Assessing dive profile safety by using A Combined Decompression Model

An empirical approach to decompression modeling

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The last 100 years has seen many mathematical models and empirically developed procedures developed to predict the human body's decompression requirements for ascent after utilizing breathing gases at high ambient pressures.

Decompression 'dissolved gas' models developed to provide safe procedures for military or commercial divers with saturation recompression facilities 'on site', were proven unsuitable for use by recreational divers or self supported 'technical divers' carrying out dives utilizing Air, Nitrox and Helium mixed gases. Subsequently more relevant models were developed for mainstream use.

Decompression researcher J.P Imbert (ref1. 1998) first identified the need for a combined model to better predict safer decompression. This paper proposes a new 'combined' model containing elements representing the decompression limits identified in formally researched 'man-tested' experiments, and attempts to predict safe decompression for all dive exposures and breathing gases. The model also includes additional tissues to accurately predict deep stops plus a rules system to prevent Isobaric Counter Diffusion (ICD) using Trimix buffer gases for decompression.

Why a 'Combined' Decompression Model? The need for such a 'meta model' that takes into account all observed phenomena without triggering decompression sickness is well documented(1). The bulk of all formal 'man tested' research data suggests that such a Combined Decompression Model would likely take the form of a 'neo-Haldanean' tissue matrix of m-values and half-times (2).

An historic trend has been established that new decompression models incorporate progressively more conservative tissue constants. This indicates, that a decompression model combined of the most conservative tissue m-values and half times discovered by all previous man-testing, should be at the 'heart' of any new Combined Model. However, there are still circumstances where a diver using a table based on such a model, could receive a DCI 'hit'

Abnormalities have existed within all current Neo-Haldanean models that require procedural techniques to avoid injury (4). DCI injuries received while well within the non-decompression limits, and more recently, the need for maximum ascent rates while not exceeding any currently identified 'tissue critical tensions', have encouraged the implementation of procedural techniques such as 'safety stops'.

'deep-stops' and hyperoxic Trimix decompression gases are utilized to further lower DCI stress during technical exposures. These techniques both improve diver safety for recreational 'non-decompression diving' and have prevented serious decompression injuries occurring during technical dives (6, 7).

Thus the challenge for a 'Combined Model' is to predict safe decompression for all breathing gas mixtures at all depths. The dive profile generated by the Combined Model should not require additional 'safety stops', 'deep-stops' or other measures to compensate for shortcomings in the model, and furthermore should identify the correct decompression gas choice that avoids counter-diffusing gas complications possible when using Helium mixed gas for 'bottom mix'.

Decompression Model use

Early decompression models evolved from a combination of animal testing and ultimately 'man testing'. The resulting decompression model was then used to determine the divers 'no decompression limit' or the maximum time a diver could safely stay down at a particular depth and ascend directly to the surface without DCI. All decompression models predict that divers exposed underwater for longer than the no decompression limit are required to carry out decompression stops during their ascent to arrive safely at the surface without DCI. The research and 'man testing' necessary to develop such a decompression model could take several years, and hundreds of 'chamber dives'

In the 1980's divers began to use submergible 'dive computers' with embedded Neo-Haldanean decompression models to determine a safe dive profile 'in real time' during the dive.

In the 1990's the availability of inexpensive desk-top computers and decompression software, encouraged technical divers planning dives in the depth range 30-300meters to compute their own 'custom dive profiles' based on individual gas mixtures and decompression gas combinations.

Since each computed dive plan & gas combination is a 'custom profile' that has likely never undergone extensive 'man-testing', undiscovered decompression phenomena generated by this unique profile may still exist and jeopardize the divers safety.

Millions of dives are carried out every year by recreational divers, thus the 'no decompression limits' for air diving are widely known, and may be considered a reliable data set.

Additionally, driven by the need to carry out work on the sea bed during oil exploration, extensive 'man testing' has been carried out to develop decompression profiles for commercial saturation divers down to depths of 700 meters/2,300ft.

In comparison with recreational and commercial diving, there has been comparatively little work carried out to develop a reliable decompression model for technical divers carrying out short duration bounce dives in the 30-300meter/100-1,000ft range.

Thus a computerized 'meta model' that takes into account all depths, breathing gases, descent/ascent rates etc, and correctly predicts the safe dive profile and gas choices for both recreational, technical & saturation diving has still to be developed.

This paper analyses what form such a 'meta-model' will likely take, and further examine the development of such a model that has proven useful in generating the first successful bounce dive profiles for technical divers in the 1,000ft range, that did not generate significant DCI.

Proven decompression models?

'Man tested' models for bounce dives in excess of 100meters/330ft are particularly poorly researched. Most data in this range has been developed with a commercial diving task in mind, and with 'saturation divers' as the tool. It was only 25 years ago, that the French commercial diving company COMEX carried out the then unprecedented 2 hour bottom time 'bounce dive' to 180meters. The depth was not exceptional, but the subsequent decompression of 47 divers who used the table to recompress to the surface in only 48 hours without any DCI incidents, was a world first(1).

Nowadays, self contained tech divers with limited surface support, carrying out all their decompression 'in water' using 'custom dive profiles', carry out dives to twice this depth, and expect to be back on the surface in less than 10 hours (7).

Most recently (late 1990's) the wide availability of high power computers and advanced analytical tools has assisted in the development of new decompression models based on either purely mathematical theories or observations of bubbles in gel samples or fish(9).

Decompression techniques based on 'bubble models' typically require the diver to carry out many small stops during ascent from the bottom, in an attempt to reduce bubble growth. Bubble models postulate that by preventing bubble growth in the early stage of ascent, the final, shallower, decompression stops, may be much shorter than 'man tested' data indicates.

Although bubble models have achieved varying degrees of success for recreational non-decompression dives, and the many short 'deep stops' during ascent are known to lessen decompression stress(3), the proof that subsequent shallower 'long half time' stops may be greatly shortened without creating DCI has yet to be proven by extensive 'man based' testing.

The need for Long Half times

half time (mins)	80	100	120	240	480	640
M-Value (bars)	1.43	1.34	1.34	1.34	1.34	1.34

Much previous work on Neo-Haldanean models have focused creating procedures that correctly predicted the decompression requirements of saturation divers. Saturation divers spend extended periods at depth (often up to 28 days) and are then slowly brought back to the surface at just a few feet per hour. Following extensive problems with commercial divers suffering from DCI in the late 1970's being exposed to dive profiles with apparently insufficient decompression, subsequent research in the 1980's with Doppler bubble detectors used to detect bubbles flowing in the divers blood, revealed the need to add much longer tissue half times to the existing models than were previously thought necessary. The prevention of type IV osteo-necrosis, or bone death, caused by bubbles generated in the bone marrow from blocking tiny capillary vessels in the long bones, required the addition of very long '10 hour' tissue half times.

Note, that saturation divers are decompressed very slowly indeed, often equivalent to an ascent rate of a few feet (1 meter) per hour. This is much slower than would be achieved on a technical dive ascent planned with a 'bubble model' with short 1-2 minute stops added into the ascent, that would supposedly remove the need to carry out long decompression stops in accordance with bubble theory postulates.

Research during the 1970's into the causes of brittle bones in saturation divers has proven that even with the saturation divers ultra slow ascent rate, the diver is still required to carry out slow ,laborious decompression of his 'long half time tissues' or risk debilitating Type IV DCI (osteonecrosis).

Prior to the research by Prof A. Buhlmann research, most dive tables had only a 120min half time as the slowest tissue. Buhlman's research indicated the need for a 640min half time tissue to avoid DCI.

Thus long half time tissue compartments should be a key feature in any decompression model that attempts to predict a safe dive profile for all dive exposures.

For recreational (non-deco) diving only, research has proven that long tissue half times (longer than 60mins) may be all but ignored accept in special circumstances (5).

But for technical(decompression) diving and saturation diving, it is essential that the decompression model either has long half time tissues or in the case of 'bubble models' that generate the custom dive profiles using alternative mathematical techniques, the dive profile must generate a profile that mimics their existence in accordance with the 'man tested' evidence.

Generating Deep stops within the Meta model.

These were accidentally discovered by a fish collector making a short break during his ascent towards the surface in order to equalize the swim bladders of live specimens (3). The initially anecdotal evidence of feeling better after performing these short 'non formal' deep stops, was rapidly confirmed by the many divers who included them in their ascent profile, even though existing neo-Haldanean models did not require them.

From personal experience deep stops seem to reduce the profound 'dive tiredness' experienced around 90mins after long deco dives performed without deep stops. The post dive fatigue normally goes away within a few hours without any need for recompression treatment and is not present on dives which include deep stops. Plainly the carrying out of the deep stops is reducing the 'decompression stress' my body is subjected to during the dive, and this suggests something is missing within the existing neo-Haldanean models.

Early decompression models did not specify ascent rate for divers carrying out non decompression dives, apart from the speed a diver can swim towards the surface(4). Modern research into micro bubbles flowing in divers bloodstreams using Doppler bubble detectors reveals that divers should not exceed an ascent rate of around 10 meters per minute. This again points to something missing within the existing neo-Haldanean decompression models.

Intuitively, all these effects (such as the need for deep stops & the need for an ascent rate limit of 10meters per minute) indicate that current neo Haldanean tissue models need additional tissue compartments with carefully chosen m-values'(2) to generate both 'deep stops', and the requirement to ascend slowly towards the surface.

An example of the additional fast tissues that would correct the neo-Haldanean decompression model results are given below.

half time (mins)	1.1	1.8	3	5
M-Value (bars)	2	2.72	2.94	2.72

Gas switching techniques to prevent Isobaric Counter Diffusion ICD or Narcotic shock.

Divers breathing Helium Trimix as a bottom mix have long been concerned about phenomena called 'narcotic shock' which generally occurs during the ascent portion of a dive when switching from Trimix onto Nitrox during accelerated decompression. A number of high profile divers carrying out extreme dives (6, 7) have suffered severe Type III DCI (vestibular decompression sickness) following Trimix→Nitrox gas switches. The resulting inner ear barotrauma or 'vestibular hit', results in a physical injury to the inner ear. The diver subsequently looses all sense of balance and is not able to hold 'in water decompression stops' without the assistance of support divers. As an unfortunate side effect, the dizziness brought on by the injury causes the diver to vomit every few breaths making the divers remaining in water decompression time a very uncomfortable experience.

By examining the many troublesome profiles that have resulted in type III DCS (#Ref:-troublesome ICD profiles), it is possible to deduce a rules system that both identifies the root causes of this distressing injury and by the use of Narcosis buffering decompression gases prevent it's occurrence during future Trimix dives.

ICD Event triggers

Analysis of many Trimix dives involving type III DCI reveals that any dive that contains the following events must use a 'Buffer Trimix' deco gas switches to prevent injury.

1. A dive deep enough to generate formal decompression stops that are deep enough to require the use of Trimix
2. A dive that includes condition #1 plus Trimix being breathed on one deco stop with a switch to Nitrox being breathed at the next shallower deco stop.
3. Any Trimix dive that involves a gas switch generating a jump in the partial pressure of nitrogen that creates a step increase in 'END' that exceeds the distance from the current depth to the 'ascent ceiling'

Preventing type III DCI (ICD)

1. Any dive that generates formal decompression stops using Trimix, the diver must not switch directly to any gas that causes an increase in the ppN2.
2. Rule #1 indicates that Trimix dives that require formal Trimix decompression stops must continue the use of Helium within the breathing mixture of the decompression gases so as to prevent a ppN2 jump.

Combined Decompression Model Tissue Matrix

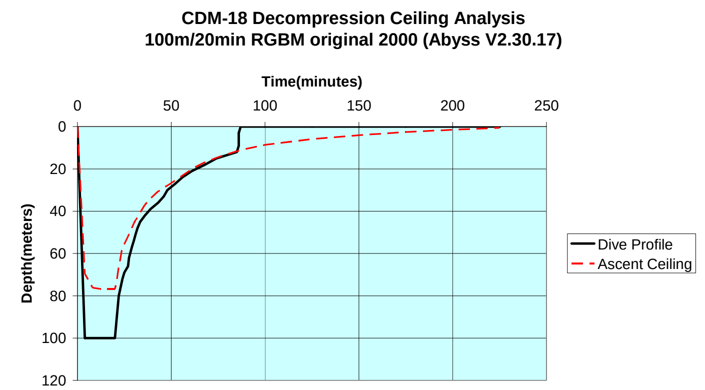
The tissue matrix for the Combined Decompression model is derived from 3 empirical sources.

Half time range	**Basis of M-values choice**
1.1 - 1.8 minute half times	empirically derived M-values chosen to generate deep stops and 10m/minute ascent rate
3.0 - 30minute half times	Approximates COMEX Helium tissue M-values
40 - 640 minute half times	Approximates DCAP 1988 Tissue M-values

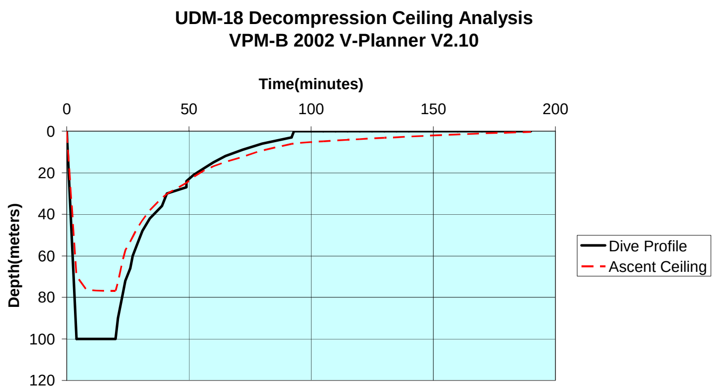
half time(mins)	**1.1**	**1.8**	**3**	**4**	**5**	**7**	**8**	**10**	**12.5**	**15**	**18.5**	**20**	**25**	**27**	**30**	**38.3**	**40**	**50**	**55**	**60**
Model Name																				
DSAT RDP-14 1987					3			2.5				2.02			1.81		1.69			1.56
COMEX			2.94		2.72	2.54		2.38		2.2		2.04			1.82		1.68	1.61		1.58
Buhlmann-B 1990				3.21	2.95		2.52		2.24		2.02			1.89		1.74			1.64	
DCAP 1988					3.15			2.44					1.88						1.47	
USN-Workman 1965					3.15			2.66				2.18					1.69			
Deep Stop tissues	2	2.72																		
UDM-18 M-VALUES	**2**	**2.72**	**2.94**		**2.72**	**2.54**		**2.38**		**2.2**		**2**			**1.82**		**1.66**	**1.6**		**1.5**

half time(mins)	**77**	**80**	**95**	**100**	**109**	**120**	**146**	**160**	**187**	**200**	**240**	**285**	**360**	**383**	**480**	**520**	**640**	**670**
Model Name																		
DSAT RDP-14 1987		1.49		1.45		1.42				1.36	1.35		1.33		1.32			
COMEX		1.56		1.55		1.54												
Buhlmann-B 1990	1.57				1.51		1.46		1.42		1.38				1.33		1.26	
DCAP 1988			1.37				1.35			1.34		1.33		1.33		1.33		1.32
USN-Workman 1965		1.63				1.57		1.54		1.54	1.51							
Deep Stop tissues																		
UDM-18 M-VALUES		**1.43**		**1.34**		**1.34**					**1.34**				**1.34**		**1.34**	

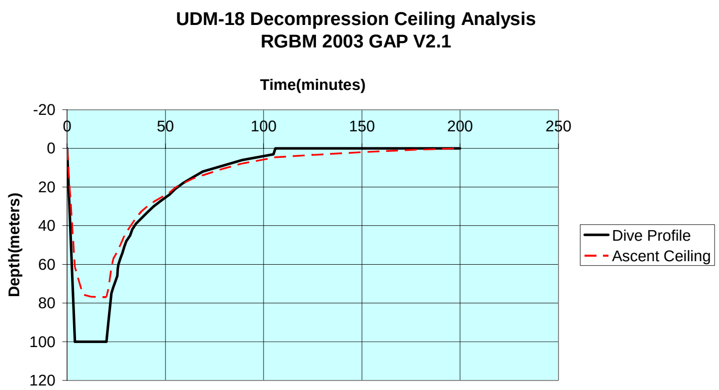
Comparisons of dive profiles against the CDM-18 analysis model



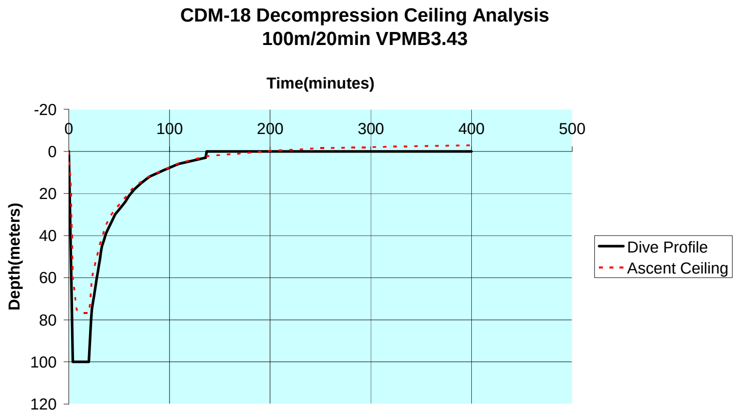
1. Trimix dive to 100meters/330ft 20mins bottom time. Overall decompression insufficient in this early version of RGBM. The diver will likely experience Type I DCI shortly after the dive



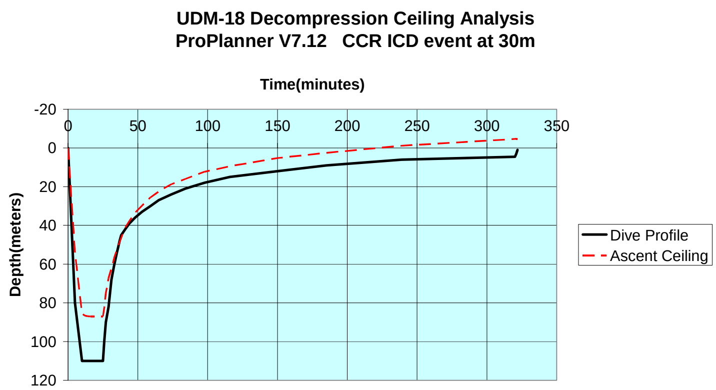
2. Trimix Dive to 100meters/330ft 20mins bottom time. Again, overall decompression insufficient as generated by this VPM-B model, although moderately longer than profile(1), the diver will likely experience type I DCI shortly after the dive



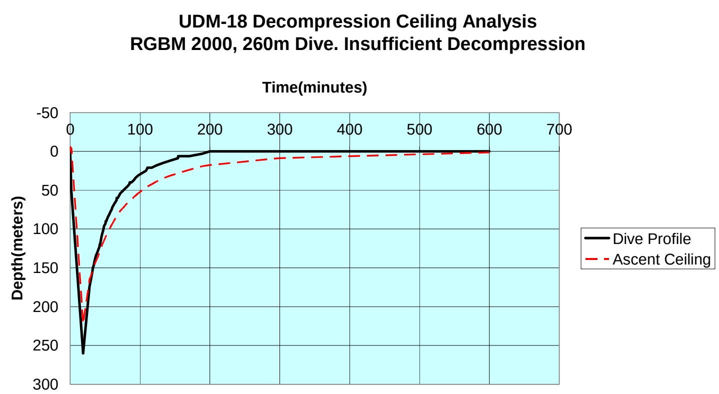
3. A more recent version of the RGBM model predicting decompression for the same Trimix 100meter/330ft 20min bottom time dive shows a more tolerable decompression profile. The diver will likely not exhibit immediate DCI symptoms; although repeated use will likely result in type IV DCI (osteo-necrosis) due to surfacing with insufficiently decompressed long half time tissues.



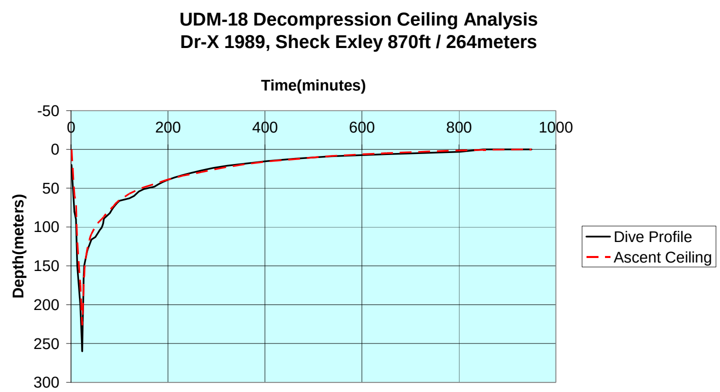
4. Current evolution of the VPM-B model. The ascent prediction of this 2004 version of this bubble model shows a profile for this 100m/330ft 20min dive to be far longer than previous versions. The ascent profile is closer to that proven to be tolerable by 'man based' testing. The next evolution will likely add additional shallow water stop time.



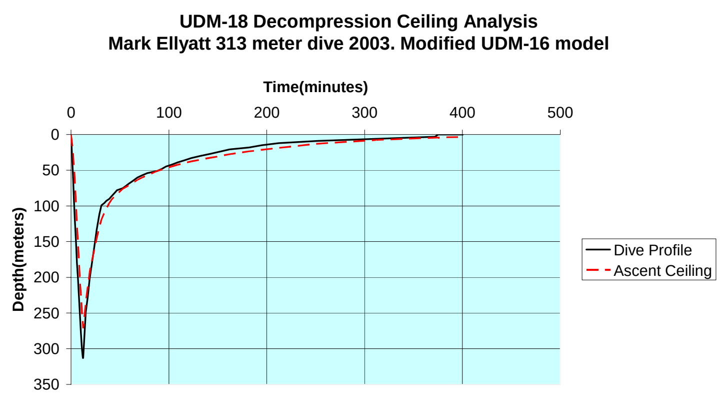
5. Trimix dive to 110m/365ft for 25mins. The profile dived generates sufficient decompression to avoid predictable type 1 & type 2 DCI. However, the diver switched from Trimix to Air at 30meters causing a step increase in ppN2 which triggered Type- III DCI (see below)



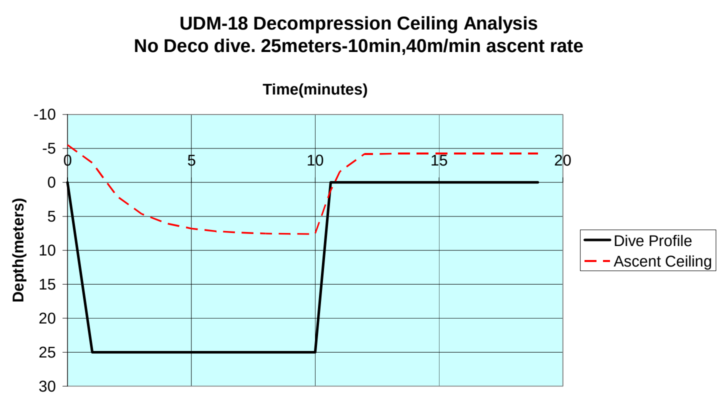
6. Trimix exploration bounce dive to 260meters/860ft. This recent profile generated by an early RGBM model clearly shows insufficient decompression. The diver experienced type I, II & III decompression prior to surfacing and will likely suffer type IV DCI as a result of the extremely short decompression profile followed.



7. The profile generated in 1989 for a dive to the same depth as example (6) predicts sufficient decompression to avoid type I & II DCI, although problems occurred caused by the rapid ascent rates and insufficient deeper stops.



8. Trimix exploration bounce dive to 313meters/1033ft. This profile provided adequate decompression avoiding significant type 1 & II DCI. Subsequent analysis suggests additional decompression necessary in the shallow phase of the dive to remain entirely symptom free.



9. A recreational 'air' dive of only 10mins at 25 meters/83ft depth. Analysis reveals ascent ceilings present even during this non-decompression dive, which if violated by a rapid ascent could cause DCI.

Note:- The typical NDL for a 25 meter dive is 29minutes (PADI/DSAT)

Conclusions

The analysis of decompression profiles using the Combined Decompression Model(CDM) correctly identifies abnormalities in dive profiles that are proven to cause DCI, and leads to the following important observations:-

1. Existing Neo-Haldanean tissue models require additional faster tissue compartments to control ascent speed and generate deeper formal decompression stops.
2. Previous anecdotal evidence concerning the beneficial effects of 'deep stops' suggests the need for quicker, more sensitive tissue compartments within all decompression models to prevent sub-clinical DCI
3. The existence of faster 'deep-stop' tissues suggests an explanation for the existence of DCI injuries occurring to divers within existing recreational dive table No Decompression limits.
4. The bubble model hypothesis that by carrying out many 'bubble controlling' deep stops early in the ascent profile, negates the requirement to carry out long duration 'slow tissue' shallow water stops, is not confirmed by man testing evidence.
5. Dive profile comparisons (1) & (3) reveal evolution within 'bubble models' so as to increase their previous short duration 'long tissue stops' to be more in line with 'man tested data'
6. The use of Trimix buffer gases during dives requiring formal Trimix decompression stops where recommended by the CDM algorithm, prevents type III DCI (Isobaric counter diffusion).

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Acronyms & Technical terms

Bottom Mix; the gas breathed during the bottom deepest portion of the dive.
Buffer Trimix; A breathing mixture with helium content chosen to prevent a jump in ppN2 when switching from a previous breathing gas.
COMEX; The French commercial diving company based in Marseille, France. Currently one of the few places still able to carry out research into decompression model design for extremely deep Helium mixed gas dives. COMEX currently holds the world record for the deepest ever chamber dive (using hydreliox) to 701meters/2292ft
Counter Diffusion; A poorly understood phenomena that had previously been thought responsible for causing minor DCI 'hits' such as skin-bends amongst technical divers utilizing Helium Trimix as a breathing mix but utilizing Argon as a dry suit inflation gas. Historically suspected as causing problems only when the diver switched from Nitrox to Trimix. Now understood to cause type III DCI (inner ear vestibular bends) in divers when switching from Trimix to Nitrox during the decompression phase of deep technical dives.
DCI; Decompression Illness. Commonly referred to as 'the bends'
Deep stops; non formal decompression stops carried out to make the diver 'feel better' after the dive. Initially discovered by Dr Richard Pyle. Anecdotal evidence suggests they reduce decompression stress by reducing the micro bubbles that cause migraine like head-aches during the dive and extreme tiredness following the dive.
DrX; A computer based dive profile generator based on neo Haldanean principles
Formal Decompression stop; A stop during the ascent period of a dive predicted by the decompression model that is the diver is required to prevent
GAP; The Gas Absorption Program – A computer based dive profile table generator
Nitrox; a mixture of Oxygen and Nitrogen, with the Oxygen content being generally greater than 21%.
Neo-Haldanean; a dive table model that attempts to predict correct decompression based on principles proposed by the eminent Scottish scientist John Scott. Haldane in 1908,
Non-decompression diving; dives carried out of a short duration that permit the diver to ascend direct to the surface at any time without risk of suffering DCI.
Onsite recompression facilities; a recompression chamber, and support personnel, located at the dive site, to provide immediate re-compression treatment for divers suffering un-earned DCI.
ProPlanner; A computer based dive profile generator based on neo Haldanean principles
RGBM; Reduced Gradient Bubble Model. An example of a bubble model for predicting decompression profiles
Safety stop; a non formal decompression stop carried out by the diver in the hope of reducing the chance of suffering from DCI. The decompression model doesn't call for this stop, but by doing it; researchers have discovered that non-clinical bubble levels are reduced drastically.
Saturation diver; A commercial diver who lives underwater at pressure. Most countries limit the time a commercial diver is allowed to stay at depth to around 28 days. The body is able to with withstand the pressurized environment for longer, but man is poorly adapted to being enclosed with other divers in a close environment for longer than this period of time without exhibiting psychological problems.
Tech Divers; scuba divers carrying out dives in excess of the no-decompression limits and carrying more than one tank or one gas mixture. Tech divers generally use accelerated decompression gases such as Nitrox or pure oxygen to reduce their decompression obligation.
Tissue critical tensions; The maximum difference allowed between the dissolved inert gas partial pressure and the current ambient pressure. Exceeding the critical tension (often expressed as an m-value') causes an unacceptable risk of DCI
Trimix; A deep diving 'bottom mix' containing Oxygen, Helium & nitrogen. The oxygen content is generally less than 21%. The Helium is added to the breathing mix to lessen Nitrogen narcosis and reduce the Oxygen ppO2.
Un-earned-DCI; a diver suffers a DCI hit, although he has followed the recommendations of the decompression model used.
Combined Decompression Model; A decompression model that attempts to combine all previous observed physiological phenomena and anecdotal evidence of DCI into one 'meta-model'(2) that predicts the correct decompression profile for all breathable gases.
VPM; Variable Permeability Model. An example of a bubble model for predicting decompression profiles.

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