Decompression sickness from saturation diving: a case control study of some diving exposure characteristics

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Department of Community Medicine and General Practice, Norwegian University of Science and Technology, Trondheim, Norway; SINTEF UNIMED, Section for Extreme Work Environment, Trondheim, Norway; Stolt Comex Seaway, Haugesund, Norway; Peterson Technical Service, West Chester, Pennsylvania; National Hyperbaric Center, Ltd., Aberdeen, Scotland; Phillips Petroleum Company Norway, Stavanger, Norway

Jacobsen G, Jacobsen JE, Peterson RE, McLellan JH, Brooke ST, Nome T, and Brubakk AO. Decompression sickness from saturation diving: a case-control study of some diving exposure characteristics. Undersea Hyperbaric Med 1997; 24(2):73–80.—A comprehensive computerized database of diving activity for a Norwegian offshore diving contractor [Stolt-Nielsen Seaway (SNS)] covering the years 1983–1990 has been established. The database contains detailed dive information about 12,087 surface-oriented and 2,622 saturation dives. During this period a majority of the divers were permanently employed. Preliminary analysis had suggested that decompression sickness (DCS) might be the result of exposure to factors causing pathophysiologic effects which accumulate over the course of a single dive or a series of dives. This concept evolved into the HADES (Highest Accumulated Decompression Score) theory which assumes that DCS is predictable once the underlying exposure factors are understood. The incidence of DCS among the SNS divers from saturation diving in the North Sea was studied by use of a "nested" case-control design. Twenty-one case dives (i.e., dives where DCS occurred) were compared with 41 randomly selected control dives. For these dives, several saturation dive characteristics were established. The relative pressure change between maximum and minimum storage depths was significantly greater among the cases. For each 1% increase in the relative pressure change there was a 5% increase in the probability of a saturation dive resulting in DCS. Significantly more cases than controls performed a saturation dive with more than one storage depth, and the data suggested that there were more and greater ascending and descending changes in storage depth conditions among the affected divers.

decompression sickness, saturation diving, exposure stress, bubbles, effect accumulation

During the period 1987–1989, Stolt-Nielsen Seaway (SNS) (Stolt Comex Seaway after 1992) experienced a considerable increase in the incidence of decompression sickness (DCS) following saturation dives. As there were no changes in the diving procedures when these cases of DCS were recorded, the trend seemed to be in keeping with the concept that DCS is probabilistic in nature (1). Further analysis, which showed that unaffected divers made significantly fewer decompressions per year than both afflicted divers and their dive partners, would fit this probabilistic concept. However, the data also showed that unaffected divers were engaged in significantly fewer saturation dives per year that involved multiple storage depths than were the affected ones. This indicated that unaffected divers, in addition to doing fewer dives, had a different dive pattern with fewer pressure changes. It therefore appeared that the total diving activity *and* some critical exposure-related factors may play a role in the development of DCS.

In theory, the stress factors contributing to the occurrence of DCS may be accumulated over the course of a single saturation dive, or even over the course of a series of dives. This hypothesis of DCS development was given the acronym HADES for Highest Accumulated Decompression Score (2). It seeks to explain the occurrence of DCS on the basis of specific identifiable exposure-related factors, in this case occurring during saturation diving.

The objective of this case-control study was to conduct comparative analyses to provide supporting evidence for the HADES theory. The null hypothesis was that there is no difference in the exposure characteristics between saturation dives that produced DCS and randomly selected control dives.

MATERIAL AND METHODS

Description of dives and divers

Data were collected from the commercial dive operations performed by SNS in the North Sea during 8 yr from 1983 to 1990 (Table 1). The main aim was to establish a computerized database, with comprehensive pressure-time profiles of each dive, that allowed for more detailed analyses. During this period a total of 2,662 individual saturation dives took place which resulted in 779,623 man saturation hours and 18,539 bellruns. Further, 12,087 surface-oriented dives using air took place of which 9,310 were conducted with in-water decompression and 2,777 using surface decompression with oxygen breathing. A "typical" saturation dive profile with its characteristics is shown in Fig. 1.

A total of 495 divers were employed by SNS during the same time period (Table 2). The number of divers who performed only saturation diving or surface-oriented diving was small compared to the number of divers who performed both kinds of diving. There was a general increase in the number of dives per diver and year over the study period, with a peak in 1986–1987 for surface-oriented diving and in 1989 for saturation diving (Table 2). With few exceptions, it was shown that a relatively stable population of divers conducted an increasing number of dives over the study period.

Incidence of decompression sickness

During the study period, 37 DCS cases were diagnosed, with the majority (i.e., 26 cases) occurring in the period 1987–1989. Twenty-two of the recorded cases occurred during saturation diving and 15 during surface-oriented diving. In saturation diving, all cases of DCS occurred toward the end of the saturation decompression or within a few hours after surfacing. The 37 cases of DCS occurred among 27 divers, which implies that several divers were afflicted more than once and some even 3 times.

The annual incidence of DCS by dive categories is shown in Fig. 2 while Fig. 3 gives the incidence averages for the whole study period. In general, the incidence was much higher for saturation diving than for surface-oriented diving even if there were annual fluctuations. For both types of diving there were years with no cases of DCS, whereas for saturation diving the maximum incidence was 18 cases per 1,000 dives. The maximum was 15.4 per 1,000 dives for surface-oriented diving, in this latter case using surface decompression breathing oxygen. As shown in Fig. 3, the cumulative overall incidence of DCS in surface-oriented diving (1.2 per 1,000 dives) was significantly lower than that of saturation diving (8.2 per 1,000 dives) for the whole study period ($P < 0.001$).

Test protocol—data analysis

The effect of diving (i.e., exposure) was measured against the occurrence of DCS as the outcome under study. The aim of the analysis was to study exposure characteristics of the saturation dives that produced DCS, so a "nested" case vs. control study design was chosen. One of the 22 DCS cases had to be rejected because we could not fully reconstruct the pressure–time profile of that dive.

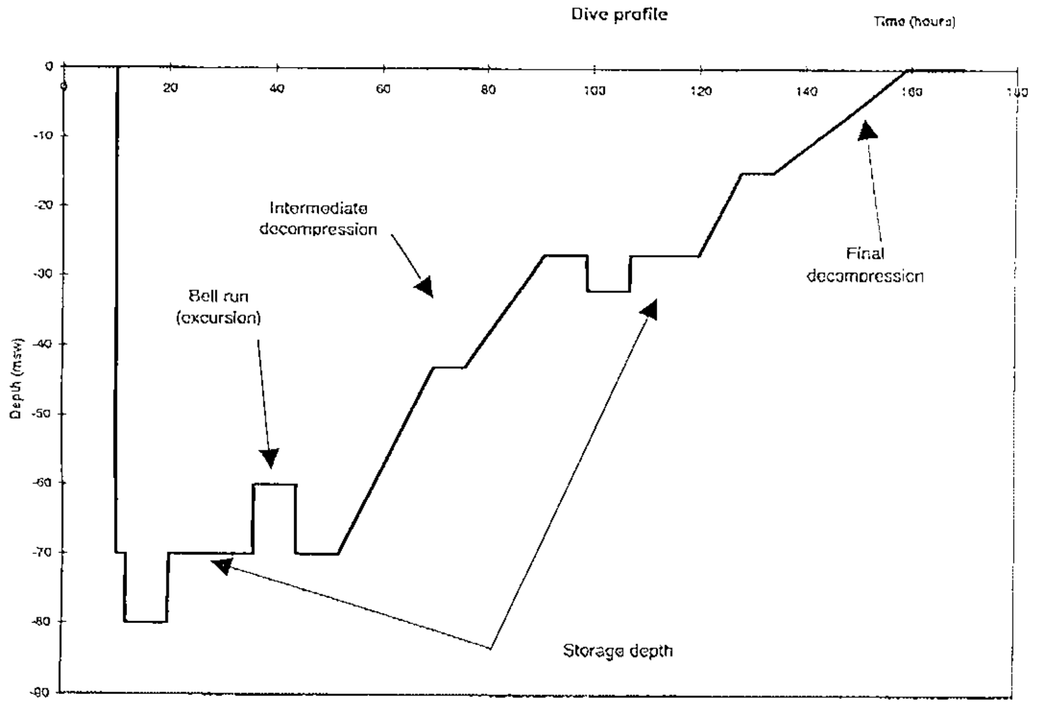


FIG. 1–Illustration of a "typical" saturation dive profile which shows a rapid compression to 80 msw, several storage depths, bellrun excursions, and intermediate and final decompressions within a time period of about 160 h of diving.

Table 1: HADES Database 1983–1990: General Diving Activity

Diver Characteristic	1983	1984	1985	1986	1987	1988	1989	1990	Total
Saturation dives (SAT)									
No. Dives	187	265	266	338	334	355	444	473	2,662
No. bell runs	1,424	2,096	2,246	2,158	2,098	2,551	2,858	3,108	18,539
Hours in SAT	62,603	88,156	77,903	99,036	101,197	106,889	118,280	125,559	779,623
Surface oriented dives (SO)									
No. Dives	589	576	1,213	1,732	2,710	1,877	1,604	1,786	12,087
with IWD[a]	327	366	959	1,380	1,960	1,438	1,345	1,535	9,310
with SDO[b]	262	210	254	352	750	439	259	251	2,777
Hours of SO	864	824	1,918	2,811	4,566	3,181	2,707	2,911	19,783

[a] IWD = in water decompression; [b] SDO = surface decompression with oxygen breathing.

Table 2: HADES Database 1983–1990: Diver Activity

Diver and Diver Characteristics	1983	1984	1985	1986	1987	1988	1989	1990	Overall
Saturation diving (SAT)	80	99	111	121	121	117	126	161	305
Only SAT	11	33	16	9	15	21	20	18	29
Surface oriented diving (SO)	84	82	118	151	242	190	198	224	466
Only SAT	15	16	23	39	136	94	92	80	190
Total number of divers	95	115	134	160	257	211	218	241	495
Number of SAT/diver	2.3	2.7	2.4	2.8	2.8	3.0	3.5	2.9	8.7[a]
Number of bell runs/dive	7.6	7.9	8.4	6.4	6.3	7.2	6.4	6.6	7.0
Number of SO/diver	7.0	7.0	10.3	11.5	11.2	9.9	8.1	8.0	25.9[a]

[a] Cumulative average per diver, 1983–1990.

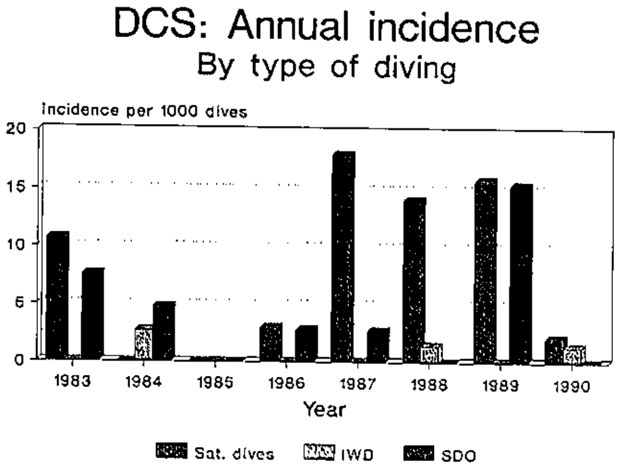
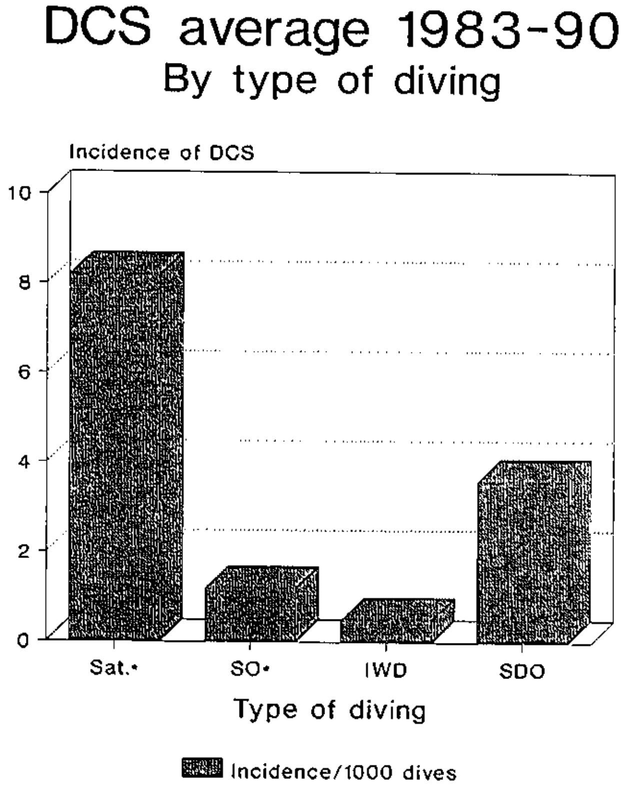


FIG. 2—Annual incidence of DCS among professional off-shore divers in Stolt-Nielsen Seaway 1983–1990 by various categories of diving (for legends *see* Table 1).

Two uneventful dives per case were selected at random from all the non-DCS dives conducted at the same time as the case dives. To obtain seasonal stability and to avoid a potential bias of organizational and procedural changes that inevetably took place during the study, selection of the control dives was limited to a time window of 1 mo in both directions from the DCS dive. One control dive was not included in the analysis due to lack of crucial information. As part of the selection rules it was not replaced by another dive. The analyses, therefore, included data from 21 cases and 41 controls.



•Difference Sat. vs SO dives: p<0.001

FIG. 3—Cumulative incidence of DCS among divers in Stolt-Nielsen Seaway 1983–1990.

As a preliminary step, a large number of saturation dive characteristics were identified and analyzed. Their selection was based on two conditions: a) that they would give a good description of the dive and its decompression-related stress and b) that they were mutually independent. Based on the preliminary analysis, the following six characteristics were eventually selected:

- *Number of decompressions* (N_{DC}), i.e., all intermediate decompressions plus the final decompression during a saturation dive.
- *Relative pressure change of the largest decompression* (RPC_{lPC}), i.e., the the pressure difference (bar) of the largest decompression divided by the depth (bar) from which the decompression was started.
- *The storage depth* (SD) is the depth at which the diver stayed for more than 24 h. Compression and decompression between storage depths were performed according to standard saturation procedures. Under normal circumstances there would be an 8-h stabilization period before the commencement of a decompression, during which period no excursions were allowed.
- *The storage depth with the longest duration* (D_{lSD}).
- *Sum of the bell dive stress at the storage depth with the longest duration* (ΣBDS_{lSD}). Bell dive (decompression) stress is equal to the maximum depth minus the shallowest depth for the bell dive, the distance converted to bar, and multiplied by the square root of the time duration of the bell dive. A bell dive takes place during a bellrun. If the diver is not exposed to a change in pressure during the bellrun, no bell dive is recorded.
- *Maximum relative pressure change between storage depths* ($mRPC_{bSD}$), i.e., the deepest storage depth minus the shallowest storage depth, converted to bar, and divided by the deepest storage depth in bar.
- *Trend of the storage depth changes* (SD_{tc}), i.e., if there was more than one storage depth, the direction of changes were either ascending only, descending only, or mixed, meaning both ascending and descending.

Statistical analysis

Data were analyzed by use of the PC version of the SAS statistical software package (SAS Institute Inc, 1987). The outcome (i.e., cases vs. controls) was treated as a categorical variable, while the independent (exposure) variables were either continuous (counts or averages) or categorical ones. The unpaired t test and χ^2 statistics were used. In addition, the outcome was modeled with some selected exposure variables by use of multivariable log-linear methods. A *P* value of 0.05 or less and an odds ratio, with 95% confidence intervals that did not include the null value, were regarded as statistically significant.

RESULTS

The mean number of decompressions (N_{DC}) and the maximum relative pressure change between storage depths ($mRPC_{bSD}$) were significantly higher among the cases than the controls with *P* values below 0.05 and 0.001, respectively (Table 3). The relative pressure change of the largest decompression (RPC_{lDC}) was higher among the controls, but achieved only borderline significance. For the two other characteristics shown in Table 3, the mean values were in general higher among the cases. For example, the sum of the bell dive stress at storage depth with the longest duration (ΣBDS_{lDS}) was nearly 50% higher, but failed to meet the appropriate level of significance.

A comparison of characteristics of the trend of storage depth changes (SD_{tc}) is shown in Table 4. When all four categories were considered, no differences were found between cases and controls ($P > 0.10$). However, there were significantly fewer cases (0/21) than controls (8/41) who performed a dive with only one storage depth compared to a dive with ascending, descending, or mixed directions of storage depths as one category ($P < 0.05$).

In multiple logistic regression, the two significant characteristics of the descriptive statistics between cases and controls in Table 3 (N_{DC} and $mRPC_{bSD}$) were chosen as independent variables. When both variables were modeled, we found that the model did not fit the data well ($P > 0.05$). After N_{DC} was dropped from the model, $mRPC_{bSD}$ increased its significant contribution to the outcome prediction ($P = 0.002$; Table 5).

Based on the variable estimate and its standard error, the odds ratio with 95% confidence interval, was calculated. Since $mRPC_{bSD}$ is a characteristic with values that range from 0 to 100%, the data showed that for each 1% increase in maximum relative pressure change between storage depths, there was a 5% (2–9%) increase in the probability of a saturation dive resulting in DCS (Table 5).

DISCUSSION

This study has shown that dives with only one storage depth were associated with a significantly lower DCS occurrence and that an increase in maximum relative pressure change between storage depths increased the probability of a dive resulting in DCS. We explored several other dive characteristics than the ones presented here, e.g., the total decompression distance [meters of seawater (msw)], maximum depth of the dive, if the largest decompression also was the final decompression, and if the final storage depth either was the longest, shallowest, or deepest one. Since no differences between cases and controls were shown, these dive characteristics were not included in the further analysis.

As could be expected, the analysis (Table 3) showed that

Table 3: Differences in Mean Values (SD) of Some Key Dive Characteristics for DCS Cases and Controls

Dive Characteristic	Cases, *n* = 21 Mean (SD)	Controls, *n* = 41 Mean (SD)	*t* Test, *P* value
Number of decompressions	2.2 (1.1)	1.6 (0.6)	<0.05
Relative pressure change of the largest decompression (RPC_{lDC})	0.779 (0.105)	0.824 (0.082)	$0.05 < P < 0.10$
Storage depth with the longest duration (D_{lSD})	62.9 (21.7)	61.5 (31.5)	N.S.
Sum of bell dive stress at storage depth with longest duration (ΣBDS_{lSD})	15.1 (15.4)	10.5 (10.4)	N.S.
Maximum relative pressure change between storage depths ($mRPC_{bSD}$)	0.554 (0.201)	0.338 (0.225)	<0.001

N.S. = not significant

Table 4. Differences in Storage Directions Between DCS Cases and Controls[a]

	Cases, *n* = 21	Controls, *n* = 41
Ascending only	1 (4.8%)	2 (4.9%)
Descending only	6 (28.6%)	13 (31.7%)
Mixed (= both ascending and descending)	14 (66.7%)	18 (43.9%)
Only one storage depth	0 (–)	8 (19.5%)

[a] Chi-square statistics (3 df) = 5.11 ($P > 0.10$).

the divers with DCS had performed a larger number of decompressions than the controls and had significantly fewer dives with only one storage depth.

Since a dive with only one saturation depth will lead to a relative pressure change between storage depths equal to zero, and as there was no DCS dive with only one saturation depth (Table 4), the difference between cases and controls for this characteristic was smaller for dives with more than one storage depth.

The data showed that dives with multiple storage depths, in particular if a shallow storage depth was used in combination with a relatively deep one, had a higher risk of producing DCS. It is interesting that the diving pattern seemed to be more important than the number of decompresions performed. Additional support for this is that the bell dive stress was higher in the DCS dives, even if it did not reach statistical significance.

The endpoint used in this study were treated cases of DCS. The diagnosis of DCS is an equivocal undertaking, particularly in field operations (3). We complied with the general operational maxim "when in doubt, treat." Thus, in some cases, treatment itself will confirm or negate a diagnosis of DCS. The incidence reports were reviewed to ensure that symptomatology and treatment outcome were consistent with a diagnosis of DCS (4). No case was rejected on the basis of this review.

If misclassification of cases and controls occurred, it was probably a random event due to the nature of the study design. Because the hypothesis was unknown when the diagnoses of DCS were made, any association between dive exposure and DCS would be attenuated toward the null value, i.e., in a more conservative direction (5).

Most decompression procedures in use have been validated in the field using DCS as an endpoint. In commercial diving, however, it is not unreasonable to believe that there is a certain degree of underreporting of DCS, and some preliminary studies seem to support this (6,7). We hold that major changes in the saturation depth time profile may have an effect on the outcome of the final decompression, and this could have considerable implications for the future evaluation of decompression procedures.

Most saturation diving decompression procedures are linear, where the rate of decompression is determined by the oxygen tension of the atmosphere during decompression (8). By use of statistical techniques of maximum likelihood, Weathersby et al. (9) were able to relate the incidence of DCS to exposure. However, their approach disregards the events that take place during the bottom phase, whereas our results indicate that these factors have to be considered.

The assumption that DCS is probabilistic in nature is based on the concept that chance events occur during decompression which lead to DCS. A mechanistic view of DCS assumes, on the other hand, that it is the result of a generally identifiable sequence of exposure events. These events may be further modified by health and physiologic factors, thereby affecting a diver's sensitivity to decompression stress. DCS may occur when that stress exceeds a certain individual threshold, which can be regarded as the limit for tolerable gas accumulation. Even if an accumulation of risk occurs with changes in pressure, it is not known how long this increased risk will last.

The number of decompressions during saturation dives was greater among the cases suggesting that there was a greater chance for developing DCS during those dives. However, the fact that DCS did not occur during changes of storage depth may eliminate all but the final ascent from consideration of a purely probabilistic nature of DCS. Since any saturation dive can have only one final ascent and the case and control dives were equal in that respect, the number of decompressions throughout a saturation dive probably sensitize the diver by subjecting him to additional, decompression-relevant stress before the final ascent.

The relative difference between the maximum and

Table 5: Decompression Sickness: Results of Logistic Regression Modeling (Analysis of Maximum Likelihood Estimate) for "Maximum Relative Pressure Change Between Storage Depths," i.e., the Only Dive Characteristic that Reached the 0.05 Level of Significance

Effect	Parameter Estimate	Standard Error	Chi square	Probability	Odds Ratio, 95% CI
Intercept	−2.9598	0.8673	–	–	–
Maximum relative pressure change between storage depths	0.0501	0.0164	9.36	0.0022	1.05[a] (1.02, 1.09)

[a] Maximum relative pressure change between storage depths is a characteristic with values that range from 0–100%. The results show that for each 1% increase in relative change, there is a 5% (2–9%) increase in the probability of a dive resulting in DCS

minimum storage depths was unrelated to the final ascent and therefore unrelated to an increase in chance for DCS to occur during that ascent. This relative difference indicates that together with the larger number of ascending and descending changes in the DCS dives and because none of these dives had only one storage depth, the depth-change maneuvers conducted during the bottom phase of the dive could produce gas phase separation and associated stresses. In other words, the dive characteristics that were significantly associated with DCS could exert their influence by causing decompression-relevant stresses before the final decompression.

This study has demonstrated that a saturation dive resulting in DCS seems to have a more complex diving pattern than dives that did not. Thus, the results support good operational practice where a minimum of multidirectional changes in storage depths during a saturation dive operation take place, and that the number of storage depths be kept at a minimum. Dives with only descending changes in storage depth followed by a single decompression to the surface, or dives starting at the deepest storage depth with only ascending changes preceding the ultimate decompression to the surface, may seem preferable.

The aim of this paper was to analyze our *saturation* dive data to seek supporting evidence for the HADES theory (2). We acknowledge that issues raised by Shields and Lee (10) in relation to the occurrence of DCS from *surface-oriented* diving have not been addressed here. Additional analysis of the comprehensive HADES database is needed for comparisons with their data.

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