commercial diving: 90 mSW operational aspects

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After the collapse of the offshore diving industry in the 90's, there still remains a need for conducting bounce diving operations down to at least 90 m. The development of technical diving has brought new options in terms of the diving methods. Although heliox is still the best bottom mix, trimix appears as a good compromise for the depth range considered. However, decompression safety is the key to such operations. Former bounce diving tables from the offshore and military diving have too high DCS incidence rates. New tables need to be developed.   The design of a table requires deciding upon a critical bubble scenario. Using the arterial bubble assumption, it is shown that at least to aspects of the bubble growth need to be controlled: the bubble radius in the earlier stage and the bubble volume in the later stage of the decompression. The review of the classic models shows that they only cover one aspect of the decompression. The new bubble growth models do produce deep stops but miss the last part of the decompression. A new model is presented that combines the two aspects in a multi-model approach to decompression safety.

Introduction

The North Sea operations had leadership in commercial diving from 1970 to 1990 and set standards, regulations, code of practice for the whole industry. Since the success of ROVs and deep subsea operations, commercial diving has much recessed and its technology has stagnated.

Diving operations are still running in the air diving range. They include inland diving, military diving, search and rescue, scientific diving, fishery, and recreational diving. Because of the collapse of the offshore industry, these divers need to fill in the gap and extend their operational capacity to at least 90m. The most active group are the technical divers, who have already integrated and adapted some of the professional techniques to extend their explorations. In light of the past commercial diving experience and the rising technical diving achievements, several options are reviewed that could support new bounce diving operations to 90m.

Diving Procedures Options

Commercial diving methods of intervention are well defined in the local laws, industry regulations and company's manuals. However, each job having its own tools, methods may differ from one diving site to the other. The classic commercial diving methods of intervention include (1):

- SCUBA diving, to a limited extent. This method has a limited gas supply, no communication with the surface, and in most cases, no safety link between surface and the diver. SCUBA diving is forbidden in the North Sea.
- Surface-supplied is the preferred method of intervention. The diver is supplied from the surface through an umbilical that provides him with gas, communications, a safety line, a hot water hose for his heating, a TV cable, etc. The diver can be deployed from a basket. The bottom mix can be air or mixed gas, the decompression mix nitrox or pure oxygen at 6 m. Decompression procedures include in-water decompression or surface decompression in a deck chamber.
- Wet bell diving. The divers are deployed into a wet bell with a gas filled dome. The wet bell provides more comfort and controls and allows for longer time in water. Wet bells are used for air and mixed gas, and because of the dry environment in which they are sitting, divers can take oxygen on a mask at 12 m.
- Bell bounce dive. Small bell systems have been designed that can be easily mobilized and include a two-man bell, a handling frame and a chamber for TUP. Divers can breathe air or mixed gas at the bottom but are usually recovered in the chamber filled with air. They perform pure oxygen breathing sessions on mask by the end of the decompression. Small bell systems support bounce diving down to 120 m and for bottom times up to 2 hours.

Commercial diving has rugged and proven methods but the requirements for the surface support are heavy. Unfortunately, after ROVs took over manned intervention, a lot of small bell TUP systems were put aside and later scrapped. It would be difficult to mobilize such systems nowadays. New methods of intervention have been developed recently by the cave and wreck divers that are lighter and cheaper:

- The trimix "tech" configuration where the diver carries his bottom mix in a twin cylinder set on his back and clips one or two stage cylinders on his harness as decompression gases. The evolution in the equipment (double-wing BCD, steel back plate harness, argon dry suit, DPV, etc.), procedures (tables, trimix computer, dive planning) and training (risk analysis, what if sessions, etc.) has turned SCUBA diving into a safer and more efficient method permitting reasonable intervention up to 90 m (2). The best technical divers now explore to depths in excess of 150 m and the deepest dive performed was 330 m.
- Rebreather diving, once the monopole of military divers, is now a common practice in technical diving. The offer is large (Inspiration, Evolution, Megalodon, KISS, etc.) and the training is available through specialized agencies (IANTD, TDI, etc.).

At least several options are now available for extending bounce diving operations. One particular issue is related to the PO_2 control during the decompression. Deep bounce decompressions represent a heavy off-gassing process and divers need to adopt an aggressive oxygen protocol during their ascent. In open circuit, the diver has to change his decompression mix to raise the PO_2 during the ascent. The PO_2 profile looks like saw teeth. The CCR divers have the possibility to breathe constant PO_2 during the entire ascent. Despite the longer training and heavier maintenance, CCRs represent a new way to more efficient decompression. However, it is admitted that their use in commercial diving still requires solving several safety problems (degraded conditions, bail out situation, link with surface, etc.).

Bottom Mix Options

The choice is between heliox and trimix. Apparently a simple issue that requires some considerations.

Heliox is certainly the best bottom mix, as proven by the North Sea construction. It is also the best decompression mix. This is more difficult to document as air tables and heliox tables seldom overlap. It is also biased by the fact that heliox tables are deeper, less used, and certainly less accomplished. At least, in saturation diving, heliox decompressions appear much faster than air decompression (3). Dr. Fructus, who designed most of the Comex tables in the 70's, used to say, as a man of experience, that helium is much "easier" than nitrogen.

The main limitation of heliox is its cost. This is why heliair (a simple blend of air and helium also called "poor man mix") and trimix were invented. Trimix was also chosen to avoid the need to use a speech unscrambler and to cut down on the respiratory heat loss associated with heliox, an important point for divers using passive thermal protection.

In France, trimix was developed in the 70's based on the French Navy tables (4) and their further adaptations. See Appendix 1.

In the USA, to my knowledge, trimix was introduced by André Galerne at the IUC Company. In the early 80's, the US Navy collaborated with the Royal Navy on some trimix tables testing at the Deep Trials Unit. Later, with the advent of deep cave diving, Dr. Bill Hamilton used his DECAP model to cut tables for cavers Bill Gavin and Parker Turner during their dives at Indian Spring. The WKKP used trimix intensively for the exploration of the Wakulla Spring system. Caver Sheck Exley designed his own trimix tables. Finally, when technical diving started in the early 90's, new trimix tables became available through decompression software and dive computers.

Despite its operational success, trimix is based on a trade off of gas density and narcosis. Trimix divers evaluate narcosis with the concept of the equivalent air depth (EAD) and usually dive with an EAD between 30-40 m. They select mixtures depending on depth and the specified values of the bottom PO_2 and EAD. Table 1 lists trimix mixtures used in technical diving. Heliox breathed in closed circuit loop could be a way

around that. Limiting the cost and providing the full benefit of helium, the CCRs again present an attractive alternative.

Table 1. Trimix gas mixtures used in technical diving.

Trimix gas	Operational depth range
T20/25	40-60 m
T19/30	50-70 m
T16/40	70-80m
T14/50	80-90 m

Decompression Table Options

Safe decompression procedures are the key to the development of bounce diving to 90m.

Previous experience with commercial diving tables is worrisome. Table 2 below presents the safety performances of a set of heliox tables called "Cx70" that were used by the Comex Services Company between 1970 and 1982. The tables were available in two versions. The first one was designed for surface-supplied diving and limited to 75 m. The diver breathed heliox as bottom mix and 100% oxygen at the 6 m stop. The second one was designed for bell TUP diving and provided exposures up to 120 minutes, down to 120 m. The diver breathed heliox in water and in the bell, air once transferred in the deck decompression chamber, and finally oxygen on mask from 12 m to the surface. The overall incident rate was around 4% and thus far exceeded the tolerated decompression sickness (DCS) incidence of modern tables that range between 0.1%-0.5% (5). Most of the symptoms were type I pain only DCS. However, a significant number of type II DCS symptoms, essentially vestibular hits, were recorded in association with the short bottom times.

Table 2. Safety performances of the Comex Services Company Cx70 heliox decompression tables used between 1970 and 1982.

Table Cx70	Exposures number	Type I number	Type I rate	Type II number	Type II rate	All DCS number	All DCS rate
Surface supplied	1450	18	1.24 %	3	0.2 %	21	1.4 %
Bell TUP	3820	140	3.6 %	15	0.3 %	145	3.8 %

One might minimize the risk by recalling that this corresponded to the state of the art. People were trained to identify the symptoms and apply recompression procedures as soon as the diver reported a problem. This way, in most cases, the symptoms were relieved and the DCS treated. However, the concern is that a lot of symptoms occurred at depth, a situation that has no consequence when inside a bell or a chamber, but that turns critical when the diver is hanging at his decompression stop in the water. No treatment is available and no access to the surface is possible. Moreover, if the symptoms involve the vestibular function, the diver is likely to vomit, a dramatic situation when breathing from

a regulator. For this reason, tables using in-water decompression must have an additional safety margin to insure that no symptoms will occur while the diver is in the water.

Recent experience with technical diving tables is more reasonable. IANTD, a technical diver training agency developed by Tom Mount in the USA, uses trimix tables for diver education that are typical of a prudent approach. The tables are based on a classic Bühlmann model but have additional built in precautions that make them longer and more conservative. They are far from being optimal but that is not the objective. Although no official safety records are published, my experience with IANTD training in France culminates in:

- 534 divers exposures performed between 42 and 60 m (IANTD trimix 20/25 tables),
- 105 exposures between 63 and 69 m (IANTD trimix 19/30 tables),
- 315 exposures between 72 and 81m (IANTD trimix 16/40 tables),

and not a single decompression problem was reported for 954 dive exposures.

But the tables lack flexibility and the trend is towards computer diving. Divers have now a large choice of commercially available decompression software and dive computers. There are currently 5 families of models used for trimix diving:

- The classic Bühlmann algorithm (6) as in the Voyager dive computer,
- Bühlmann algorithms adapted with extra deep stops as in the VR3 dive computer and Pro Planner software, from the Delta P company, UK,
- Bühlmann algorithms modified by the gradient factors method (7) as in the GAP software.
- VPM algorithm of Dr. David Yount (8) as in the V Planner software,
- RGBM algorithm of Dr. Bruce Wienke (9) as in the Abyss software.

It is difficult to evaluate the safety performances of these decompression tools because there is no independent organisation that could collect the information and turn it into scientific data. There is also a lot of concern in the way the computers are used. A recent paper published on trimix DCS cases treated at the hyperbaric chamber of Toulon suggests that inadequate training, equipment and procedure can lead to serious decompression accidents (10).

Decompression Table Calculation Options

The traditional "Haldanean" models work on dissolved gas. These models cannot be denied certain efficiency since the present commercial air diving tables have an overall safety record around 0.5% DCS incidence (11). The question is their relevance for deeper diving. Such models have a strategy of an initial rapid ascent to create an off-gassing gradient. Their profile is typical. Such a strategy is now questioned and current empirical practices rather tend to slow down the initial part and introduce additional deeper stops. It is obvious that extending the operational range will require different models to produce different profiles. We need to bolt a new model layer onto the existing one.

Analysis of bounce tables indicates that the dive profile controls the bubble formation and decides on the safety outcome of the decompression. As the profile is related to the exposure, it seems that, with the existing tables:

- Short bottom time tables (10-30 min) characterized by a rapid ascent to shallow stops produce vestibular symptoms,
- Average bottom time tables (30-90 min) produce other neurological symptoms
- Longer bottom time tables and saturation diving, associated with slow ascents, produce type I pain only DCS in the last meters of the decompression.

Such facts support the following new vision of decompression modelling:

- The DCS risk must be appreciated separately for each symptom,
- Each symptom depends on a different bubble scenario,
- Each bubble scenario must be associated to a different model.

The arterial bubble assumption allows for the structuring of this concept (figure 1). Arterial bubbles were already mentioned by Haldane on page 352 of his 1908 publication (12). Closer to our time, in 1971, Hills (13) was able to show, using an animal model, that DCS symptoms could change from Type I to Type II by changing from continuous decompression to surface decompression, thus suggesting different mechanisms. Later in 1989, Hennessy published the physical aspects of the arterial bubble scenario in a paper (14) that became the foundation of the arterial bubble assumption.

The issue in the arterial bubble assumption is the filtering capacity of the lungs. The threshold radius is suspected to be the size of a blood cell. During the initial phase of the decompression, when bubbles are small, they are likely to pass trough the lungs into the arterial side. Later in the ascent, bubbles grow to a larger size and remain trapped in the lung.

The arterial bubble assumption introduces variability in the decompression outcome through the lung function. It is reasonable to accept that the filtering capacity of the lungs may vary from person to person, and for one individual, from one day to the other. It thus accounts for the inter-individual variability (age, fat content, smoking, etc.) and intra-individual variability (fatigue, hang over, etc.), which has been observed for a long time in DCS susceptibility. Basically, a good diver is a good bubble filter. The arterial bubble assumption is also consistent with the accidental production of arterial bubbles.

One scenario is related to the diver's physiology. It considers shunts at the heart or lung level that accidentally pass bubbles from the venous to the arterial side. A vast literature is now available on the subject of permeable patent foramen ovale (PFO) (15). The studies have shown a high correlation between central neurological DCS and the detection of a permeable PFO (16). A permeable PFO conveniently explains neurological accidents after recreational air diving without any procedure violation.

Another scenario is related to the diving procedures. It considers pressure variations during decompression that reduce bubble diameters. This way; bubbles trapped in the lung during a normal decompression could suddenly cross through the capillaries and later generate type II DCS symptoms. This explanation has been proposed for the

difference in safety performances between in-water decompression and surface decompression (17). Data collected in the North Sea have shown that if the overall incidence rate of the two diving methods is about the same. However, surface decompression tends to produce ten times more type II DCS than in-water decompression. The scenario is that at the moment the diver ascends to the surface, bubbles are produced that are stopped at the lung level. Upon recompression of the diver in the deck chamber, these bubbles reduce their diameter due to Boyle's law and go to the arterial side, later causing neurological symptoms. The same scenario was proposed for type II DCS recorded after yoyo diving or multiple repetitive diving.

Finally, the arterial bubble assumption provides an explanation for the criticality of the initial ascent phase. Bubbles associated with symptoms are not necessarily generated on site. There is an amplification process at the beginning of the ascent that may last for several cycles. Once the bubbles have reached a critical size, they are either filtered in the lung or stopped at the tissue level. It is believed that the showering process of small arterial bubbles during the first minutes of the initial ascent prepares the prognostic for further DCS symptoms. It is consistent with the current empirical practice of deep stops and slower rates of ascent.
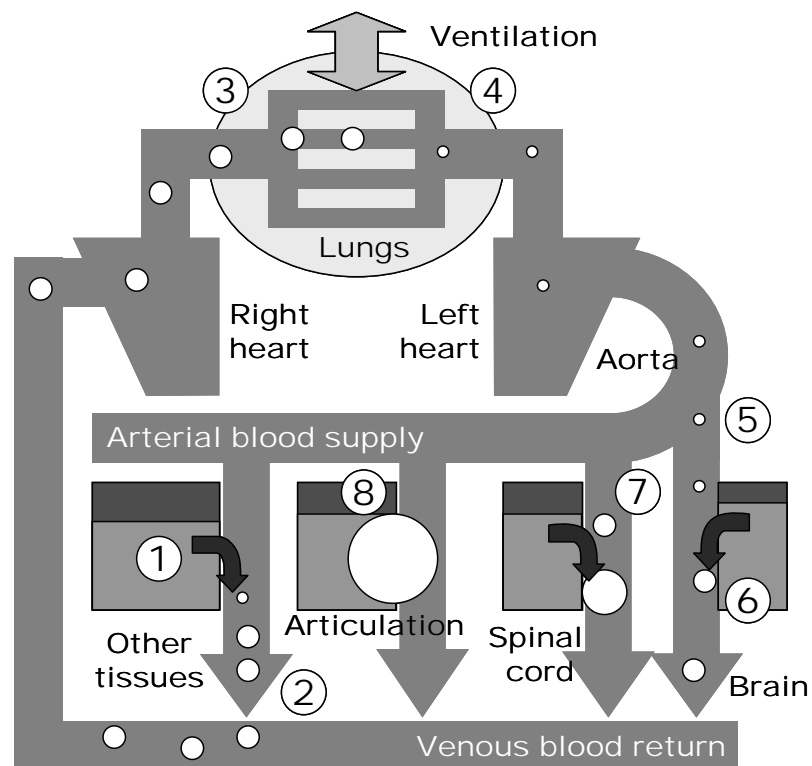

Figure 1. The Arterial Bubble Assumption

1. Diving requires breathing a compressed inert gas that dissolves in the various tissues during the bottom exposure. When the ascent is initiated, the compartments off-load the inert gas as soon as a gradient is created.
2. Bubbles are normally produced in the vascular bed and transported by the venous system to the lung.
3. The lungs work as a filter and stops the bubbles in the capillaries by an effect of diameter. Gas transfer into the alveoli further eliminates the bubbles.
4. The critical issue is the filtering capacity of the lung system. Small bubbles may cross the lung and pass into the arterial system.
5. At the level of aorta cross, the distribution of blood is such that the bubble is likely to reach the brain via the carotids.
6. The brain is a fast tissue and might be in a supersaturated state in the early phase of the decompression. It acts as a gas reservoir and feeds the bubble that starts growing. The bubble may just proceed to the venous side for another cycle. It may also grow in place causing alteration of the blood supply and finally ischemia. The

The rationalization of the arterial bubble assumption requires two models covering two situations (figure 2):

- In the initial phase of decompression, the critical event is the arrival of an arterial bubble in a de-saturating tissue. The site is a neurological tissue. The bubble exchanges gas with the surrounding tissue and the blood. The strategy for a safe rate of ascent is to balance gas exchanges. If the bubble does not exceed a critical radius, it will eventually leave the site without growing. In the other case, it will block the blood circulation and cause ischemia. The bubble radius is the critical parameter. The condition is used to prevent type II neurological symptoms.
- In the last phase of the decompression, the critical event is the presence of a large bubble that has drained a large quantity of dissolved gas from the near-by tissue. The site is an articulation. The strategy for a safe ascent is to prevent any gas phase to grow beyond a critical volume. If the bubble reaches a critical volume, it will have a mechanical effect on the nerve endings causing pain in a tendon. The bubble volume is the critical parameter. The condition is used to prevent type I pain-only symptoms.
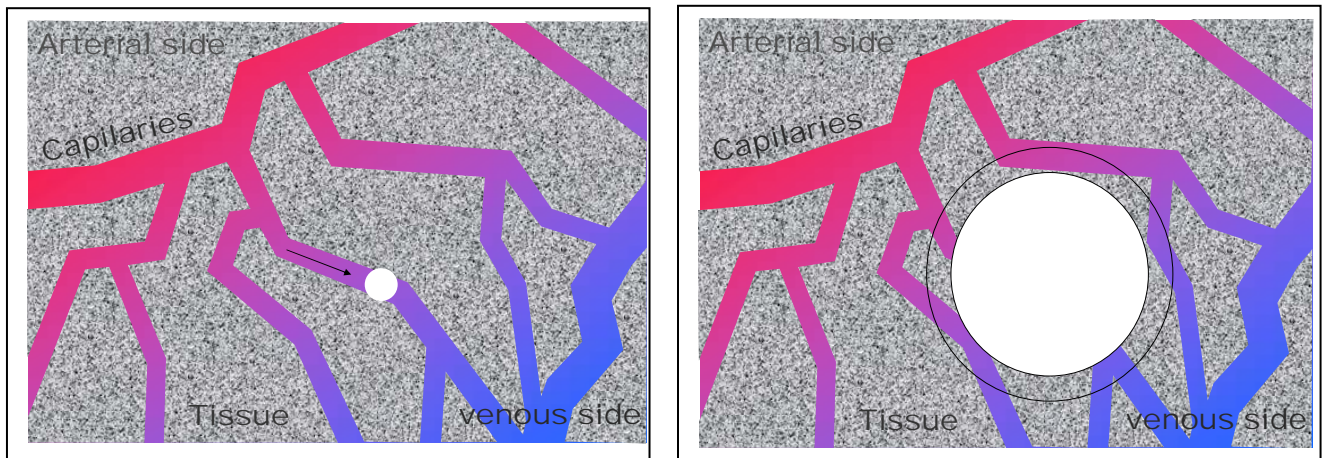

Figure 2. On the left, in the initial phase of the decompression, an arterial bubble enters a tissue capillary net. It exchanges gas with the surrounding tissues and starts growing. If it reaches a critical radius, it might block the blood supply and cause ischemia. On the right, in the last phase of the decompression, a bubble has grown to a large volume using dissolved gas available in the surrounding tissue. Its mechanical action might cause pain.

The critical volume concept was developed by Hennessy and Hempleman (18) who formulated a simple mathematical condition linking the dissolve gas and the safe ascent pressure:

$$Ptis_{gas} \leq aPamb + b$$

Where P_{tis} represents the dissolved gas tension, P_{amb}, the ambient pressure and a,b two coefficients. This linear relationship between dissolved gas and ambient pressure has the same mathematical form as an M value. It suggests that all the Haldanean models (including the US Navy tables, the Bühlmann tables and all the French tables), are just an

expression of the critical volume condition, regardless of the justifications presented by their authors. This has some serious implications on the currently available algorithms.

First, if we admit that dissolved gas models only control large volume bubbles, they only deal with one part of the problem that is the prevention of type I DCS. Effectively, such models work perfectly with saturation diving where type I DCS is the concern (3). They could also work at shallow depths because the initial ascent phase is short. We know that they must be adapted (slower rate, deeper stop, etc) when used with deep bounce diving, where neurological symptoms are the concern. The reason is that they missed the initial part, the bubble growth process and the critical radius assumption.

Second, if we admit that bubble growth models may adequately control the initial part of the decompression, they might miss the final part of the decompression. For instance, the popular VMP algorithm, with its complex thermodynamic study of a bubble population growth, produces decompression profiles with very deep stops. However, close to the surface, stops become shorter than the equivalent Bühlmann model. It is suspected that this algorithm over-emphasizes the initial problem, the bubble radius, but underestimates the second one, the bubble volume.

The truth must lie between the Bühlmann and the VPM algorithms. There must be alternatives.

One possibility consists in modifying the Bühlmann algorithm using gradient factors. It modifies empirically the M value and twists the dive profile to produce the deep stops. The method works beautifully but the problem is the definition of the gradient factors. Of course, because the technique is purely empirical, it has no predictive value. A set of different values must be found for each depth and time component.

Another alternative consists in combining the two issues. We recently developed and published the arterial bubble model or "AB model" (19) that follows the two states of the bubble growth (Appendix 2). The algorithm produce tables with stops deeper than with a classic Bühlmann model but shallower than with the VPM model. The model was fitted with data from the offshore industry, both for air diving and heliox diving. It is being calibrated with trimix diving using deep cave diving and coral diving data. It represents a potential alternative to the exiting ones.

Conclusion

There is an operational pressure to extend bounce diving to 90 m. In this depth range, new methods of intervention are available such as the technical diving configuration or closed-circuit rebreather. For these methods, the most cost-effective mix seems to be trimix, a well validated bottom mixture. However, considerations on decompression safety and work performances may support the use of heliox, especially with rebreathers.

With such improved techniques, the key to safety remains the decompression procedure because past experience with the offshore industry has shown that the DCS incidence rate could be high. Recent development of technical diving has shown,

however, that at least for short time exposures, the tables derived from the Bühlmann algorithm can provide a reasonable level of safety. However, for deeper or longer exposures, new developments are required.

The arterial bubble assumption provides a new vision of DCS mechanisms and proposes different bubble scenarios for the onset of the different symptoms. The concept is based on two critical events: one during the initial phase of the ascent when the size of the bubble is critical to avoid tissue ischemia, the second during the last phase of the ascent when the volume of the bubble is critical to avoid mechanical effects and pain.

The classic Haldanean model using a M-value mathematical formula seems to describe the second scenario, while the bubble growth model such as the VPM algorithm seems to only describe the first one. Decompression modelling now requires a multi-model approach that is illustrated by the recent development of the AB model. It provides the deep stops as in the new bubble-growth algorithms and the traditional end of decompression as in the dissolved gas algorithm.

References

1. Comex diving manual, 1974 edition.
2. Mount, T. 1998. IANTD Trimix Diver. Student manual and workbook. Published by IANTD Inc, Miami, Florida, USA.
3. Imbert, J.P., and M. Bontoux. 1998. Diving data bank: a unique tool for diving procedures development. 20th Annual Offshore Technology Conference, Houston, Texas, 2-5 May 1988.
4. Annexe 1 de l'Arrêté du 22 décembre 1995 relatif aux modalités de formation à la sécurité des marins de certaines entreprises d'armement maritime intervenant en milieu hyperbare. 4 janvier 1996. Publisher : Journal Officiel de la République Française, 26 rue Desaix, 75727, Paris cedex 15, France.
5. Imbert, J.P. and M. Bontoux. 1986. Safety analysis of French 1974 air decompression tables. Undersea and Hyperbaric Medical Society Workshop on Decompression in Surface-based Diving. Tokyo, Japan, 11-12 September 1986.
6. Bühlmann, AA. 1984. Decompression-Decompression Sickness. Berlin: Springer-Verlag.
7. Baker, E.C. 1998. Understanding M-values. Immersed. Vol. 3, No 3.
8. Yount, D.E. and D.C. Hoffman On the use of a bubble formation model to calculate diving tables. Aviat. Space and Environ Med. :57:149-156.
9. Wienke, B.R. 1992. Modeling phase volume constraints under repetitive decompression. Math; Comput. Modeling. Vol. 16, No 3, pp. 109-120.
10. Bergmann, E, Queruel, Durand-Gasselin. 2004. Accidents during Trimix recreational dives. First considering elements. Med. Sub. Hyp. Post congress Meeting Proceeding. Ajaccio, France , 19 September 2004.
11. Imbert, J.P. and M. Bontoux. 1987. A method for introducing new decompression procedures. Proceedings of the Undersea Medical Society Workshop on validation of decompression schedules. Bethesda, Maryland, 13-14 February 1987.

12. Boycott, A.E., G.C. Damant, and J.S. Haldane. 1908. The prevention of compressed-air illness. J. Hygiene, 8, 342-443.
13. Hills, B.A. 1971. Decompression sickness: a fundamental study of surface excursion diving and the selection of limb bends versus CNS symptoms. Aerospace Medicine, Vol. 42, No 8.
14. Hennessy, T.R. 1989. On the site of origin, evolution and effects of decompression microbubbles. Proceeding of the International Symposium on supersaturation and bubble formation in fluids and organisms. Trondheim, Norway, 6-10 June 1989.
15. Balestra, C., P. Germonpre, and A Marroni. 1998. Intrathoracic pressure changes after Valsalva strain and other maneuvers: implication for divers with patent foramen ovale. Undersea Hyperb. Med. 25(3): 171-4.
16. Germonpre, P. et al. 1988. Patent foramen ovale and decompression sickness in sport divers. J. Appl. Physiol. 84(5): 1622-6.
17. Imbert, J.P. 1991. Decompression tables versus decompression procedures: an analysis of decompression sickness using diving data-bases. Proceedings of the XVIIth annual meeting of Diving and Hyperbaric Medicine, Heraklion, Crete, Greece, 20 September-3 October 1991.
18. Hennessy, T.R. and H.V. Hempleman. 1977. An examination of the critical release gas volume concept in decompression sickness. Proc. R. Soc. B179, 299-313.
19. Imbert, J.P. 2004. The arterial bubble model for decompression table calculations. Proceedings of the 30th Annual Meeting of the European Underwater Baromedical Society, Ajaccio, France, 15-17 September 2004.

Appendix 1. History of Trimix Table Development in France

Trimix and heliair are part of our diving culture but the facts and the persons that led to their invention are lost in history. To my knowledge, part of the action took place in France.

In 1963, the French Navy unquestionably designed original trimix tables under the direction of Dr. Lucien Barthélemy. Cdt. Cousteau who commanded the GERS in the 50's (the French Navy diving department) had access to these tables and used them later during several expeditions and in particular during the Britannic dives in Greece to 105 m. The trimix tables left the Navy with Dr. Pierre Cabaroux when he joined the Sogetram, a large commercial diving company in 1970. They were used in conjunction with the semi-closed rebreather FGG III. André Galerne, one of the founders of the Sogetram, took them over to the USA when he left to set up International Underwater Contractors. André Galerne must have further developed these tables as IUC is known to have conducted heavy trimix operations down to 180 m.

The French tables crossed the border for a second time as Dr. Cabaroux went working at the DFVLR, in Germany. DFVLR ran a series of research programs on deep bounce diving in the 70's, that included trimix dives.

Later, the CG Doris Company took over Sogetram and got the trimix tables in that deal. The tables were revised with the help of the French Navy in a version now referred as the "Doris tables". They were later used intensively during a difficult dam repair job in Iran, when the war with Iraq made the helium supply uncertain.

Not far from France, Dr. Zanini in Genova, Italy, developed trimix tables, using surface decompression, for coral divers in Sardinia and in Ustica. The tables arrived in France through the Corsican coral divers who developed a generation of heliair tables that are still in use.

More recently, with the advent of deep cave diving, the Doris trimix tables were revived. In 1982, Jochem Hasemayer, a daring German caver, used trimix tables (apparently self designed) for his 220 m dive at Fontaine de Vaucluse in the south of France. Meanwhile in the USA, Dr. Bill Hamilton used his DCAP model to cut tables for Olivier Isler during his push at the Doux de Coly, in the centre of France.

Finally, with the advent of deco software and dive computers based on the Bühlmann model, trimix tables invaded the technical diving world. It must be remembered, however, that Dr. Bühlmann derived some excellent air tables, some less successful heliox tables, but never edited any trimix tables.

Appendix 2. Definition of the AB Model

Following the scenario of the arterial bubble assumption, the critical case is defined as the arrival of an arterial bubble in a tissue compartment (figure A2.1); it is assumed that:

- The bubble was formed elsewhere. Its growth did not modify the local tissue gas load.
- The bubble is reputed to be small when compared to the tissue gas capacity, at least at the beginning of the decompression process. It does not change the tissue perfusion time response.
- Stuck in place, the bubble exchanges gases with both blood and the adjacent tissue.
- However, the bubble is stable and keeps a critical volume.

Figure A2.1. Definition of the critical case.
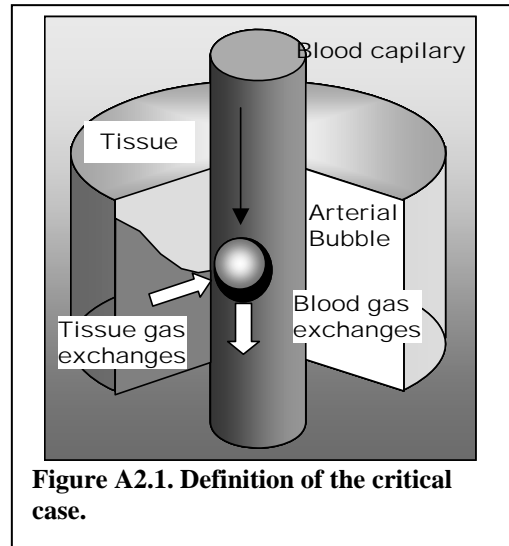
The Tissue Gas Exchange Model

Tissue compartments are just an historical approach and their identification is not important. The use of a series of compartments avoids the difficulty of accurately defining the process of the gas exchanges, whether perfusion, diffusion, or combined perfusion and diffusion. Thus, in this model, the exponential compartments are considered as harmonics of a complex mathematical solution that are control the decompression one after the other. For this reason, we used the general classic expression for compartment gas exchanges:

$$\frac{dPtis_{gas}}{dt} = \frac{0.693}{T}(Pa_{gas} - Ptis_{gas})$$

Where T is the compartment half-time as defined in the perfusion equation, P_a and P_{tis}, the arterial and tissue inert gas tensions.

The modern trend in table computation is to consider all the possible compartments and treat their half-times as a continuous variable. The difficulty then is to express the safe ascent criteria in terms of the compartment half-time. Because modern computers are fast, we decided to treat tissue compartments individually but express them with a geometrical series to remove any subjectivity in their selection. We used the Renard's series, named after a French admiral who faced the standardization of ropes, sails, planks, etc. in navy arsenals, and elegantly solved the problem with a geometric progression

based on a square root of 10. For instance, with 10 values per decade ($\sqrt[10]{10}$), the series gives the following values:

10 - 12.5 – 16 – 20 – 25 – 32 – 40 – 50 – 63 – 80 – 100 minutes

Experimentally, we found that the computation becomes stable when the number of compartments is set in between 15 to 20 values per decade. This way, the description of the tissue gas exchange model only requires defining the boundaries. The fastest compartment obviously corresponds to instant equilibration and does not need to be specified. The slowest compartment is defined as the one used in saturation decompressions. Based on Comex saturation experience, these values were set at 270 minutes for heliox and 360 minutes for nitrox saturation. Finally, the tissue gas exchange model only requires one parameter to be defined, corresponding to the half-time of the slowest compartment.

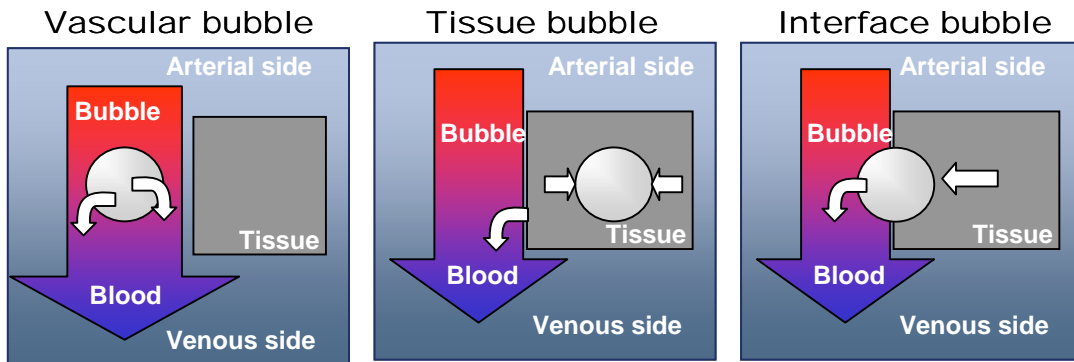## The Bubble Gas Exchange Model

Figure A2.2. Possible bubble gas exchange situations.

To cope with the complexity of the inert gas exchanges in the bubble, we decided to simplify the process by considering two extreme situations (figure A2.2).

In one case, the bubble is purely vascular and remains in place. The blood flows around it and exchanges gas by convection so efficiently that there is no laminar layer and no diffusion delay at the bubble interface. In these conditions, we adopted for the bubble gas exchanges a formula similar to the classic tissue perfusion equation. We further assumed that the blood flow draining the bubble is a small fraction of the tissue perfusion and that the blood leaves the bubble equilibrated with its gas pressure. This permits an arbitrary expression of the quantity of inert gas molecules transiting through the bubble interface into the blood as:

$$\frac{dn, blood_{gas}}{dt} = C \frac{0.693}{T} (Pa_{gas} - Pb_{gas})$$

Where $dn, blood_{gas}$ is the number of molecules of inert gas passed from the bubble into the blood, Pa_{gas} the arterial inert gas tension, Pb_{gas} the bubble inert gas pressure, T the compartment half-time and C a coefficient that accounts for the fraction of the tissue blood perfusion that governs these exchanges, the relative capacity of the bubble to the surrounding tissue, etc.

In the second case, the bubble is purely extravascular. The bubble exchanges gas with the surrounding tissue by diffusion. We used the classic assumption of a linear gradient in a surrounding shell and obtained a second general expression for the number of inert gas molecules diffusing through the bubble interface from the tissue.

$$\frac{dn, tis_{gas}}{dt} = \frac{1}{K}(Ptis_{gas} - Pb_{gas})$$

Where dn,tis_{gas} is the number of molecules of inert gas diffusing from the tissue into the bubble, $Ptis_{gas}$ the tissue inert gas tension, Pb_{gas} the bubble inert gas pressure, K a coefficient that accounts for the diffusibility of the gas, the thickness of the layer, the surface of the bubble, etc.

Finally, we imagined an intermediate situation where the bubble is at the interface between the blood and the tissue and exchanges gas through the two above mechanisms. The importance of the exchange varies with the relative area of the bubble exposed to each medium. The ratio between the two exposed areas of the bubble is called α and varies from 0 to 1. The inert gas mass balance of the bubble becomes:

$$\frac{d(PbVb)}{dt} = R\tau(\alpha \frac{dn, tis_{gas}}{dt} + (1-\alpha)\frac{dn, blood_{gas}}{dt})$$

Where R is the gas constant, τ the absolute temperature and Vb the volume of the bubble.

The Safe Ascent Criteria

The ascent criteria simply seeks the stability of an arterial bubble, with a critical size, stuck at the interface of the blood vessel and exchanging gas with both the blood and the tissue. We translated this statement by specifying that the overall mass balance of the arterial bubble remains unchanged in these conditions:

$$\frac{d(PbVb)}{dt} = Pb\frac{dVb}{dt} + Vb\frac{dPb}{dt} = 0$$

This last condition means that the sum of all the internal gas pressures equals the external ambient pressure plus the stabilization pressures (surface tension, skin elasticity, tissue compliance). This is written as:

$$Pb_{gas} + Pb_{O2} + Pb_{H2O} + Pb_{CO2} \leq Pamb + Pbstab$$

Where Pb_{gas}, Pb_{O2}, Pb_{H2O}, Pb_{CO2} are respectively the pressures of the inert gas, oxygen, water vapor and CO_2 inside the bubble, Pamb the ambient pressure and Pbstab the sum of the various stabilization pressures.

Assuming Pb_{O2} is constant and equal to the tissue oxygen tension and introducing B, a coefficient of obvious definition, we obtained a simpler form of the criteria:

$$Pb_{gas} \leq Pamb + B$$

In these conditions, the total of gas transfers between the bubble and its surroundings are balanced. For each gas, the same amount of molecules enters and leaves the bubble during a unit of time. There is no gas accumulation inside the bubble.

$$(1-\alpha)\frac{dn, blood_{gas}}{dt} = -\alpha\frac{dn, tis_{gas}}{dt}, \text{ and yields:}$$

$$\frac{\alpha}{K}(Ptis_{gas} - Pb_{gas}) = -(1-\alpha).C\frac{0.693}{T}(Pa_{gas} - Pb_{gas})$$

Finally, the two equations above are combined to eliminate Pb_{gas}. After defining another coefficient A, the final expression of the safe ascent criterion becomes:

$$\boxed{Ptis_{gas} \leq (1+\frac{A}{T})(Pamb+B) - \frac{A}{T}Pa_{gas}}$$

This last equation sets the condition for a safe ascent to the next stop according to the initial hypothesis: an arterial bubble exchanging gas with blood and tissue that keeps a critical size during the ascent. It is a function similar to an M-value. With the tissue compartment tension perfusion equation, it permits the classic computation of a decompression stop time. The rate of ascent to the first stop is not part of the model control and is set arbitrarily to 9 m/min. The AB Model-2 provides deeper stops than for a classic decompression model.