CHAPTER

5

DECOMPRESSION ALGORITHMS

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Decompression algorithms are sets of instructions designed to minimize the risk of decompression sickness following the reduction of ambient pressure, whether from surfacing from a dive, flying to high altitudes, or performing space walks. In this chapter, an overview of the variety of decompression algorithms is presented, which includes decompression tables, dive computer models, and decompression software packages that are utilized in recreational diving.

The chapter also reviews factors influencing a diver's susceptibility to DCS, and explores the question: "Is there a need to add gender as a variable to decompression algorithms?"

DECOMPRESSION ALGORITHMS

Since the first description of DCS in caisson workers in the 1800s, many techniques have been developed to prevent its occurrence. In diving, these algorithms range from the urban myth that a diver cannot get bent on a single dive using a single 72 cubic foot (2039 liters) standard steel tank, to decompression table rules prescribing the use of the next deeper depth and/or next longer time entry if a dive is cold and/or arduous, to sophisticated two-phase "bubble" decompression models programmed into some of today's dive computers and decompression software packages. However, it should be remembered that no matter how simple or complex the decompression algorithm is, it does not "know" what is going on in a diver's body.

VARIATIONS IN DECOMPRESSION ALGORITHM

Decompression Tables

During the last century, decompression tables were the primary decompression algorithms utilized. In the early 1900s, J.S. Haldane was contracted by the British Admiralty to solve the problem of decompression sickness in Royal Navy divers. Using data obtained in experiments on goats, Haldane[1] developed a basic model which approximated the diver's "body" with five theoretical "tissue" compartments. In the model, each of these compartments were exposed to the ambient nitrogen pressure (Figure 1a), absorbed and eliminated nitrogen at a specific rate (half-time), and was permitted a certain level of supersaturation (nitrogen pressure in excess of the total ambient pressure). Since there is no transfer of gas between compartments, this model is referred to as a "parallel" model. Using this model, Haldane calculated a set of decompression tables and performed human subject tests on a few of the schedules before presenting them to the British Admiralty. The adoption of these decompression tables had the desired effect of reducing the incidence of DCS in the Royal Navy divers.

Many subsequent decompression models adjusted the number, half-times, and supersaturation limits of the compartments while maintaining the underlying parallel structure of Haldane's work.[2-6] These models are categorized as Haldanian models.

Other groups used different underlying models to calculate decompression requirements. The British Royal Navy Physiological Laboratory's decompression model[7] approximated the diver as a tissue slab

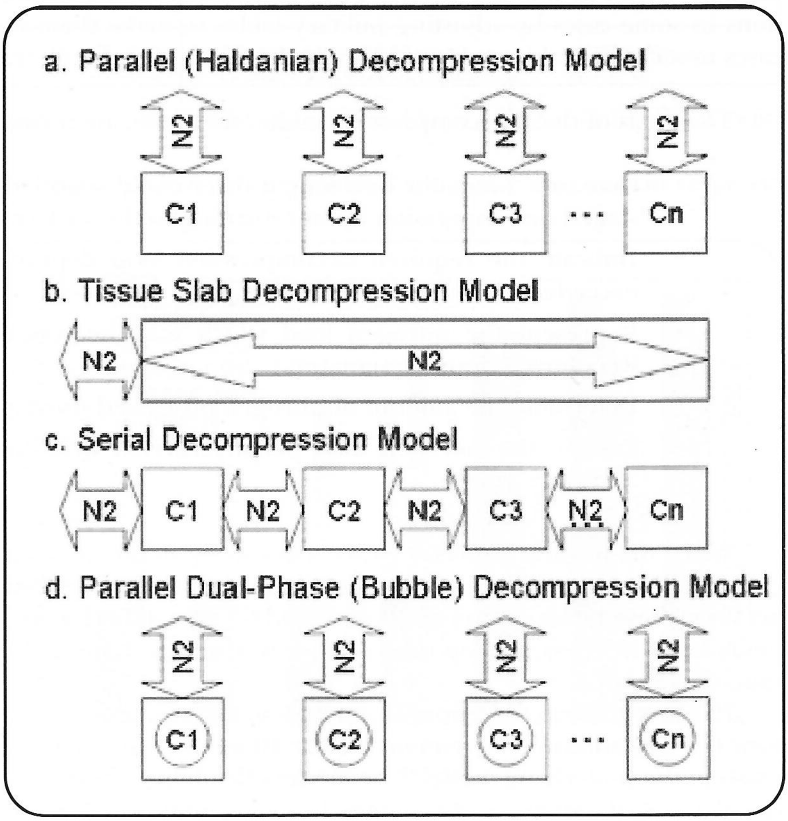

Figure 1. Various decompression model configurations.

(Figure 1b). Its limits were based on the area under the nitrogen pressure curve calculated to exist in the slab. A version of this tissue slab model was used in the calculation of the 1988 British Sub Aqua Club decompression tables.[8] The Canadian Defense and Civil Institute for Environmental Medicine (DCIEM) model[9] used a "series" of attached compartments which allowed ambient nitrogen to flow into one compartment and from there into a series of compartments (Figure 1c). Each of these compartments had a half-time and supersaturation limit assigned to them.

In the previous models, nitrogen was assumed to remain dissolved in the compartments as long as supersaturation limits were not exceeded. In reality, nitrogen bubbles do form and to some degree are tolerated. A family of models called dual-phase look at both dissolved as well as gaseous nitrogen (bubbles) phases present in the system,[10-13] and work at keeping bubble growth below critical limits (Figure 1d). One of these dual-phase models, VVAL18, is the basis of the most recent version of the U.S. Navy decompression tables.[14]

No matter the underlying theory or model, the vast majority of decompression algorithms are deterministic, indicating only if a dive profile falls within or exceeds the limits of the model. However, there also exists a class of probabilistic decompression algorithms which will calculate an estimated risk of DCS associated with a dive profile.[15-17]

Many of these models and tables were developed and validated for military divers and their operational needs. When recreational diving began to emerge in the 1950s, these military decompression tables were incorporated into their practices. As the years progressed, the applicability of military tables to the general recreational diving population was questioned. Doppler bubble studies[18-21] showed that dives to the U.S. Navy no-stop limits generated asymptomatic venous gas emboli (VGE) in the majority of test subjects. This lead to recommendations for the reductions of these limits to reduce the risk of bubble formation, especially in the recreational diving community which is not as mission driven as military divers. The recreational diving community adopted these recommendations in some cases by adjusting military tables to make them more conservative,[22-24] while in other cases models and tables were specifically developed for the recreational diving community.[5,6]

The goals of these decompression tables, no matter their origin, were to:

- Give time limits for how long a diver could spend at a specific depth without requiring staged decompression upon returning to the surface (No-Stop Limits)
- Indicate the required decompression stop depths and times if No-Stop limits were exceeded
- Represent the nitrogen load which was theoretically built up during the dive (e.g. Repetitive Group Designators)
- Determine the amount of nitrogen off-gassed during a surface interval, and
- Present the nitrogen load penalty carried over from a previous dive (e.g. Residual Nitrogen Time)

When the no-stop limits for a dive to a specific depth are compared, the different models used to generate decompression tables produce a range of No-Stop Times (Table 1). The greatest variation between these tables occurs at 30 msw and 33 msw (100 fsw and 110 fsw), where the DCIEM table limits have 40% less no-stop time relative to the U.S. Navy 1957 limits (25 min. vs. 15 min. and 20 min. vs. 12 min.).

In order to keep decompression tables to a reasonable size, depth increments of approximately 3 msw (10 fsw) and time increments of 5 or 10 minutes are generally used, reducing the flexibility that exists in the underlying model. The model's flexibility is further reduced by assumptions made in the calculations of repetitive dive times by using only a subset of the model. The U.S. Navy 1957 Repetitive Dive Tables uses only the 120-min. half-time compartment in the Calculation of Repetitive Group Designators (RGD) and Residual Nitrogen Time (RNT),[3] where Buhlmann's Tables uses the

TABLE I. COMPARISON OF NO-STOP LIMITS FROM VARIOUS DECOMPRESSION TABLES

	Decompression Table / No-Stop Limits				
Depth	U.S. Navy 1957	U.S. Navy 2008	PADI RDP	BSAC 88	DCIEM
9 msw (30 fsw)	∞	371 min.	no entry	243 min.	300 min.
12 msw (40 fsw)	200 min.	163 min.	140 min.	122 min.	175 min.
15 msw (50 fsw)	100 min.	92 min.	80 min.	74 min.	75 min
18 msw (60 fsw)	60 min.	60 min.	55 min.	51 min.	50 min.
21 msw (70 fsw)	50 min.	48 min.	40 min.	37 min.	35 min.
24 msw (80 fsw)	40 min.	39 min.	30 min.	30 min.	25 min.
27 msw (90 fsw)	30 min.	30 min.	25 min.	24 min.	20 min.
30 msw (100 fsw)	25 min.	25 min.	20 min.	20 min.	15 min.
33 msw (110 fsw)	20 min.	20 min.	16 min.	17 min.	12 min.
36 msw (120 fsw)	15 min.	15 min.	13 min.	14 min.	10 min.
39 msw (130 fsw)	10 min.	10 min.	10 min.	13 min.	8 min.

80 minute. compartment from his model,[4] and the PADI Recreational Dive Planner (RDP) uses its 60 minute. compartment.[6]

The different methods used to handle repetitive diving leads to additional variation in response to a simple repetitive dive series. Figure 2 shows the allowable No-Stop times from five different decompression tables for a repetitive dive to 18 msw (60 fsw) following a 30 minute dive to 24 msw (80 fsw), at various surface intervals. With a two hour surface interval the allowable no-stop time at 18 msw (60 fsw) ranges from 15 minutes on the BSAC '88 tables to 44 minutes on the PADI Recreational Dive Planner (RDP). As will be discussed later, even though the difference in allowable no-stop times is significant, the difference in DCS risk between the different table results may or may not be significant.

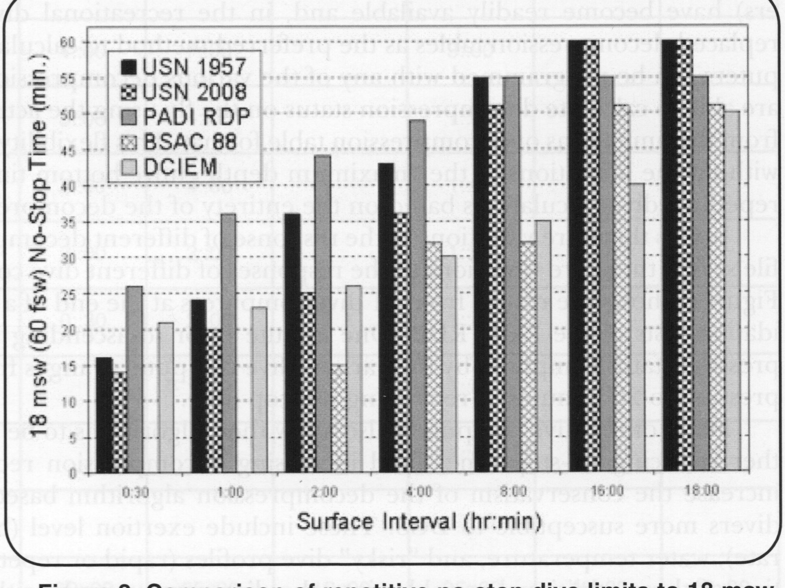

Figure 2. Comparison of repetitive no-stop dive limits to 18 msw (60 fsw) at various surface intervals following a 30 min. dive to 24 msw (80 fsw).

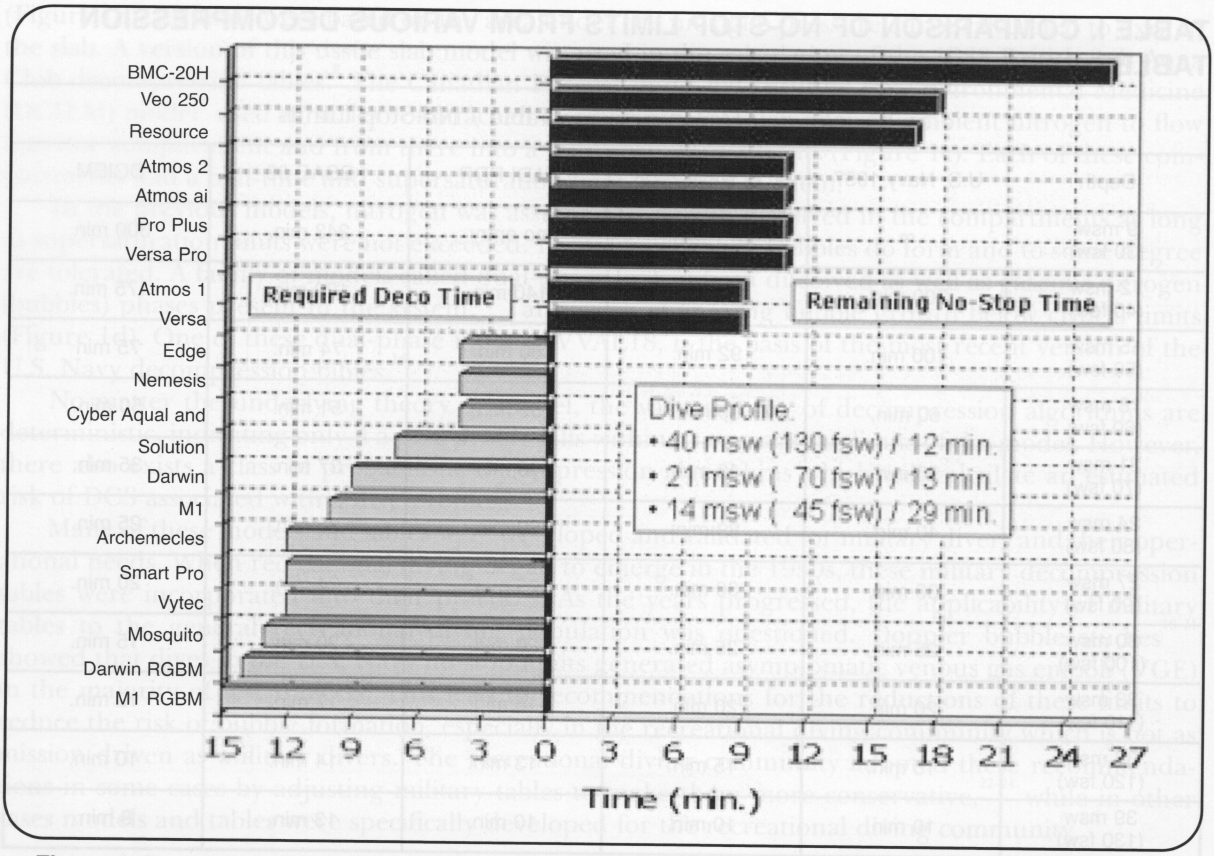

Figure 3. Response of 21 dive computers to a multi-level dive profile (one minute prior to ascent from 14 msw [45 fsw]).

Dive Computers

Since the early 1980s, diver carried microprocessor based decompression devices (dive computers) have become readily available and, in the recreational diving communities, have essentially replaced decompression tables as the preferred method to calculate decompression status. Dive computers can be programmed with any of the various decompression models previously discussed and are able to calculate decompression status on the fly using the actual dive profiles, thus freeing divers from the limitations of decompression table format. This flexibility allows multi-level dive calculations, without the limitations of the "maximum depth entire bottom time" rule that is found in tables and repetitive dive calculations based on the entirety of the decompression model.

Just as there are variations in the response of different decompression tables to the same dive profile series, there are variations in the responses of different dive computer decompression algorithms. Figure 3 shows the results from 21 dive computers at the end of a multi-level dive taken from the validation tests of the PADI RDP.[6] One minute prior to ascending from 14 msw (45 fsw), the decompression status computed by the various dive computers ranges from 15 minutes of required decompression to 26 minutes of remaining no-stop time.[25]

Many of the dive computers also allow their algorithms to be set at more conservative levels, further reducing no-stop times (and increasing decompression requirements). Some dive computers increase the conservatism of the decompression algorithm based on other factors known to make divers more susceptible to DCS. These include exertion level (based on air consumption or pulse rate), water temperature, and "risky" dive profiles (rapid or repetitive ascents).[26] With the incorporation of these additional variables into the dive computer algorithm, some divers may get the erroneous impression that dive computers "know" what is going on in their bodies.

Decompression Software Packages

Another method for calculating decompression requirements, especially in the technical diving community, is the decompression software package. These programs are used to generate a set of decompression tables for a specific dive profile based on the gasses and equipment used. Just as with decompression tables and dive computers, decompression software packages will generate a wide range of decompression requirements for the same dive profile. Table 2 shows the decompression requirements for a 50 msw (165 fsw) dive with a 15 minute bottom time generated by four different decompression software packages set at their most liberal and more conservative settings. Total decompression times range from 16 minutes to 55 minutes.

While the decompression models and tables developed for military and commercial use have had human subject validation tests done prior to their release, there have been very few cases[6,27,28] of validation tests done for recreational diving decompression tables, dive computers, and software packages. Therefore, those divers who are pushing the limits of dive computers and decompression software packages outside of any tested profiles are essentially performing human subject tests upon themselves.

TABLE II. DECOMPRESSION REQUIREMENTS FOR AN AIR DIVE TO 50 MSW (165 FSW) FOR 15 MINUTES USING VARIOUS DECOMPRESSION SOFTWARE PACKAGES AT DIFFERENT CONSERVATIVE SETTINGS

	50 msw (165 fsw) / 15 min. Air Decompression Schedule (min:sec)							
	Pro-Planner v7.12C		V-Planner v3.84 (VPM-B)		Deco Planner v2.0.49		Abyss-2001 v2.3.0.17	
Deco Stop Depth	SF0 MB0	SF50 MB100	Cons 0	Cons 5	GF 100/100	GF 5/80	Abyss 100	Abyss 150
3 msw (10 fsw)	8::00	24::00	11::00	21::00	7::00	13::00	7::00	10::00
6 msw (20 fsw)	5::00	9::00	6::00	11::00	3::00	6::00	3::00	5::00
9 msw (30 fsw)	1::00	6::00	4::00	7::00		3::00		
12 msw (40 fsw)		1::00	3::00	4::00		1::00		
15 msw (50 fsw)			2::00	4::00		1::00		
18 msw (60 fsw)			2::00	2::00		1::00		
21 msw (70 fsw)		1::00	0::30	2::00		1::00		
24 msw (80 fsw)				1::10		1::00		
27 msw (90 fsw)						1::00		
30 msw (100 fsw)		1::00				1::00		
Total Deco Time	19::00	47::00	32::00	55::00	16::00	35::00	16::00	12::00

Susceptibility and DCS Risk

When a dive is compared to a deterministic decompression algorithm, it either falls within the limits of the algorithm or exceeds the limits. There is no middle ground; one moment the diver is fine according the algorithm, and the next they have "fallen off the precipice." If everybody responded identically to decompression situations, then everyone would develop DCS as soon as this calculated limit was exceeded. In the real world this set limit does not exist. Risk of DCS follows a standard dose-response pattern. Figure 4 shows four hypothetical dose-response curves comparing the risk of DCS to an increasing diving dose (increasing depth and/or bottom time). In Figure 4, curve "a" represents the view of deterministic decompression algorithms, showing 0% risk up to a limit and then 100% risk once the limit is exceeded. Curve "b" in Figure 4 shows a standard dose-response which, hypothetically, represents the general response of a large diving population (and risks that probabilistic decompression algorithms would calculate). Initially, the probability of someone developing DCS is null, but as the dose increases some of the more susceptible divers will start to develop DCS. Further increasing the dose will place more and more divers at risk until even the most resistant divers succumb to DCS (100% risk). Curve "c" in Figure 4 represents a subset of divers who, because of individual or exposure conditions, are more susceptible to DCS where curve "d" represents a subset of those who are more resilient.

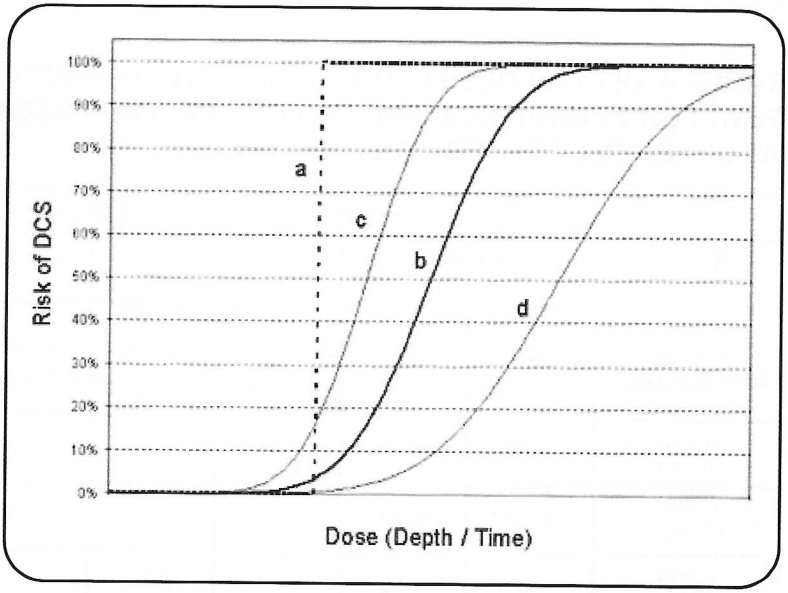

Figure 4. DCS risk dose response curves.

The results calculated by the various deterministic decompression algorithms represent a range of "doses" along the dose-response curve. The question is, where along the curve, do these results fall? If they fell along the high risk end of the curve the algorithm would be rejected early on due to an unacceptable incidence of DCS. Therefore, most algorithms should fall at the lower risk end of the dose response curve (Figure 5). If the different decompression algorithms produced results within the range designated as "A" in Figure 5, then pushing the most liberal algorithm to its limit would produce an insignificant risk of DCS even in the most susceptible diver. Since some divers do develop DCS while diving within the limits of the various decompression algorithms it can be concluded that the "A" range does not represent reality. Conversely, if the different decompression algorithms produced results in the "C" range in Figure 5 the number of divers developing DCS would be much greater than what is currently seen. Range "B" in Figure 5 shows a 0% risk for the most conservative algorithms and a low, but non-zero risk for the most liberal algorithms in the general population. However, with the more liberal algorithms a susceptible diver could be at a significantly higher risk of DCS.

Susceptibility to DCS not only varies from individual to individual, but it also varies within a single individual depending upon their physiological state at any given time. Francis & Mitchell[29] and Vann[30] have summarized the major individual and environmental factors known, and hypothesized, to affect decompression sickness susceptibility including dive profile, ascent rate, exercise, temperature, hydration, age, fitness, and gender. Studies dealing with two of these factors, temperature and exercise, show that their influence on DCS susceptibility can be significant.

Depending upon the intensity and timing, exercise can result either in an increase or decrease in an individual's susceptibility to DCS. While at depth, exercise can increase the risk of DCS. Vann[31] reported that in one study, 40 minutes of resting decompression was sufficient to decompress resting divers from a 60 minute dive to 30 msw (100 fsw); however, divers who had been working at a light level of exertion at depth required 90 minutes of resting decompression, while those at a moderate level of exertion required 115 minutes of resting decompression to achieve comparable results. Vann also quotes other studies which have shown "...that air schedules which were safe for resting divers produced 20-30% decompression sickness incidences in working divers," and "...divers doing light work while breathing helium-oxygen required 20-40% more decompression time than did resting divers."

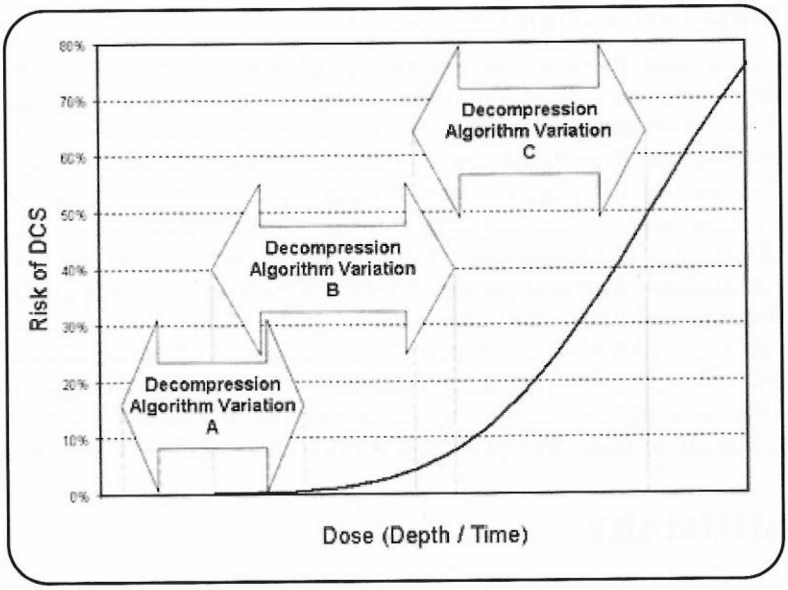

Figure 5. Range of decompression algorithm variation vs. DCS risk.

Exercise during and following decompression can also alter DCS susceptibility. Van Der Aue[32] showed that divers who performed moderate exercise for two hours following decompression developed more cases of DCS than those who had bed rest for the same two hours. Other studies report that mild to moderate exercise during decompression decreases decompression stress. Jankowski[33] reported that "Moderate intermittent exercise during decompression apparently reduces the amount of Doppler-detectable VGE after diving." Also, a study by Dujić[34] indicates "...that a mild, underwater swimming during a 3-min decompression period reduces postdive gas bubbles formation."

One of the more interesting effects of exercise on decompression stress that has been looked at in the last decade is the impact of heavy aerobic exercise the day prior to diving. Wisløff[35] reported that a single bout of high intensity aerobic exercise 20 hours prior to diving dramatically increased the survival, and decreased bubble formation, in rats exposed to a 700 kPa / 45 minute dive. In a cross-over study Dujić[36] showed that a single 40 minute bout of exercise in man 24 hours prior to diving significantly reduced bubble formation.

The primary influence of exercise on decompression stress is thought to be caused by changes in blood flow.[31] Additional exercise influence is hypothesized to involve micronuci generation[37] and endothelial conditioning.[36]

In looking at the effects of temperature on decompression stress, Vann[31] states that "As with exercise, temperature appears to exert its influence on decompression through changes in blood flow..." Divers who are cold during the dive and warm during decompression have a lower decompression stress than divers who are warm during the dive and cold during decompression. Gerth[38] reported that in the case where divers were cold during the dive and warm during decompression there was only once case of DCS out of 84 divers from a 46 msw (150 fsw) dive for 60 minutes, compared to five cases in twenty divers who were cold during the dive and decompression with a decompression schedule which was nearly 2.5 times longer. Their paper stated that "...effects of a 10 °C increase in TW,D [decompression water temperature] were comparable to effects of halving BT [bottom time]."

What Dive Computers "Know"

As seen above, environmental and individual variations can have major influence on DCS susceptibility. Most dive computers are relatively simple devices with a limited view of the world, blind to many of these variables. In the calculation of decompression status from their decompression algorithms, the majority of dive computers only use depth and time as their input variables. Although they may have access to water temperature, rapid ascent indicators, recordings of higher risk dive profiles, and air consumption rates to estimate exertion levels, the majority of the decompression algorithms in dive computers do not use these variables to make adjustments to the decompression calculations. As stated previously, there are some dive computers which do make adjustments to their decompression calculations based on these additional variables. However, there are variables which can impact DCS susceptibility which even these more sophisticated dive computers are ignorant of, such as the diver's physical condition, hydration level, body composition, age, limb positioning, etc. Divers should be aware of the limitations of dive computer "senses" and can always add extra conservatism to their dive profiles if they consider themselves to be at a higher risk on any dive.

SUMMARY

Should gender be added as a variable to decompression algorithms in an attempt to get their calculations to better "fit" an individual? There is still a question as to a whether a significant difference in DCS susceptibility exists between males and females. Within the female population, preliminary evidence points toward a difference in susceptibility to DCS at different times in the menstrual cycle, and if oral contraceptives are used.[39,40] If a gender variable were to be added, would it need to be accompanied by oral contraceptive and phase of menstrual cycle variables? How much difference the addition of these variables would make to the decompression calculations of any decompression algorithm would depend upon how much weight they would be given. Even if a gender difference did exist, it is likely that the magnitude of the difference would be overshadowed by the variability in DCS susceptibility due to other physiological and environmental conditions and the variability that exists in the different decompression algorithms, thus making the inclusion of gender variables unnecessary.

The most important component of any decompression algorithm is not the decompression model, table, dive computer, or software package. It is the diver. Awareness of the individual and environmental factors which can alter susceptibility to DCS and understanding the limitations of all decompression devices allows the diver to make their own decisions on how to plan and execute their dive to minimize the risks of DCS.

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KEY POINTS

- The differences between "dose" (dive profile) in the available observational data makes it impossible to draw firm conclusions regarding the effect of gender on DCS or VGE among scuba divers.

- Well-controlled NASA altitude DCS studies did not demonstrate that female gender is a risk factor for altitude decompression DCS.

- After exercise PB, the incidence of VGE (including Grade IV VGE) was the same for males and females.

- After resting PB, the incidence of VGE was lower for women, suggesting that women responded more favorably to resting PB than men.

THE MENSTRUAL CYCLE AND DCS: A REVIEW OF THE LITERATURE

Key Points

1. Few hypo or hyperbaric studies have focused specifically on the relationship of DCI risk and time of the menstrual cycle.
2. Despite diverse study conditions and methodologies, results of published literature (Table 1) have consistently found a relationship between the risk of DCI (from both hyperbaric and hypobaric exposures) and the point in the menstrual cycle.
3. The relationship between DCI and the menstrual cycle is particularly evident in women who are not taking oral contraceptives (OCPs). The differing results noted among women taking OCPs may be due, in part, to weaknesses in study design or analysis such as assuming a 28 day cycle, normalising OCP data, small numbers, or incomplete data.
4. The risk of DCI appears to be greatest in the first week of the menstrual cycle, falling to the lowest risk in week three.
5. The mechanism by which the risk of DCI varies across the menstrual cycle is not known but hormonal fluctuations may be a possible reason.

.......AND FINALLY

As we went to press on this book at the close of 2009, *Diver Magazine*, London, UK, published a survey which looked at attitudes between men and women in diving (see Chapter 22). One male respondent indicated surprise that in 2009, gender questions remained an issue. However, males still greatly outnumber females in diving activities, both recreational and professional. Yet, it appears that female divers are less likely to die in diving accidents, less likely to engage in risky behaviours, and overall, appear no more at risk for DCS, AGE, VGE, oxygen toxicity or nitrogen narcosis than male divers. The menstrual cycle does, however, appear to alter DCS risk, but even so, women are still at no greater risk of altitude or diving DCS than males. Women respond slightly differently to altitude pre-breathe, but are in fact, less likely to have altitude induced venous gas emboli. While women do exhibit differences in cold response and certain aspects of exercise physiology, these differences are less related to gender than overall fitness. The female anatomy has created specific challenges for the altered pressure environment, particularly in regards to urine collection. Overcoming these challenges proved useful for both males and females in space and aviation situations. The effect of diving on the unborn child remains an open question, leaving pregnancy as perhaps the only condition unique to women which contraindicates diving. It seems that this text represents a rather long discussion of the ways in which men and women are NOT different in the altered pressure environment. Nevertheless, this book was necessary to address the perception that men and women differ in significant ways. Perhaps these questions persist because, as the Talmud says, "We do not see things as they are. We see them as we are."

Caroline & Marguerite