NDTT – Probability of decompression sickness

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Background, objective and reservations

The editors of the Norwegian Diving and Treatment Tables (NDTT) have since the fourth edition tried to inform the reader on the safety performance of the tables. "Safety" has been described with metrics such as reports from the Norwegian Society for Underwater Contractors (NBU). As mentioned in the introduction the observed incidence of treated decompression sickness (DCS) was in the order 0.05-0.2 % per hour or per dive – depending on type and location of diving (see serial 8 in the introduction of NDTT 6th ed). This number seems conflicting to the predicted probability of DCS (pDCS) ranged approximately 2-5% (serial 12 and 15 in the introduction of NDTT 6th ed.).

The objective of this document is to describe in more detail the seeming disparity between the observed and predicted DCS incidence rates.

This document has been developed by the first author of the editorial team. It should not be construed as part of the tables but is provided as supplementary information. It is not intended to meet the quality criteria of a scientific manuscript.

Obseved DCS

The observed incidence of DCS will depend on the characteristics of the population examined. A recent review estimated DCS incidence in recreational diving in the order of

0.4-1 per 10 000 dives[1]. Norwegian in-shore occupational diving experienced a DCS incidence in the order of 0.5 per 10 000 hours[2]. Petroleum Safety Authority Norway distributes an annual report (Norwegian text only) detailing diving within their supervisory responsibility[3]. They report approximately 480 man-hours of surface-oriented diving annually, and the last reported incidence of DCS was 1999, i.e. approximately 1 per 10 000 hours. Shields et al.[4] reported an overall DCS incidence of 0.26 % DCS in 126 980 offshore commercial dives during 1982-1988. However, the incidence for no-decompression dives was an order less – typically 2-4 /10 000 dives – while surface decompression with oxygen carried a burden of 0.4-0.5 %. The work by Shields et al. may seem irrelevant for present operational diving due to obsolete diving and decompression procedures. However, the report illustrates an important aspect: observed DCS incidence will depend on diving method (no-decompression, in-water staged decompression or surface decompression with oxygen). DCS incidence rates in the order <<1/1000 dives do most likely include large number of dives not dived to the table margins.

Decompression models

Deterministic models

Decompression profiles, i.e. the instructions on ascent rates, decompression stops and breathing gases, are constructed from models, usually termed algorithms. Except for US Navy, most decompression tables are based solely on a deterministic model. A deterministic model gives a "yes/no" answer to safety. The most common algorithms are those estimating the amount of inert gas pressure during and after the dive. DCS is expected to occur if the inert gas pressure exceeds the ambient pressure more than the allowed threshold level. The algorithm may be complex including varying compartments with different kinetics for gas uptake and gas elimination, but in the end the result will be an inert gas pressure subseeding or exceeding the allowed threshold. The benefit of such deterministic models is that they are cost-effective: They can be easily implemented in dive computers, spreadsheets or other software. However, they are unable to predict the reality. Most diving manuals would accept direct ascent to surface (no-decompression) following a dive to 18 msw for 60 min. However, there are many examples of dives of shorter duration that has caused DCS. Such a deterministic model is thus not able to predict the *likelihood* of DCS. A deterministic model will assume that DCS will occur if the permissible supersaturation is violated but is unable to tell *when* the DCS will occur.

Probabilistic models

The probabilistic models share some of the similarities of the deterministic models. The US Navy probabilistic model will be used as an example. The core of the probabilistic model is an algorithm estimating inert gas pressure in nine compartments with half-times ranging 5-240 min. If the dive profile is known, this algorithm will calculate inert gas pressure and relative supersaturation during and after the dive. The output of this algorithm will be forwarded to the probabilistic model. The probabilistic model is a statistical tool producing p_{DCS} estimate. The probabilistic model will predict a higher p_{DCS} for a dive causing high supersaturation post dive than a dive with less supersaturation. The risk function will express the likelihood of experiencing DCS depending on inert gas supersaturation. The probabilistic model will not only produce an overall p_{DCS} estimate, but may estimate the time distribution of DCS occurrence (i.e. the likelihood at any particular time during the dive that DCS reportable symptoms will occur). This model has been trained and validated with thousands of carefully monitored dives in the USN.

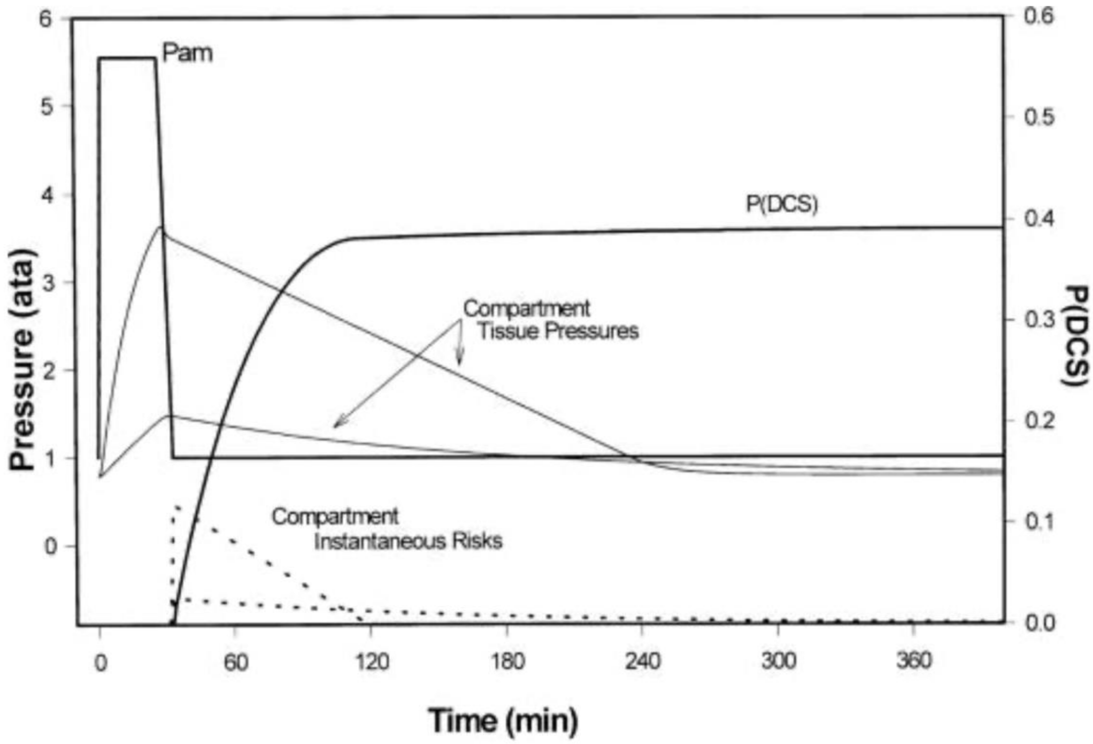

Figure 1 Illustration of the underlying principles of a decompression probabilistic model. The curves show changes in ambient pressure (Pam), compartment inert gas pressure and the estimated instantaneous as well as accumulated DCS probability (p_{DCS})

Predicted DCS

Scientific testing of individual profiles – deterministic models

The reader of a decompression table would be most interested in the predicted likelihood of experiencing DCS if he/she adheres to the table advice. A proper answer to that question would call for a large number of carefully designed experiments. Table 1 gives an impression of the order of accuracy you can achieve for the DCS probability estimate depending on the number of experimental dives and the DCS outcome. Consider that you want to assure yourself with 95% certainty that a given profile will have less than 5 % probability of DCS (p_{DCS}). You have to make at least 59 dives without any incidents or at least 93 dives with one DCS incident to reassure you that this single profile meets your requirement. If you need reassurance that the profile has p_{DCS}<1 % you will have to test the profile 300 times without any DCS incidents. These numbers show that due to logistical constraints it is totally unrealistic to be able to scientifically verify even a single profile if you need reassurance for a p_{DCS}<10%.

Table 1 Upper 90% confidence interval of predicted DCS probability (%) for a specific dive profile dependent on number of tested dives and DCS outcome in the sample (zero or one DCS).

Number of dives	Number of DCS 0	1
10	26	39
20	14	25
50	6	9
100	3	5

Scientific validation of probabilistic models

Rather than testing an endless number of diving depths, bottom times and decompression profiles you could opt for validating a probabilistic model. This is done by comparison of expected incidence by observed incidence. USN has done thousands of carefully monitored experimental dives and they have access to similar data from the UK Royal Navy and the Canadian Forces. Consider Figure 2 below. It shows the performance of a probabilistic model with respect to estimating both the incidence of DCS as well as timewise distribution of DCS symptom appearance. These particular models were calibrated from 2383 carefully monitored experimental dives[5] (no-decompression dives, staged decompression dives, nitrox +++).

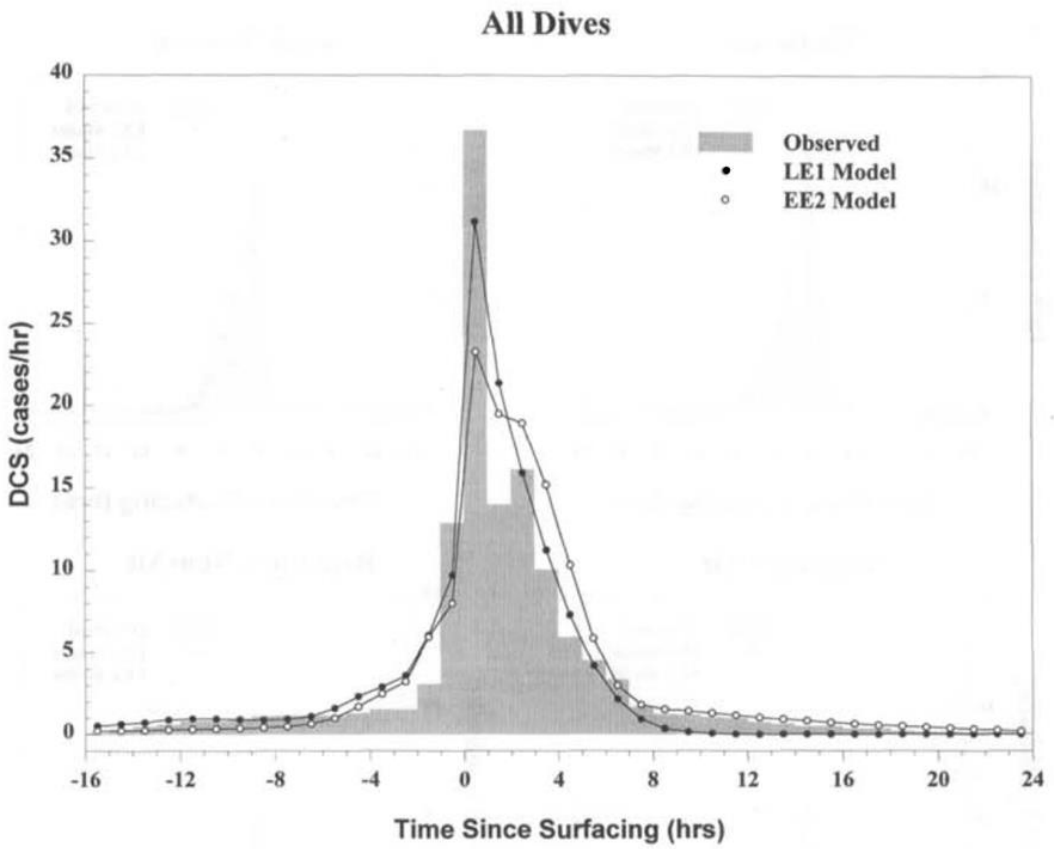

Figure 2 Estimated (black lines) and observed (grey bars) DCS incidencse distribution relative to time of surfacing. Two models (LE1 and LE 2) shown. From [5]

The probabilistic model can be used to estimate DCS probability of a decompression table. Consider the USN Diving Manual[6]. Predicted p_{DCS} for schedules can be calculated based on a probabilistic model. The outcome can be presented as shown in Figure 3 below.

Estimated Risks of DCS

Depth (fsw) /BT(min)	VVal-79 AIR; 20 fsw Last Allowed In-Water Stop TOTAL STOP TIME (min)	P(DCS) BVM(3) (%)	low - high	NMRI98 (%)	low - high
90/ 60	56	4.334	1.780 - 8.668	4.031	3.343 - 4.812
90/ 70	83	5.295	4.511 - 6.163	5.115	4.358 - 5.954
90/ 80	130	6.151	3.314 - 10.205	5.905	5.099 - 6.788
90/ 90	171	6.924	5.976 - 7.961	6.729	5.832 - 7.709
90/ 100	204	7.577	6.512 - 8.743	7.508	6.501 - 8.606
90/ 110	249	8.065	6.875 - 9.372	8.070	7.003 - 9.229
90/ 120	286	8.429	7.104 - 9.892	8.636	7.508 - 9.857
90/ 130	324	8.730	7.284 - 10.333	9.188	7.998 - 10.475

Figure 3 Facsimile from[7] listing estimated p_{DCS} for a selection of schedules from USN DIving Manual Rev 7[6]. Estimated pDCS (%) and the 95% confidence interval are listed for two probabilistic models (BVM and NMRI98).

Predicted and observed DCS incidence

The predicted incidence (consider Figure 3) will usually exceed what is commonly considered acceptable for recreational as well as military and commercial diving. Incidence rate is in the order of 0.4-1 per 10 000 dives for recreational divers[1] and probably in the order of 1 per 1000 dives for occupational diving[8]. These observed incidence rates are in an order of 1:10-1:100 of the predicted incidence. What is the reason? The most commonly referred explanations for this discrepancy are:

- Most dives are not dived to the margins of the table allowance. Most dives will be significantly shorter and shallower than the decompression rate would allow for.
- Reporting bias. Divers participating in the carefully monitored scientific dives are scrutinized for any symptom suggesting DCS. It is likely that many recreational and occupational divers will experience symptoms that are not reported.

Weathersby and coworkers[9] reviewed a previous work by Berghage and Durman [10] reporting DCS incidence rate on schedules from the USN Diving Manual that had been reported to the Navy Safety Centre for a minimum of 200 dives during a seven-year period (Table 2). As can be seen the predicted incidence rates consistently exceeds the observed rates, typically overestimating in the range of two to ten times.

Table 2 Summary of data from Weathersby et al.[9] and Berghage and Dumant[10]. The tables list dive schedules reported for at least 200 dives during seven years to US Navy Safety centre and observed incidence rate (DCS obs). Predicted DCS incidence rate (P_{DCS} expected) are sampled from the report by Gerth and Doolette[11].

Depth (msw)	Time (min)	No dives	No DCS	DCS obs (%)	P_{DCS} expected (%)
30	50	549	3	0,55 %	3.45 %
33	20	209	0	0,00 %	
33	30	455	4	0,88 %	2.26 %
33	50	1198	4	0,33 %	4.43 %
36	30	244	3	1,23 %	2.61 %
36	50	474	2	0,42 %	6.44 %
39	15	227	1	0,44 %	
39	50	226	2	0,88 %	7.51 %
45	10	686	2	0,29 %	
48	30	270	3	1,11 %	4.55 %
51	10	854	4	0,47 %	
51	15	494	2	0,40 %	2.05 %
54	15	396	2	0,51 %	2.22 %
54	20	397	6	1,51 %	3.14 %
57	10	473	5	1,06 %	1.70 %
60	10	1458	13	0,89 %	
60	15	257	5	1,95 %	
63	10	345	0	0,00 %	
87	10	511	9	1,76 %	
90	10	668	13	1,95 %	
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Predicted DCS incidence NDTT

We claim that the predicted DCS incidence (p_{DCS}) of NDTT – when dived to the extreme of each schedule - is ranged from 2-5 %. p_{DCS} will increase as a function of bottom time for a given table depth. This is a rough estimate and is based on the fact that total decompression times of schedules listed in the NDTT standard air decompression table are in the order similar to USN 1956 tables. We have thus accepted the p_{DCS} estimate of of USN 1956 air decompression tables, as cited by Gerth and Doolette[11] (Figure 3), as representative for NDTT. There is scientific support for this assumption[12]. However, the p_{DCS} estimate for NDTT is not claimed to be accurate. To provide an accurate p_{DCS} estimate we would need access to a calibrated probabilistic model such as that maintained by the USN. Regrettably we don't have that resource available.

Using p_{DCS} of a probabilistic model as a measure of table safety has been repeatedly criticized by revieweres of (draft) new revisions of NDTT. It is either claimed that a p_{DCS} of 2-5 % is unacceptably high or that it is not "correct". We have tried, in this document, to explain that it is meaningsless to discuss the safety of a table unless you consider dives completed to the schedule limits. All decompression tables are safe, meaning that the DCS incidence will be extremely low, if you dive to 10 metres for 5 minutes even followed by a controlled ascent to surface afterwards. The commonly cited experience for in-shore diving (consider the data from the Norwegian Society of Underwater Contractors as cited in the latest edition of NDTT[2]) suggest DCS incidence rates in the order of 4:10 000 – 2: 1 000 dives, many orders less than p_{DCS} claimed for the NDTT. As explained, these observations will reflect population-specific DCS incidence – i.e. the incidence rates representative for a commercial diver. It does not reflect the risk for DCS for the table if you if you dive the schedules to the extremes every dive.

Whether a p_{DCS} is "acceptable" or not will finally be a decision of the risk owner. There are indeed differences in decompression schedules comparing commonly used tables[13]. However, it should be noted that a numerical difference in decompression time in the order of 5-10 min has marginal influence on expected p_{DCS}. Consider Figure 4 as facsimiled from [14]. This figure illustrate the relationship between total decompression time and p_{DCS} for a 36 msw/30 min dive. The USN diving manual 1956 stipulated 8 min decompression time (NDTT 10 min) for this dive. This will have a p_{DCS} of 2.8 %. To increase the safety reaching p_{DCS}=2.0 % the total decompression time should be increased tenfold – to 80 min. It is thus possible, but highly impractical, to decrease p_{DCS} by increasing decompression time. This topic has been addressed by others previously [15].

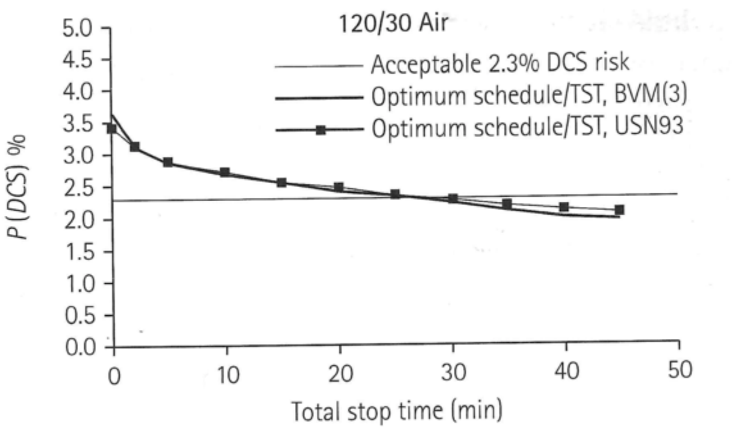

Figure 4 Estimated DCS probability (pDCS) for a dive to 120 feet (approximately 36 msw) for 30 min. pDCS will decrease monotinically as a function of total decompression time. From [14].

Why we have retained the old RN 11 Air decompression tables

It may seem illogical to retain the old (1970's) air decompression tables while we include the USN Diving Manual Rev 7 (2018)[6] for SurDO2 and TUP decompression. We will summarize the reasons for this below:

- USN transitioned from old (USN 57) to new (USN Diving Manual Rev 6) in 2008. As explained above the USNDM from Rev 6 and onwards have been calculated based on the Thalmann algorithm set, initially with the VVAL18 and VVAL18M algorithm set for air decompression tables, later with the VVAL 79 algorithm set. Introducing the Thalmann algorithm with the VVAL18 and later VVAL79 algorithm set allowed use of dive computers predicting decompression profiles close and later identical to the printed air decompression tables. They USNDM 6 and USNDM 7 stipulated generally longer decompression times than USN57, thus protecting the diver from some of the very high p_{DCS} associated with the deepest and longest profiles. However, this came to a cost: While no-decompression changes were essentially unchanged from USN57 to USNDM6 and USNDM7, total decompression time (TDT) was significantly extended for profiles previously stipulated with short TDT. Consider Table 3 below comparing six profiles (combinations of table depths and bottom times) for NDTT[2], USNDM7[6] and the USN Des Granges decompression tables ([16]used from 1957 until Rev 6 of the USN Diving Manual). As can be seen there is minimal change in the no-decompression bottom times. As bottom time increases, the USNDM7 stipulates significantly longer TDT than the NDTT and USN57. This extension will only cause a moderate reduction in p_{DCS} (typically <0.5%) for the bottom times printed in the NDTT. Introducing USNDM 7 air decompression will have a significant operational impact if the present restrictions in NDTT on a maximum TDT of 30 min should be retained. The maximum allowed bottom time for a 18 m table depth would be reduced by 30 min from 120 to 90 min. Similarly the allowed bottom time for the 27 m table depth would be reduced with 15 min from 60 to 45 min. It is our position that the moderate reduction in pDCS could not defend such an extension of TDT. By transition from USN57 to USNDM7 the USN has a 1:1 relationship between decompression stipulation in their dive computer and the printed tables. This is an appreciated benefit for an organization having implemented a dive computer. Until a similar request is raised in Norway, the benefit of retaining NDTT air decompression schedules (original Royal Navy 11) is larger than that achieved by introducing USNDM7 air decompression procedures.

Table 3 Comparison of total decompression time (TDT) and estimated DCS incidense (p_{DCS}, [7, 11]) for USN Diving Manual pre Rev 6 (USN57,[16]), NDTT[2] and USN Diving Manual Rev 7 (USNDM 7, [6])) for six different dive profiles listed as table maximum depth/bottom time.

Dive profile: Table depth/bottom time (msw/min)	TDT USN57 (min)	TDT NDTT (min)	p_{DCS} USN57 (%)	TDT USNDM 7 (min)	p_{DCS} USNDM 7 (%)
18/60	0	0	1.6	0	1.7
18/100	14	20	3.81	42	3.52
18/120	26	30	5.00	75	4.57
27/30	0	5	<2.01	0	<2.08
27/50	18	20	3.45	31	3.01
27/60	25	30	4.62	56	4.03

- We have explained above that the national experience using NDTT air decompression schedules are good and seems to have similar operationally reported DCS incidence rates as other procedures.
- USNDM7 has introduced the shallowest decompression stop at 6 msw for operational reasons. This will require an extension of TDT to reach the same p_{DCS} as that achieved by using the traditional 3 msw shallowest stop. We have not been approached with a request to move the shallowest stop from 3 to 6 msw, and to avoid extension of TDT we retain present practice.
- USNDM tabulates decompression stops in integer minutes. NDTT tabulate stops in 5-min increments. This is practically motivated, not scientifically, but seems to be appreciated as schedules may be easier to remember.

Conclusion

I have shown the background for the statements in NDTT claiming an estimated DCS incidence rate of 2-5 % for non-exceptional exposures. It is my opinion that this statement is well founded. Whether this incident rate is acceptable is the decision of the risk owner. I would claim that the probability is in the same range as other commonly used decompression tables and that a relevant reduction in p_{DCS} can only be met by an impractical extension of total decompression time. The document explains the reasons for not implementing the USN Diving Manual Rev 7 air decompression schedules.

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