is dependant of the output this work is dealing is interesting to take into account some regulations and limits imposed, for the safety of the divers. Taking the BOE (“*Boletín Oficial del Estado*”) of security normative of subaquatic activities [5], from Spain, can be taken several point that may take effect on this proposal:

For any form of professional work, it’s forbidden the praxis of autonomous diving, with no source of breathing mix other that the one the diver carries, in any form of professional work. Neither is free diving permitted.

The use of the different types of enriched-air is regulated by the maximum depth the diver will reach. **Table 1** is a summary these regulations, where the BOE itself strongly recommends he use of enriched-air in front of Air.

Depth	Air	“Nitrox”	“Heliox”
0 - 15	Optional	Optional	Forbidden
16 - 42	Optional	Suggested	Optional
43 - 50	Optional	Forbidden	Suggested
51 - 60	Forbidden	Forbidden	Obligated

Table 1. Summary BOE’s mix-depth

The proposed mix falls in the Nitrox category of the **Table 1** as it’s a mixture of Oxygen/Nitrogen in front of the current law, However the mix itself has virtually no limits and could reach greater depths.

The total time of the dive must not exceed 180 minutes, including decompression stops. At some situations, one diver can do up to two dives per shift, only if the total time

of the two, including decompression, adds up to a maximum of 180 minutes. And the maximum depth doesn’t reach 50 meters.

The minimum number of person per diving team is **5 persons**, where one must function as supervisor and the other four as divers. While one diver is underwater, there must be one diver prepared to jump in case of emergency.

7. Bühlmann algorithm

The Bühlmann decompression algorithm [6] is a mathematical model of the way in which inert gases enter and leave the human body as the ambient pressure changes. It is important to explain it because thanks to it the advantages of breathing mixes can be analysed, also it explains how the accumulation of inert gasses take part in the decompression, the main reason the proposed mixture tries to speed up.

Due the differences characteristics in the different tissues, like perfusion (blood flow), diffusion (rate of gas flow from one place to another) and others, the inert gasses we breathe are dissolved into tissues at different speeds. Tissues with high rates of diffusion build up a gas load more quickly, known as “fast” tissues. Although a fast tissue will build up a higher inert gas load (“**on-gas**”) in less time, when the pressure increases, they will also get rid of that gas load more quickly than a slower tissue when the pressure drops, “**off-gassing**”. So the body is split into different representative compartments (16 in this case), with different characteristics and speeds.

The idea is that when a tissue is exposed to a higher inert gas pressure, the gas will flow into that tissue. After the “half-time” the pressure of gas in the tissue will be half way to equalling the pressure of the gas outside. After a second half-time, the gas pressure in the tissue will have risen by half of the remaining difference. By this method the pressure in the tissue never quite reaches the same level as the surrounding gas, but after 6 half-times, it’s close enough and we say the tissue is “**saturated**”. At this point, remaining at the same pressure will result in no further overall change in gas load. If the pressure then increases, the tissue will begin to on-gas again. If the pressure reduces, the tissue will off-gas, again following the half-time principle.

If pressure is reduced by too much on a tissue, the gas will be unable to follow the diffusion route and will form bubbles [7] inside the tissue, leading to many of the symptoms that we know as decompression sickness.

The calculations of this algorithm takes this form:

$$P_c = P_b + (P_g - P_b) \cdot \left(1 - 2^{-\frac{t_e}{t_{ht}}}\right)$$

- P_c: inner gas pressure after exposure [bar].
- P_b: inner gas pressure before exposure [bar].
- P_g: Partial pressure of the breathed gas [bar].
- t_e: Time exposed to the pressure [minutes].
- t_{ht}: Half-time of the compartment [minutes].

The algorithm applied in **Fig 3** shows the concentration of Nitrogen in every compartment in front of a step profile of a depth 20 m for 30 min, in which the diver starts at 20 meters and after 30 minutes the diver goes to 0 meters (surface).

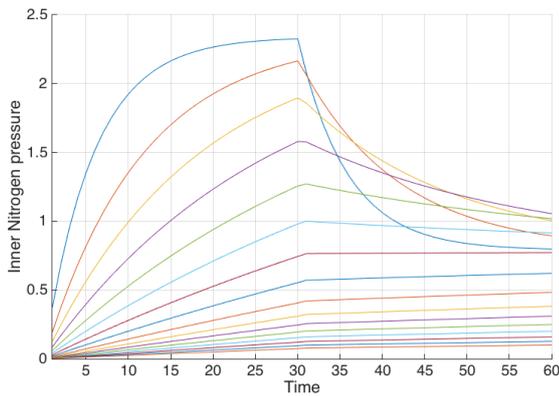


Fig 3. Compartment response in a step (20 meters; 30 minutes)

In **Fig 3** shows the 16 different pressures of inert gases for each compartment of the body. The fastest tissues (the top ones of the **Fig 3**), are the first of getting filled with gas and the fastest to dispose them. But at the end they are restricted by the slower ones, that doesn't dispose the gas as quickly.

In the same way, Dr. Bühlmann's algorithm can extrapolate the maximum pressure a compartment can ascent to without bubble formation, from the half-time, with the following expression:

$$P_{max} = (P_c - a) \cdot b$$

$$a = 2 \cdot t_{ht}^{-\frac{1}{3}}$$

$$b = 1.005 - t_{ht}^{-1/2}$$

Taking the previous example of the **Fig 3**, from the 16 compartments, we get the maximum pressure the compartment can ascent to, without forming bubbles, and from the 16 values the most restrictive pressure becomes the **ascension ceiling**, as it limits the maximum depth the diver can ascend before bubbles start appearing. In the same case as **Fig 3**, the ascension ceiling looks:

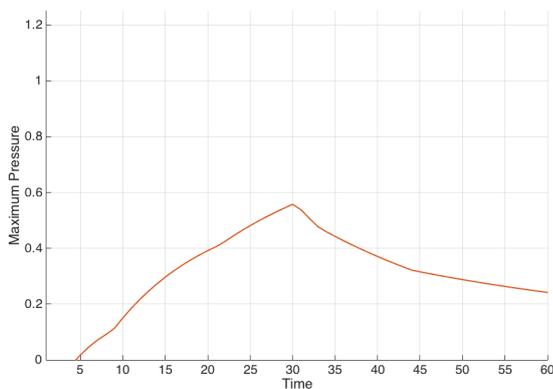


fig 4. Ascension ceiling in a step (20 meters; 30 minutes)

The interpretation of the **fig 4** shows that the diver at 30 minutes he can ascent to 0.58 bar, take in mind these values

are in absolute pressure, what means that they are over the surface of the sea, so no decompression is needed to get out of the water.

8. Behaviour of the mixes

To exemplify the models given in this paper and compare the different breathing mixes available to the professional divers. The proposed case is a slow descend to 40 meters (maximum depth of the dive) and remain there for 180 minutes, and then exit the water passing through decompression. The Breathing mixes, based in Nitrogen, proposed are:

- **Air:** 21% Oxygen maximum depth 57.8 meters.
- **Nitrox:** 27% Oxygen maximum depth 41.9 meters.
- The proposed **dynamic blend:** 28% Oxygen at 40 meters.

The three mixes will follow the same dive profile, and the difference will be seen at the decompression, as every gas will have their own.

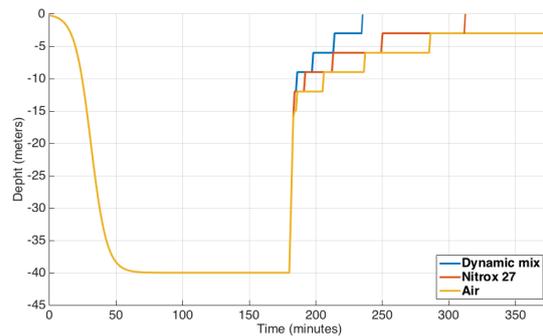


Fig 5. Dive profile (40 meters - 180 minutes)

From **Fig 5** can be compared the times of decompression. As expected air is the slowest gas, followed by Nitrox, and lastly the proposed dynamic mix, which waiting times at every stage are much shorter, letting the diver exit 139 minutes sooner than the user of air.

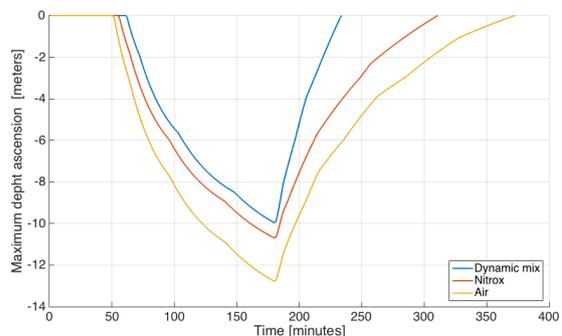


Fig 6. Ascension ceiling of dive (40 meters - 180 minutes)

At the **Fig 6** it can be seen the evolution of the ascensions ceilings for every breathing gas. Which dictate when the diver can exit safely from the water. The curves corresponding to Nitrox and Air are almost parallel, because they are a static mix, and behaves similarly. However, the dynamic mix, at the ascension, the ascension ceiling is more inclined, this is because as the diver goes upwards the mix is

richer in Oxygen, what accelerates the disposal of inert gasses, moving the ceiling. The numerical results of the example dive are:

Mix	Exit Time [minutes]	Max ceiling [meters]
Air	373	12.8
Nitrox	311	10.7
Dynamic mix	234	9.9

Table 2. Results of breathing mixes for example dive (180min-40m)

9. Implementation

The professional diver is linked to the surface by the umbilical cord which supplies him or her of the breathing mix and allows the communication between the diver and the surface team. The breathing gas can be supplied by a **low-pressure compressor** or from **high-pressure reserve**.

Usually when the breathing mix is air, the supply is done by a low-pressure compressor with atmospheric intake, as it is virtually unlimited in the amount of air. But, in our case dynamic mixes require pure gases, and a low-pressure compressor limits the range of manipulation of the gas proportions.

High-pressure reserve is the most common way professional diving supply breathing mixtures like Nitrox or Heliox. By having a container with the blend at highly compressed and through a regulator the gas pressure is reduced to the diver.

The proposed dynamic blending system is based on the high-pressure storage method. This procedure is a **continuous dynamic blending** operation which uses storage of high-pressure tanks of pure gasses, that form the composition of the breathing mix (Nitrogen and Oxygen). The high pressure of these tanks are reduced with regulators at their partial pressures for the breathing mix, followed by passing these gasses through a mixing tube, which boosts the homogeneity of the blend. At the end of the mixing tube, the blend is analysed in propose to ensure the composition of the mix. Lastly, the blend is compressed, for its use.

10. Conclusions

The end results of the simulations have shown a very promising breathing mix, with a large improvement over other methods. Improving the ascension times, which was one of the main objectives of the project.

Although the system has virtually no depth limit, it is constricted by law regulations to a maximum of 42 meters, as it falls under the Nitrox blends (**Table 1**). All through, being the range from 0 to 42 meters is not a big inconvenience, as this range is the most common for professional divers to operate.

Introducing automatizations on a sector which the major part remains manual, as the traditional mixes currently are, may bring a safer and more controlled environment to work at.

However, there are still ways to improve and polish. For example, it wasn't taken into account the delay of the gas traveling through the hose, neither the little buffer the umbilical cord creates at its length. There are some new models of bubble formation which may bring some more precision to the decompression times calculated or even help to the control to get rid of them, as they take into account more parameters in the bubble formation, like temperature.

11. Acknowledgements

I am indebted to many colleagues and relatives, one named here and others who don't, for virtually all of the information collected over the conceptualization of this project.

To my uncle, Mr. Francisco Andreu, who introduced me to diving and guided through the world of profession diving.

To install-sub, a professional company who facilitated information and resources.

To my tutor, Dr. Pau Martí, who's guidance and advises allowed conception of this projects.

And finally to my family for the support given through the conception of this project.

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