DECOMPRESSION TABLES VERSUS DECOMPRESSION PROCEDURES : AN ANALYSIS OF DECOMPRESSION SICKNESS USING DIVING DATA BASES

JP Imbert, Comex Services.

INTRODUCTION

Commercial diving relies on air diving for shallow operations. Air diving offers the obvious advantages of simplicity and reduced costs but has the inherent shortcomings of bounce diving.

The first limitation is the decompression time which reduces the ratio of the working time over the diving time. To cope with it, the diving contractors have introduced a large variety of procedures in their diving manuals :

- the ascent to surface can be performed using four decompression techniques which are no-stop decompression, in-water decompression, surface decompression using a deck chamber or transfers under pressure (TUP) using a diving bell.
- the decompressions can be conducted using various decompression tables, which usually refer to the US Navy manual, but also to specific company developments or to government publications.
- the tables can combine alternatives such as nitrox breathing, oxygen stops, multiple depth profiles, etc ....

The second limitation is the safety of the decompression. The point was documented by the UK Department of Energy (DOE) who organized a survey of air diving operations in the North Sea. The results first presented to the diving industry in 1986 (1) showed an alarming incidence of decompression sickness (DCS) for the deep and long exposures. As a consequence, the DOE issued a series of Safety Memorandums limiting air diving exposures in the UK sector. The Memorandums initially concerned surface decompression (2) but later extended to in-water decompression (3).

The DOE approach, purely based on a depth/time limitation has shown to be relatively efficient since the 1988 operations lead to 0.10% overall DCS incidence for 17,045 air dives recorded. However, it is still unsatisfactory because, among these DCS cases, 11 serious neurological accidents were reported, which represent a threat for a divers' population of around 800 individuals. In this paper, to further refine the analysis, we decided that DCS should not be considered as a whole but rather studied through its two manifestations, type I and type II occurrences.

In paper a published in 1971, Hills (4) was able to show, using an animal model, that DCS occurrences could change from type I to type II symptoms by changing from continuous decompression to surface decompression. This remarkable experiment demonstrated the existence of different mechanisms for the onset of type II DCS which was later accounted for by the arterial bubbles model. This model can be summarized as follows :

- bubbles are normally produced during a decompression in the vascular bed, transported by the venous system and filtered out in the lung,
- in case a bubble crosses the lung and is injected in the arterial system, it is likely to reach a neurological tissue,
- there, the neurological tissue will act as a gas reservoir and the bubble will start growing, causing major alteration of the blood supply, and finally ischemia.

The arterial bubbles were first detected and their possible role discussed by the scientists running doppler detection studies (5,6). The model of the diving.

MATERIAL AND METHOD

Data for the study were collected from the Comex data base (12) and from the published information on the DOE data base. Unfortunately, because the DOE did not publish the raw information, referring to their data requires to adapt to their classification of the decompression severity. In the last report, the partition is based on the "Prt Index", which is the product of the dive pressure by the square root of the bottom time. This index was thus adopted in the study.

The first source of information is the information published on the North Sea air diving operations by the DOE in 1988 (13). The period ranges from 1982 to 1988. All the diving contractors contributed to the dive reports collection and the data therefore include the Comex UK dive reports for this period. See table no 1.

Table no 1 : Data published in the DOE reports on air diving operations in the UK sector of the North Sea from 1982 to 1988.

DOE report air no-stop	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	35,555	2,184	8
Number of type I DCS	3	0	0
Number of type II DCS	5	1	0

DOE report air in-water D and bell TUP	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	12,739	4,669	2,744
Number of type I DCS	11	11	11
Number of type II DCS	4	1	9

DOE report air SDO	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	9,491	49,222	6,252
Number of type I DCS	3	110	58
Number of type II DCS	1	71	31

The second source of information is the 1974 French official air tables. These tables were included in the Comex diving manuals and used world widely for its operations (14). The tables offer air no-stop decompression, standard decompression, and in-water decompression using oxygen breathing at 6m. The data presented in the table no 2 were collected using Comex data base. The period selected ranges from 1976 to 1983. The dives concerned world wide operations except the North Sea in 1982 and in 1983 to avoid overlapping with the data from the DOE report.

Table no 2 : French 1974 air tables. 1976 to 1983 Comex operations.

French 74 air no stop	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	26,004	0	1,235
Number of type I DCS	2	0	0
Number of type II DCS	1	0	0

French 74 air in-water D	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	17,683	9,590	2,426
Number of type I DCS	18	55	49
Number of type II DCS	1	1	1

The third source of information is related to the Comex 1974 air surface decompression using oxygen (SDO) tables. The data presented in the table no 3 were collected using the Comex data base. The dives mainly concerned the Comex North Sea operations. The period selected ranges from 1976 to 1981 to avoid overlapping with the DOE report.

Table no 3 : Comex air SDO tables. 1976 to 1981 Comex operations.

Cx 1974 air SDO	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	591	3,470	3,071
Number of type I DCS	0	7	29
Number of type II DCS	0	3	4

The last source of information is related to the revised Comex air tables, which were developed during 1984, validated offshore during 1985-86, and introduced in the Comex diving manuals in 1987 (15). The tables include air no-stop, standard decompression, in-water decompression with oxygen breathing at 6m, in-water decompression with oxygen breathing at 12 m, and surface decompression. The air SDO tables are limited to exposures close to the ones recommended by the DOE. The data presented in the table no 4 were collected using the Comex data base. The 1988 results are missing because on that year, the data base was not kept operational. The 1986 and 1987 dive reports come from locations other than the North Sea to avoid overlapping with the DOE report. The 1989 and 1990 dive reports come from world-wide operations. Very few bell TUP dives were recorded with these tables and are not mentioned in the table.

Table no 4 : Comex 1986 revised air tables. 1986,1987, 1989 and 1990 Comex operations.

Cx 86 air no-stop	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	12,827	1,284	0
Number of type I DCS	0	0	0
Number of type II DCS	0	0	0

Cx 86 air in-water D	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	7,129	8,384	2,055
Number of type I DCS	1	12	17
Number of type II DCS	0	1	2

Cx 86 air SDO	Prt<=25	25<Prt<=35	Prt>35
Number of exposures	592	1,538	0
Number of type I DCS	1	1	0
Number of type II DCS	0	0	0

RESULTS AND DISCUSSION

Influence of the decompression technique

Commercial diving decompression techniques can be classified in two categories, the continuous ascent to the surface, as in in-water and bell TUP decompressions, and the surface decompression. The surface decompression has a built-in pressure variation associated to the excursion to the surface and the rapid recompression in the deck chamber.

According to the arterial bubbles model, the surface decompression should favor the occurrence of serious DCS. The scenario is that the excursion to the surface generates bubbles and the recompression in the chamber may facilitate their transfer through the lung. The process is purely physical, based on the bubbles size reduction according to the Boyle's law. To verify this assumption, the safety performances of 142,770 men dives, using either SDO or continuous ascent, have been compared in the table no 5.

Table no 5 : comparison of air in-water and bell TUP decompressions with air SDO decompression.

	Prt<=25		25<Prt<=35		Prt>35	
	In-water Bell TUP	SDO	In-water Bell TUP	SDO	In-water Bell TUP	SDO
Exposures	37,551	10,674	22,643	54,230	8,349	9,323
Type I DCS %	30 0.08%	4 0.04%	78 0.34%	118 0.22%	77 0.92%	87 0.93%
Type II DCS %	5 0.01%	1 0.01%	3 0.01%	74 0.14%	12 0.14%	35 0.38%

The comparison of the type I DCS occurrences does not permit to differentiate between the two techniques of decompression. In both cases, the observed rate of incidence increases with the exposure severity, thus indicating a direct relationship between the risk of type I DCS and the tissue gas load.

However, the comparison of the type II DCS occurrences permits to draw interesting conclusions. For moderated exposures, corresponding to the ones permitted by the DOE Safety Memorandums, the risk is low and the difference is non significant. For these exposures, the surface decompression can be considered as safe a decompression technique as in-water or bell TUP decompression.

For severe exposures, exceeding the limits of the DOE Safety Memorandums, the incidence of type II DCS becomes significantly much higher with the surface decompression ($p<0.001\%$ for $25<Prt<=35$ exposures and $p<1\%$ for $Prt>35$ exposures). Clearly, for severe exposures, the risks are higher for the divers with the surface decompression than with the in-water or bell TUP decompression, because the consequences are not the same :

- type I cases are simple accidents. They lead to symptoms that are well recognized and easily treated by recompression and hyperbaric oxygen on mask. According to the DMAC recommendations (16), a diver can return to diving only 24h after a successful treatment.
- type II cases are serious accidents. They lead to symptoms that are sometimes difficult to recognize and the treatments are often delayed and less efficient. According to the DMAC recommendations, a diver must have 7 days off after a successful treatment but may lose his diving certificate in case of residual manifestations.

It must be noted for the surface decompression, that the increase of type II DCS incidence is drastic over the Prt=25 border. This border seems to be the "natural" limit to the safe use of the surface decompression. This fact remains to be explained but apparently is a characteristic of the surface decompression only. The physics of the bubbles formation indicates that the rate of ascent to the surface, the surface interval and the depth of the recompression are critical factors for the outcome of a surface decompression. Unfortunately, the first two factors cannot be studied with a data bank dealing with diving logs and the last one, the depth of recompression is a constant in diving procedures. The question is pending whether the surface decompression technique could be improved and how.

Meanwhile, the data collected amply justify restricting the use of the surface decompression technique to its observed safe limits. However, it must be noted that such a separating line does not exist for the in-water or bell TUP decompression.

Influence of the bottom pressure profile

Normally, when working, a diver is committed to keep a constant depth and dive a square pressure profile which corresponds to the assumptions used to calculate and validate his decompression schedule. In practice, the diver may perform repetitive ascents and descents between two work depths, or when in shallow waters, ascent several times to the surface to pick up tools. These depth variations have been termed yoyo diving. According to the arterial bubbles model, yoyo diving should produce serious DCS similarly to the surface decompression.

No stop, in-water and bell TUP decompressions still provide type II DCS cases that cannot be explained by a pressure variation built in the decompression procedure. These cases cannot either be explained by the severity of the exposure because 8 types II DCS occurring in the no-stop decompression area were collected in this paper. In addition to air embolism or multi-day diving, a possible explanation could be yoyo diving, an uncontrolled practice, occurring randomly over the exposures range, regardless of the decompression technique.

The type II DCS cases reported on the Comex work sites for no-stop, in-water and bell TUP decompressions have been summarized in the table no 6 below for all the exposures not overlapping with the DOE survey. The accidents have been classified according to the suspected contributing factors. The data are scarce but however support the fact that a significant fraction of the cases can be related to yoyo diving. It may be that in the future, the systematic implementation of electronic dive recorders will permit to gather accurate information on the divers' pressure profile and start documenting the issue.

Table no 6 : Summary of type II DCS reported after no-stop, in-water and bell TUP decompressions. 1976 to 1990 Comex operations.

Suspected contributing factor	Cases
Yoyo diving	3
Rapid ascent to the surface	1
Multi day repetitive diving	1
Unknown	2

Influence of the decompression table
The above results stress the importance of the dive procedure rather than the decompression table. This is fortunate because the highly random process involved in the generation of arterial bubbles make table designers feel desperate to ever found a model for such events. However, as far as type I DCS is involved, the table no 5 has shown that it can be correlated to the dive exposure, regardless of the decompression technique used. In turn, the dive exposure can be related to the amount of gas dissolved in the tissue, a quantity that can be easily calculated by a model. By improving their model, the table designers have a chance to improve the type I DCS incidence of the decompressions.

The safety performances of the French 74 air tables and the Comex 1986 revised air tables have been compared in the table no 7 below for in-water decompression, summarizing 12 years of decompression studies.

Table no 7 : Ssafety performances of in-water decompressions from the 1974 French tables and the Comex 1986 revised air tables.

	Prt<=25		25<Prt<=35		Prt>35	
	In-water 1974	In-water 1986	In-water 1974	In-water 1986	In-water 1974	In-water 1986
Exposures	17,683	7,129	9,590	8,384	2,426	2,055
Type I DCS %	18 0.10%	1 0.001%	55 0.57%	12 0.14%	49 2.02%	17 0.82%
Type II DCS %	1 0.006%	0 0.00%	1 0.01%	1 0.01%	1 0.04%	2 0.09%

- On the one hand, it appears that no difference can be seen in type II DCS incidence. This incidence anyhow remains very low and could be related to yoyo diving, that is to say to the dive procedure and not to the decompression table.

On the other hand, a significant improvement has been achieved for type I DCS incidence (p<3% for Prt<=25, p<0.001% for 25<Prt<=35, p<0.1% for Prt>35), a much encouraging result for the table designers, even though the process is very slow.

The underlying causes to the DOE results

With the above results in hand and an increased faith in the arterial bubbles model, it becomes possible to draw a scenario explaining the results of the DOE survey of air diving operations in the North Sea. Three mechanisms are identified and their results are overlaid. The scenario is illustrated by plotting hypothetical DCS cases in a depth versus time diagram :

- type II DCS is produced by yoyo diving, regardless of the decompression technique and the decompression table. They are randomly distributed over the dive exposures with perhaps a concentration close to the surface due to the higher importance of the Boyle's law (fig 1a),
- type II DCS is specifically produced by the surface decompression, for the dive exposures with a Prt>25 (fig. 1b),
- type I DCS risks increase with the exposures, regardless of the decompression technique used (fig.1c),
- combining the three above diagrams gives a resulting picture (fig. 1d) surprisingly close to the actual ones published by the Dr. T Shields in the DOE report.

CONCLUSION

Separating the two manifestations of the decompression sickness, and working with the arterial bubbles model, it has been possible to show using commercial diving data bases that :

- the surface decompression technique seems to have a "natural" safe limit of use, corresponding approximately to the DOE Safety Memorandums.
- beyond this limit, the surface decompression technique tends to produce a significant higher rate of type II DCS than a continuous decompression.
- no-stop, in-water and bell TUP decompressions also produced type II DCS, but a significant part of these cases could be related to yoyo diving.
- type I DCS seems to be related to the severity of thte dive exposure, regardless of the decompression technique.
- the risk of type I DCS can be reduced by designing improved decompression tables.

The immediate practical implication is that adequate procedures must be followed to control the type II DCS risk while adequate tables must be supplied to control the type I DCS risk. The message is presently brought to the Comex divers in the form of :

Dive the right tables to avoid bends, Use the right procedures to avoid serious DCS.

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Figure no 1 : A possible scenario explaining the results of the DOE survey of air diving operations in the North Sea.

Fig. 1a : type II DCS is first produced by yoyo diving. These cases depend neither on the decompression technique nor the table but on the dive procedures. They are randomly distributed with perhaps a higher concentration close to the surface due to the increased importance of the Boyle's law.

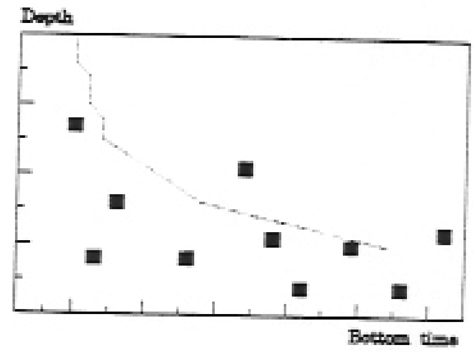

Fig. 1b : type II DCS is then specifically produced by the surface decompression associated to severe exposures. A cluster appears beyond a "natural" safe limit.

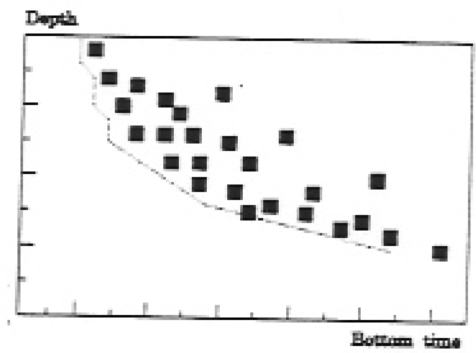

Fig. 1c : type I DCS is only related to the severity of the exposure, I.E. the tissue gas load. The cases do not depend on the decompression technique used. The more severe the exposure, the higher the number of cases.

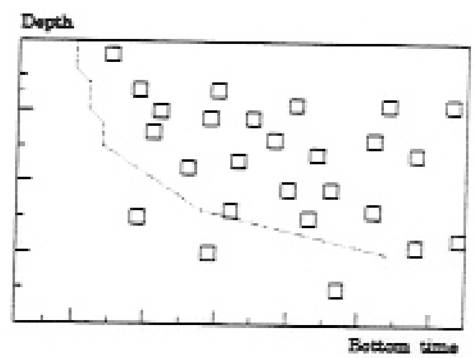

Fig. 1d : This figure summarizes the various DCS cases of the figures 1a, 1b and 1c in the same diagram.