● Original Article

Dive Tables, and Dive Computers, and Decompression Safety

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本論は，今日の減圧表およびダイブコンピュータの安全の検討であり，こうした減圧アルゴリズムの原理を検討し，減圧停止不要時間の差異について明らかにする試みである。潜水時間については1993年の合衆国海軍（U.S.Navy）アルゴリズムを用いて予想できうる減圧症（DCS）罹患の確率を比較する。また，安全性とは減圧障害の確率と重篤度で定義できる。確率の概念をよりわかりやすいものにするために，水深18mへの減圧停止不要潜水を評価する。最後に，減圧症の罹患率の予想が確定できないことを述べ，この不確定性を解消するための研究について論述する。

This paper discusses the safety of today's dive tables and dive computers. The principles of their decompression algorithms are reviewed, and differences in their no-stop dive times are illustrated. The dive times are compared with the corresponding probabilities of decompression sickness (DCS) estimated by the 1993 U.S. Navy algorithm, and safety is defined in terms of the probability and severity of decompression injury. To place the concept of probability in a more familiar context, the probabilities of no-stop dives to 60 fsw are estimated. Finally, the uncertainty of DCS probability estimates is pointed out, and studies for resolving this uncertainty are mentioned.

The Haldane Decompression Algorithm

Decompression sickness occurs less frequently today and with less severity than at the beginning of the 20th Century. The reason for the improvement is the unique theory proposed by John Scott Haldane and tested by the British Royal Navy from 1905-7 (Admiralty Report 1907).

Paul Bert (1878) had observed that animals developed many of the same signs as did humans after decompression from high pressure. He noted that these signs were often associated with nitrogen bubbles in blood and tissue, and this suggested to him that bubbles might be the cause. Haldane argued that a diver's tissues absorbed nitrogen progressively while at depth as the arterial blood carried dissolved gas from the lungs to the tissues. Upon decompression, some excess nitrogen could be tolerated safely, but too much caused bubbles to form and decompression sickness to occur.

Haldane believed that nitrogen absorption would be rapid at the start of a dive but would gradually slow as the nitrogen tension in tissue approached the nitrogen partial pressure in the lungs. When these were equal, he said the diver was saturated. Since the tissue capillaries are close together, Haldane reasoned that arterial nitrogen diffused into and equilibrated completely with tissue and venous blood.

Haldane showed that tissues could be

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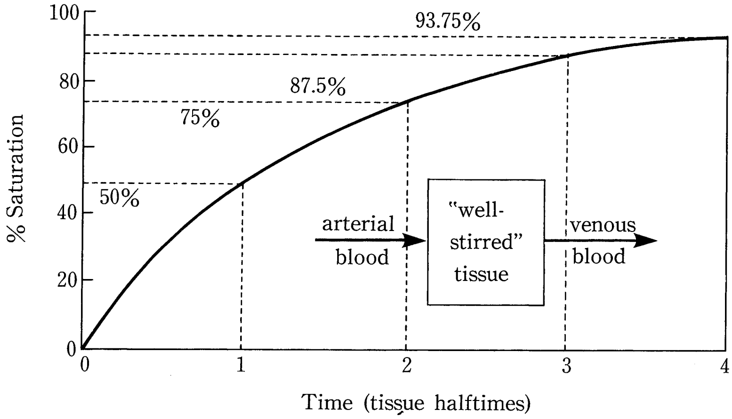

Fig.1 The absorption of inert gas as a function of time in units of tissue half-time.
A half-time defines the rate of inert gas exchange.

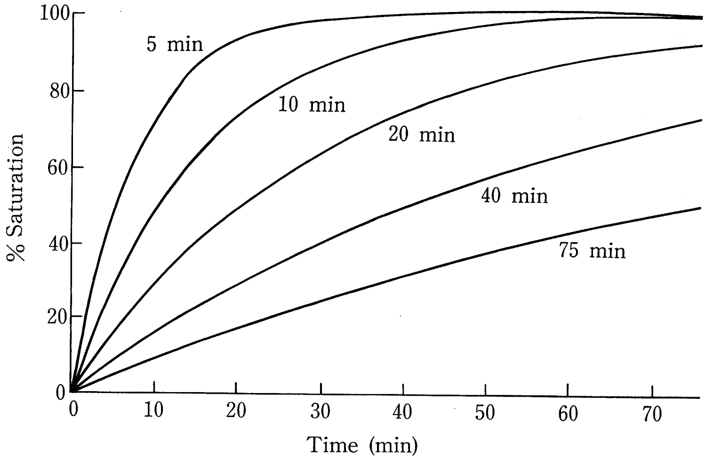

Fig.2 Nitrogen exchange in the human body as defined by J.S. Haldane's five parallel tissue model.
The tissue half-times are indicated in minutes.

characterized by half-times that defined their rates of saturation or desaturation such that the difference between arterial and tissue (or venous) nitrogen tensions was reduced by half with each passing half-time (**Fig.1**). Thus, a tissue would be 50% saturated (or desaturated) in one half-time, 75% saturated in two half-times, 87.5% saturated in three half-times, and so on until saturation or desaturation were effectively complete after six half-

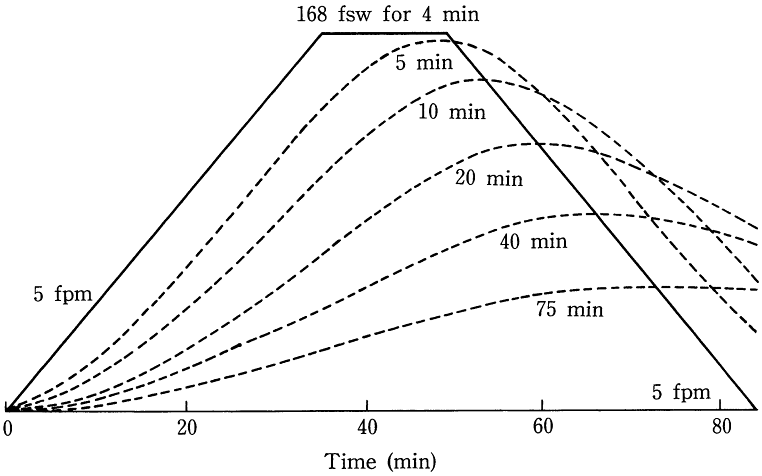

Fig.3 Nitrogen uptake and elimination from the five Haldane tissues during a 4 minute dive to 168 fsw.
Ascent and descent are at 5 fpm.

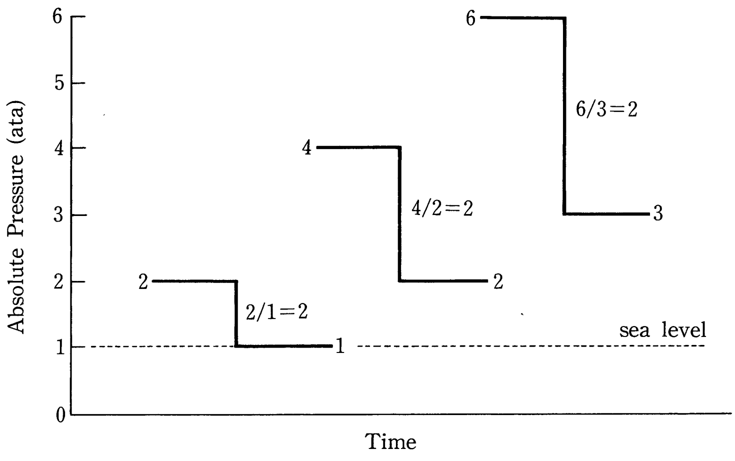

Fig.4 Origin of Haldane's 2 : 1 pressure ratio rule.
Goats were exposed for two hours at various pressures prior to decompression to lower pressure. Decompression sickness was avoided as long as the absolute pressure after decompression was greater than half the absolute pressure before decompression.

times.

Haldane postulated that body tissues have different perfusion rates that could be represented by half-times of 5, 10, 20, 40, and 75 min. Tissues with shorter half-times saturated (or desaturated) faster than those with longer

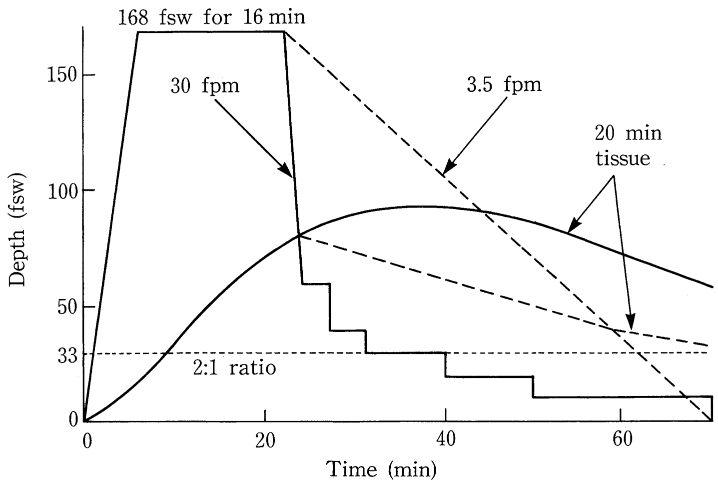

Fig.5 Theoretical comparison of slow uniform ascent and stage decompression.
The nitrogen tension in the 20 min tissue is higher after uniform ascent than after stage decompression. Other tissues are omitted for clarity.

half-times (**Fig.2**). The 75 min tissue saturated in about 7.5 hrs (six half-times). This was the time at which he believed the entire body would reach equilibrium with atmospheric nitrogen after a change in pressure.

The behavior of Haldane's five tissue model is illustrated in **Fig.3** for a 4 min dive on air to 168 fsw with descent and ascent at 5 fpm. To simplify calculations, Haldane assumed the DCS potential of nitrogen and oxygen were identical. The 5 min tissue was nearly saturated at the end of the bottom time and began to desaturate immediately on ascent. The slower tissues were still absorbing nitrogen during initial ascent.

Haldane believed that shorter dives were safe because not enough nitrogen was absorbed to cause bubble formation, but he did not know how much nitrogen could be tolerated safely. He solved this problem by exposing goats to high pressure for two hours followed by direct decompression to a lower pressure. (He thought goats would be saturated in two hours.) Finding that decompression was safe from two to one atmosphere, from four to two atmospheres, and from six to three atmospheres (**Fig.4**), he concluded that bubbles would not form so long as the ratio of the tissue gas tension to the final absolute pressure did not exceed 2:1. Noting that caisson workers also were symptom-free when decompressed from two to one atmosphere, he assumed that the 2:1 ratio was safe for humans as well as for goats.

These ideas led Haldane to conclude that the recommended practice of slow uniform ascent was both dangerous and inefficient, and he proposed an alternative method he called stage decompression. In stage decompression, a rapid initial ascent at 30 fpm was followed by increasingly long stages or stops as the diver approached the surface. **Fig.5**

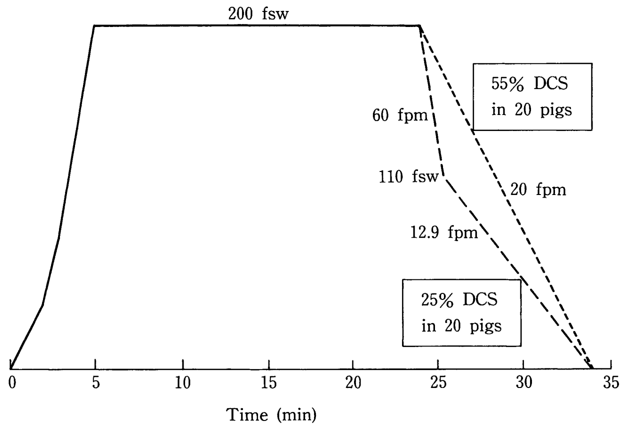

Fig.6 Experimental comparison of rapid and slow initial ascent rates using pigs (Broome 1996).

compares stage decompression with uniform ascent at 3.5 fpm for a 16 min dive to 168 fsw. Nitrogen exchange in the 20 min tissue is shown for both methods of ascent. (The other tissues are omitted for clarity.) With stage decompression, rapid initial ascent avoided additional nitrogen uptake that occurred with slow uniform ascent. The stages were chosen so that the 2 : 1 pressure ratio was never exceeded in any tissue. Stage decompression allowed the diver to surface with a 2 : 1 ratio in the 20 min tissue while with uniform ascent, the ratio was 3 : 1.

A recent study with pigs has confirmed the danger of too slow an initial ascent rate for certain dives (Broome 1996). After a 25 minute exposure at 200 fsw, pigs were decompressed either at a linear rate of 20 fpm or at a two-phase rate of 60 fpm to 110 fsw and 12.9 fpm from 110 fsw to the surface (**Fig.6**). The decompression time was the same for both ascents. With the slower initial rate, the incidence of serious DCS was 55% in 20 pigs while the faster initial rate resulted in a 25% incidence in 20 pigs. This is consistent with the Haldane theory of Fig.5, but similar results might not necessarily apply for all dives.

Haldane published two tables of stage decompression schedules. The first table was for dives as deep as 204 fsw with decompression times of up to 30 min. This table proved very successful, virtually eliminating decompression sickness for short dives, but with experience appeared to have deeper and longer stops than needed. This is illustrated in **Fig.7** for a 40 min dive to 100 fsw with decompression according to Haldane and to the present U.S. Navy schedules. The first stop of the Haldane schedule is at 30 fsw while that of the U.S. Navy schedule is at 10 fsw. The total stop times are 15 min for the U.S. Navy schedule and 30 min for the Haldane schedule.

Haldane's second table was for dives with bottom times longer than one hour and more than 30 min of decompression. **Fig.8** shows the Haldane and Navy schedules for a 120

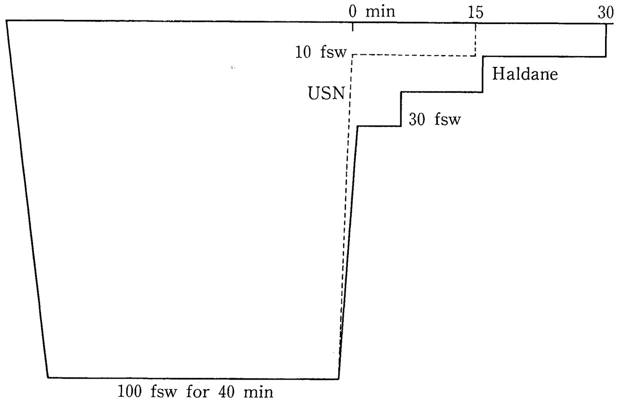

Fig.7 A decompression schedule from Haldane's Table I.
Schedules from Table I have deeper first stops and more decompression than corresponding USN schedules (Admiralty Report 1907).

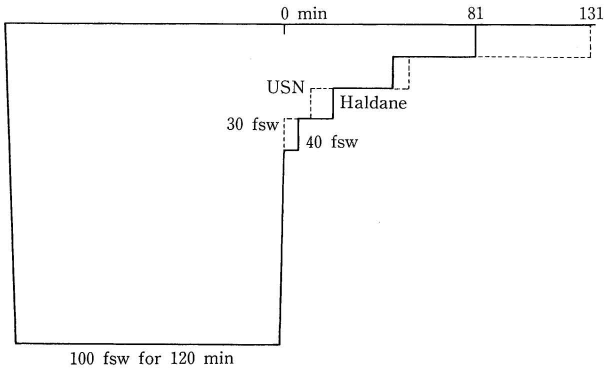

Fig.8 A decompression schedule from Haldane's Table II.
Schedules from Table II have deeper first stops but less decompression than corresponding USN schedules.

min dive at 100 fsw. The first Haldane stop is at 40 fsw while the first U.S. Navy stop is at 30 fsw. The Haldane schedule is 81 min long while the U.S. Navy schedule is 131 min. The schedules of Haldane's second table were too short to prevent decompression sickness.

The tissue half-times and pressure reduction ratios of Haldane's original model evolved with experience and the search for safe and efficient decompression (Hempleman 1993). Some of these changes are summarized in **Fig.9**. The tissue half-times appear on the x-axis and the corresponding pressure ratios on the y-axis. Haldane's original 2 : 1 ratio in the five tissues with 5-75 min half-times appear as a straight line. Later workers

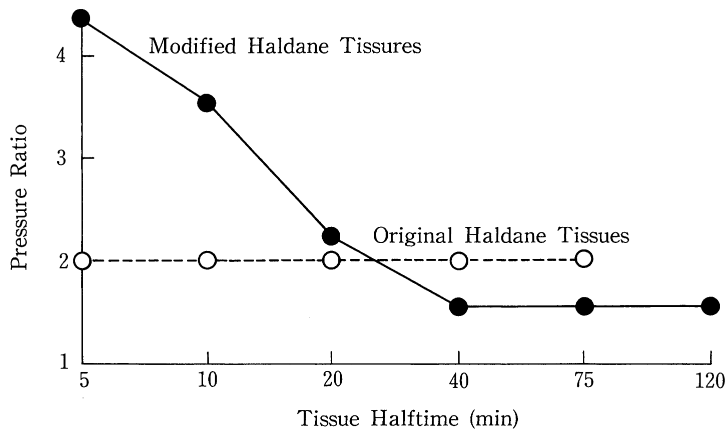

Fig.9 Allowable pressure ratios in the original and modified Haldane tissues (Hempleman 1993).

proposed higher ratios in the faster tissues although the definition of a tissue ratio was changed (see below). They pointed out that higher ratios in fast tissues would eliminate unnecessary deep stops and reduce the total stop time for short dives. For long dives, a 120 min half-time tissue was added to provide additional decompression time. Such changes eventually led to the present U.S. Navy schedules shown in Figs. 7 and 8 for which serious sickness is rare compared to diving in the Haldane era.

Other Decompression Models

Haldane established decompression modeling as a process requiring mathematical descriptions of inert gas kinetics and safe ascent criteria, and this has been the basis of practically all subsequent decompression models. Present dive computers and the Standard Air Decompression Tables in the U.S. Navy Diving Manual (referred to below as the 1956 USN Tables) use decompression algorithms that are derivatives of Haldane's original model. The principal differences are the number of tissues, their half-times, and the treatment of excess inert gas in the ascent criteria.

Haldane's original formulation of the 2 : 1 ratio included oxygen as well as nitrogen. For an air dive, this can be expressed as

$$R_{Haldane} = P_{tN2}/0.79/P_B$$

where P_{tN2} is the tissue nitrogen tension and P_B is the barometric pressure at the next decompression stop. Subsequent workers (Fig.9) omitted the oxygen assuming, in effect, that it was fully metabolized

$$R = P_{tN2}/P_B$$

To allow greater flexibility in adjusting decompression schedules in response to DCS incidents, Workman introduced the "M-value," or maximum allowable P_{tN2}, before ascent to the next stop is permitted. M-values were expressed in fsw units for convenience. The relationship between an M-value and a tissue ratio is

$$\text{M-value (fsw)} = R^* \ (D+33 \text{ fsw})$$

where D is the depth of the next stop in fsw. **Table 1** shows the equivalence between tissue ratios and M-values (Brylske 1995). **Table 2** shows how M-values are applied in 10 fsw

Table 1 Equivalence of Haldane tissue ratios, modified tissue ratios, and M-values (Brylske 1995).

	Tissue Halftime (min)					
	5	10	20	40	80	120
Handane Tissue Ratio	4.00	3.40	2.75	2.22	2.00	1.96
Modified Tissue Raito	3.15	2.67	2.18	1.76	1.58	1.55
M-Value	104′	88′	72′	58′	52′	51′

Table 2 M-value table for a current decompression model.

Safe Ascent	Permissible Tissue Tensions Tissue Halftime (min)								
Depth	5	10	20	40	80	120	160	200	240
10	120	98	78	56	48	45	44	44	43
20	130	108	88	66	58	55	54	54	53
30	140	118	98	76	68	65	64	64	63
40	150	128	108	86	78	75	74	74	73
50	160	138	118	96	88	85	84	84	83
…	…	…	…	…	…	…	…	…	…
90	200	178	158	136	128	125	124	124	123

increments for each tissue of a current decompression model.

Another measure of excess inert gas is the supersaturation (ΔP) which is defined as the difference between the tissue nitrogen tension and the barometric pressure at the next stop

$$\Delta P = (P_{tN2} - P_B) = P_B{}^* \ (R-1)$$

Buehlmann's version of the Haldane model, which is used by many European dive computers, has a different method for describing tissue ratios. The British Royal Navy Tables, the BSAC Tables, and the DCIEM Tables differ from Haldane in their handling of inert gas kinetics, but each uses a measure of supersaturation as an ascent criterion. The Royal Navy and BSAC Tables assume that gas kinetics are governed by diffusion in a slab of tissue rather than by perfusion in parallel tissue compartments. Inert gas kinetics in the DCIEM Tables are based on series rather than parallel tissue compartments.

Until recently, ascent criteria have been deterministic meaning that dives are classified as "safe" or "unsafe" according to whether some measure of the supersaturation exceeds

Table 3 Single no-stop exposure limits for six dive tables and five dive computers (Lewis and Shreeves 1990).
Computers and tables are ordered by the 50 fsw dive time.

	No-Stop Time (min) at Depth (fsw)				
Computer	50′	60′	80′	100′	130′
93 USN Tables	93	64	38	27	18
56 USN Tables	100	60	40	25	10
RN Tables	85	60	30	20	11
DSAT Tables	80	55	30	20	10
DCIEM Tables	75	50	20	10	5
BSAC Tables	74	51	30	20	13
EDGE/SkDip	73	52	31	20	10
DataMaster	70	51	29	19	10
Datascan2	65	49	30	19	5
Aladin	62	45	23	15	7
Monitor	61	45	23	15	9

Table 4 Repetitive Dive Profile #1. No-stop bottom times for a two-dive profile as specified by six dive tables and five dive computers (Lewis and Shreeves 1990).
The first dive is to 55 fsw, the surface interval between dives is 57 minutes. The second dive is to 55 fsw. Computers and tables are ordered by the second dive time.

Computer/Table	1st Dive	2nd Dive	PDCS*
Edge/SkinDip	62min	45min	3.2%
Aladin	51	41	3.2%
DataMaster	61	39	3.2%
Monitor	51	35	2.9%
DSAT Tables	54	26	2.7%
DCIEM Tables	50	23	2.5%
93 USN Tables	75	17	3.2%
56 USN Tables	60	8	2.3%
Datascan II	57	5	2.1%
RN Tables	60	0	1.9%
BSAC Tables	51	0	1.9%

*by USN 93 algorithm

Table 5 Repetitive Dive Profile #2. No-stop bottom times for a two-dive profile as specified by six dive tables and five dive computers (Lewis and Shreeves 1990).
The first dive is to 130 fsw, the surface interval between dives is 43 minutes. The second dive is to 90 fsw. Computers and tables are ordered by the second dive time.

Computer/Table	1st Dive	2nd Dive	PDCS*
Edge/SkinDip	10min	23min	3.2%
Aladin	7	19	2.5%
Monitor	9	17	2.6%
DataMaster	10	16	2.7%
DSAT Tables	10	16	2.7%
Datascan II	5	14	2.4%
DCIEM Table	8	12	2.1%
56 USN Tables	10	10	2.2%
92 USN Tables	15	4	3.3%
BSAC Tables	13	0	1.9%
RN Tables	11	0	1.7%

*by USN 93 algorithm

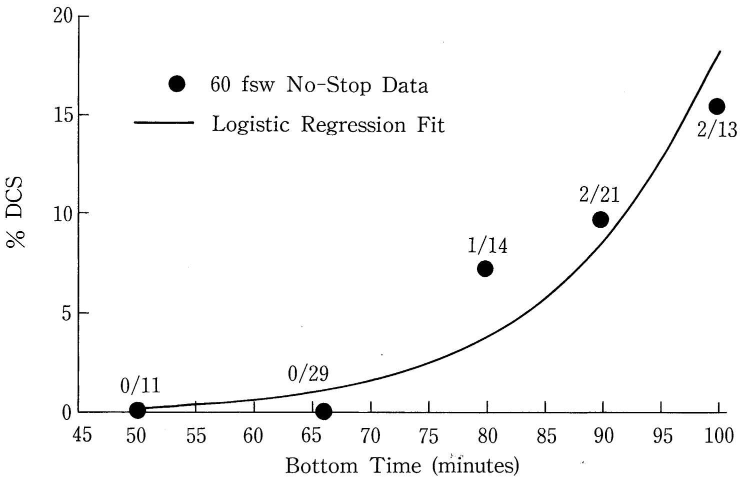

Fig.10 DCS incidence as a function of no-stop bottom time at 60 fsw for dives conducted by the U.S. Navy and Canadian Defence Forces (DCS/Individual Exposures).
The curve is the best logistic regression fit to the 60 fsw experimental data.

a threshold value. This changed with the advent of probabilistic ascent criteria in the mid-1980s. The best described probabilistic decompression model is the 1993 USN algorithm which was used to calculate the 1993 USN Tables (Weathersby 1992). Although these tables have not been officially released, their calculation method is important and is used below to help understand the ambiguity of existing tables and computers.

The Ambiguity of Decompression Safety

Tables 3-5 list no-stop dive times specified by six dive tables and five dive computers (Lewis and Shreeves 1990) including the 1993 USN Tables. **Table 3** shows exposure limits for single no-stop dives. The longest no-stop limits for a given depth are 1.4 to 4 times greater than the shortest limits.

Tables 4 and 5 show the dive times for two repetitive no-stop profiles each having two dives. The bottom times for both dives are chosen to give the longest allowed no-stop exposures for the corresponding table or computer. For Repetitive Dive Profile #1 in Table 4, the surface interval after the first dive to 55 fsw is 57 minutes. The bottom time of the first dive ranges from 50 to 77 minutes. A second dive to 55 fsw ranges from 0 to 45 min.

For Repetitive Dive Profile #2 in Table 5, the surface interval after a first dive to 130 fsw is 43 minutes. The times of the 130 fsw dive range between 5-18 minutes. A second dive to 90 fsw has times of 0-23 minutes. The wide range of bottom times underscores the uncertainty of our understanding of decompression safety. We know which dive times are safest (zero minutes), but we do not know which times are safe enough.

Why is diving safety so ambiguous? The dictionary definition of safety is freedom from danger or harm. Absolute safety can be assured only by the prohibition of activities such as diving. What we usually think of as safety is really the acceptance of risk where

Table 6 No-stop exposure limits at 60 fsw for two dive computers and four tables.
DCS probabilities are estimated by the USN 93 algorithm and by logistic regression of the 60 fsw dive trials.

No-Stop Time at 60 fsw (min)	%DCS USN93	%DCS 60'Data	Dive Table or Computer
45	1.5%	0.2%	Mon/Aladin
50	1.7%	0.3%	DCIEM Tab.
55	1.9%	0.4%	DSAT Tables
60	2.0%	0.6%	56 USN Tab.
66	2.2%	1.0%	93 USN Tab.

risk is determined by the probability and the severity of injury (Lowrance 1976). When we choose to dive, we accept a finite probability of decompression injury whether we realize it or not. To choose risk rationally, we must know how the probability of decompression injury varies with the dive profile.

The DCS incidence of recreational diving is guessed at 0.01-0.002% or about one incident in 10,000-50,000 safe dives. Recreational dives are usually well within the no-stop exposure limits of dive tables and computers, however, so that higher DCS probabilities would be expected for dives that push the no-stop limits.

DCS probabilities were estimated by the 1993 USN decompression algorithm for the no stop limits of the dive tables and computers in Tables 4 and 5. For Repetitive Profile #1, second dive times of 0-45 minutes corresponded to DCS probabilities of 1.9-3.2%. For Repetitive Profile #2, second dives of 0-23 minutes corresponded to probabilities of 1.7-3.3%. Thus, DCS probability appears to change only gradually over a wide range of dive times, and dissimilar dive profiles (#1 and #2) can have similar DCS probabilities.

More direct estimates of DCS probability can be derived from dive trials conducted at 60 fsw by the U.S. Navy and the Canadian Defense Forces (**Fig.10**). There were no DCS incidents in 11 individual exposures (0/11) at 50 minutes, 0/29 at 66 minutes, 1/14 at 80 minutes, 2/21 at 90 minutes, and 2/13 at 100 minutes. Applying logistic regression to these data provides the probability estimates shown in **Table 6** and Fig.10.

Table 6 lists the 60 fsw no-stop exposure limits for several dive tables and computers from Tables 3-5. The corresponding DCS probabilities from the 60 fsw logistic regression estimates and the 1993 USN algorithm are also given. By logistic regression of the 60 fsw data, the 60 minute limit of the U.S. Navy Diving Manual (1956 USN Tables) has a DCS probability of 0.6% while the 45 minute limit of the Monitor and Aladin dive computers has a 0.2% probability.

The probabilities predicted by the 1993 USN model are some 2-7 times greater than those derived from the 60 fsw data. The USN model overestimates the logistic regression probabilities at less than 75 minutes and underestimates them at more than 75 minutes.

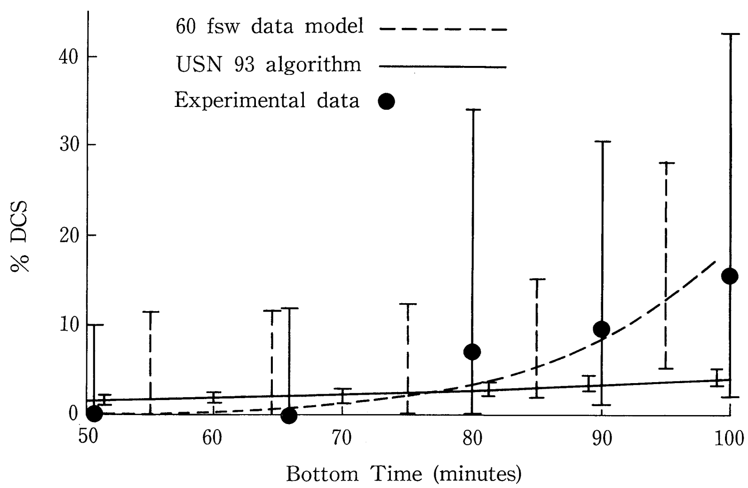

Fig.11 Experimental DCS incidence and DCS probabilities estimated by logistic regression and by the USN 93 model.
The 95% confidence intervals for the models and the 95% binomial confidence interval for the data are indicated.

The estimates from the 60 fsw data might appear the more probable as they are closer to the guesses for recreational diving, but this conclusion is not warranted statistically. **Fig.11** shows the 60 fsw data with its probability estimates (Fig.10) and associated 95% confidence limits. The probability estimates and 95% confidence limits of 1993 USN model are also shown. As the experimental confidence limits overlap the predictions of both models, the models are statistically indistinguishable, and we cannot determine which set of probabilities is more likely to be correct.

Safe diving requires accurate estimates of the probability and severity of decompression injury. Other than the 60 fsw dives of Fig.10, the data currently available do not allow such estimates. Developing these data is a central objective of DAN research. Projects such as *Flying After Diving, Project Dive Exploration,* and a planned study of *Safe Ascent Rates* were designed to provide information from which the relationships between DCS incidence and exposure time can be estimated.

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