SHORT AND REPETITIVE DECOMPRESSIONS IN AIR DIVING PROCEDURES: THE COMMERCIAL DIVING EXPERIENCE

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Commercial diving uses a wide variety of procedures, some of which can be questioned on the basis of the pressure changes they introduce. Models were used to analyze data from the Comex data base on yo-yo diving, surface decompression diving, repetitive diving and split-level diving. It was found that the arterial bubble model provides a simple explanation for the occurrence of Type II decompression sickness in yo-yo diving and surface decompression diving. This result shows the limit of the U.K. Department of Energy approach in restricting in-water decompression exposures in the North Sea U.K. sector.

Introduction

Offshore commercial diving relies on air diving for shallow operations. During the past 10 years, its importance has significantly increased due to the development of inspection and maintenance programs on platforms. However, the limits of air diving remain those of bounce diving: short bottom times and safety of decompression.

To cope with these limits, the diving contractors have developed a variety of procedures. Their diving manuals propose a range of basic diving procedures such as in-water decompression, surface decompression (sur-D) or transfer under pressure (TUP) and offer the possibilities to combine them with oxygen stops, repetitive diving, split-level diving or nitrox diving for operational flexibility.

The resulting safety performances can be estimated from the information compiled by T. Shields (Giles, 1989) for the U.K. Department of Energy (DOE) in a survey of air diving operations in the North Sea U.K. sector (this report will be later referenced as the DOE report). Examining exposures of 1988, 17,044 dives were recorded which lead to 6 Type I cases and 11 Type II cases, corresponding to an overall decompression sickness (DCS) incidence of 0.10%.

This paper proposes to further investigate the safety performances of special air diving procedures using the Comex diving reports data base (Imbert and Montbarbon, 1990).

Selecting a Model for Data Analysis

We selected two models for analysis to help clarify the data. The first one will be called the tissue gas load model. Analysis of these DOE report data was conducted by Shields using pressure versus time diagrams. It must be noted that plotting DCS in pressure versus time diagrams implicitly refers to a relationship between DCS occurrences and tissue gas loads. In a first approximation, the tissue gas load depends on the depth and the bottom time of the dive.

Shields used these diagrams to draw a limiting line separating safe and unsafe exposures assuming that:

- DCS is related to tissue gas load at the end of the bottom phase;
- therefore there must be a tissue gas load threshold that induces DCS;
- since tissue gas load is a function of depth and time;
- hence depth and time limitations will be the way to safer diving.

This rationale was the basis of the DOE Safety Memorandums (DSM) restricting the air diving exposures in the U.K. sector. These DSM initially concerned surface decompressions (U.K. DSM, 1986) but later extended to in-water decompressions (U.K. DSM, 1988). Such limitations for in-water or TUP decompressions were questioned at the 1990 EUBS Workshop on operational dives data bases (Imbert and Montbarbon, 1990).

The tissue gas load model provides a reasonable explanation for tissue bubble formation. It is accepted that bubbles in the connecting tissues of the articulations may induce pain-only DCS. The tissue gas load can be easily modeled and is the basis of decompression table calculation. However, the use of the tissue gas load model for the prediction of Type II DCS is subject to controversy.

One alternative approach is the arterial bubble model or critical diameter model (James, 1982; Hills and James, 1982). This model considers gas bubbles initially trapped in the lung filter during normal decompression. Following a recompression, they may pass the lung and be dumped into the arterial bed, reaching a neurological tissue and causing a Type II DCS. Another scenario considers that a rapid ascent to the surface may generate bubbles of a diameter small enough to cross the lung (Hennessy, 1989). This model raises three points:

- DCS should not be treated as a whole. Type I and Type II DCS should be studied separately because their mechanism differs.
- Current decompression tables might only cover the Type I DCS risk: the models they use cannot predict Type II DCS occurrence.
- Some diving procedures should be questioned: the recompression they introduce might facilitate the transfer of bubbles through the lung.

The concern is whether a higher risk of Type II DCS exists with diving procedures involving short and/or repetitive recompressions such as:

- "Yo-yo diving", which applies to the case of shallow diving associated with frequent returns of the diver to the surface to pick up tools or equipment.
- Surface decompression where the divers rapidly ascend to the surface prior to recompression in a deck chamber for the rest of their decompression need.
- Split-level diving which is used in inspection works and permits the divers to operate at various depths on jacket nodes.
- Repetitive diving when the divers perform a second dive with a surface interval of less than 12 hours.

The Comex Air Diving Procedures

Comex has developed a strong company culture under the influence of Dr. X. Fructus and has always used original decompression procedures.

The 1974 Comex air tables.

The first Comex air decompression tables were computed in 1972 and validated during onshore trials by Dr. X. Fructus and C. Agarate. The final version of the tables for in-water decompressions became the French official air tables in 1974.

These tables were computed using a classical "Workman model" based on 12 tissue half-times and M-values (Workman, 1965). The model was further complicated as DCS occurred during the trials and modifications were introduced: the tissue half times were altered during the ascent and some of the M-values became a second degree function of the ambient pressure. The final model (unpublished) has some interesting features.

Repetitive tables assumed the worst possible case for the computation of the second decompression. The 12 tissue residual nitrogen contents were supposed to be equal to their M-values at the end of the first dive. Of course, this is never the case, but the assumption allows the computation of a repetitive table without having to consider the characteristics of the previous dive. The advantage was that the 1974 Comex repetitive tables were printed for each surface interval and ready for use without any calculation.

It must be noted that these tables only permit one repetitive dive. During the trials, Dr. Fructus attempted to use the model to design tables for a second repetitive dive but the project aborted after a series of serious Type II DCS occurrences.

Surface decompression tables were provided for limited exposures. The model ignored the ascent to the surface but introduced a safety margin to compensate for it. These tables remained in use at Comex until 1986. At this time, the concern became the increasing number of Type I DCS associated with deep and/or long exposures. This risk was documented statistically using 60,000 man-exposures stored in the Comex computer data base (Imbert and Bontoux, 1986) and the tables were revised.

The 1986 Comex Air Tables.

New tables were calculated using an extremely simple model (unpublished). It consisted of an unlimited series of tissue half-times associated to a single M-value and had only 3 parameters or degrees of freedom. The parameters were determined by fitting the model predictions to the Comex 1974 table exposures using the maximum likelihood method (Homer and Weathersby, 1985).

Because the model was fitted to data which only contained Type I DCS, it is recognized that its predictions remain limited to this type of DCS. However, the new set of decompression tables was successfully validated during two years on Comex work sites, both for in-water and surface decompression, single and repetitive dives (Imbert and Bontoux, 1987) without any Type II DCS recorded. These tables became the 1986 Comex tables and were later included in the new 1990 French regulations.

The 1986 Comex tables introduced a method for determining a decompression after a split-level dive. The principle is based on the equation:

$$P_1.t_1 + P_2.t_2 <= P_e.(t_1+t_1)$$

Where:

- P_1: pressure at the first work level,
- t_1: time at the first work level,
- P_2: pressure at the second work level,
- t_2 : time at the second work level,
- P_e : pressure at the equivalent depth.

Using an exponential tissue model, this holds true when the first level is the deeper one and allows selection of a decompression for a two-level dive using an equivalent depth $P_{e.}$ computed from the above equation. The equivalent depth can be derived from a simple table without calculation (figure 1).

TABLE OF EQUIVALENT DEPTHS FOR SPLIT LEVEL DIVING

TIME SPENT AT WORK LEVEL	DEPTH OF WORK LEVEL														
	9 m	12 m	15 m	18 m	21 m	24 m	27 m	30 m	33 m	36 m	39 m	42 m	45 m	48 m	51 m
5 min	5	6	8	9	11	12	14	15	17	18	20	21	23	24	26
10 min	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51
15 min	14	18	23	27	31	36	41	45	50	54	59	63	68	72	77
20 min	18	24	30	36	42	48	54	60	66	72	78	84	90	96	102
25 min	23	30	38	45	52	60	68	75	83	90	98	105	113	120	128
30 min	27	36	45	54	63	72	81	90	99	108	117	126	135	144	153
40 min	36	48	60	72	84	96	108	120	132	144	156	168	180	192	204
50 min	45	60	75	90	105	120	135	150	165	180	195	210	225	240	255
60 min	54	72	90	108	126	144	162	180	198	216	234	252	270	288	306
70 min	63	84	105	126	147	168	189	210	231	252	273	294	315	336	357
80 min	72	96	120	144	168	192	216	240	264	288	312	336	360	384	408
90 min	81	108	135	162	189	216	243	270	297	324	351	378	405	432	459
100 min	90	120	150	180	210	240	270	300	330	360	390	420	450	480	
110 min	99	132	165	198	231	264	297	330	363	396	429	462	495		
120 min	100	144	180	216	252	288	324	360	396	432	468	504			
130 min	117	156	195	234	273	312	351	390	429	468	507				
140 min	126	168	210	252	294	336	378	420	462	504					
150 min	135	180	225	270	315	360	405	450	495						
180 min	162	216	270	324	378	432	486	540							
210 min	189	252	315	378	441	504	567								
240 min	216	288	360	432	504	576									
270 min	243	324	405	486	567										
300 min	270	360	450	540											

Always work out the calculation of the equivalent depth before the dive in order to make sure there is an available corresponding decompression table.

HOW TO USE THE TABLE :
- Determine the first working depth D1 and the associated bottom time T1.
- Enter the table with D1 and T1 and read the coefficient C1.
- Determine the second working depth D2 and the associated bottom time T2.
- Enter table with T2 and D2 and read coefficient C2.
- Add T1 to T2 to obtain the total bottom time T3.
- Add C1 to C2 to obtain the sum of the coefficient C3.
- Use the table to determine the equivalent depth. Find T3 in the time column. Read across to find the coefficient equal to or greater than C3. Read up from this to get the equivalent depth.
- Select the decompression table using this equivalent depth and T3 as bottom time.

Figure 1. The Comex method for calculating split-level decompression using an equivalent depth. Two levels are permitted but the first one must be the deepest one.

Use of the Comex Air Procedures

The divers.

Each year, between 350 to 600 divers are involved in air diving on Comex work sites. Most of them carry out no more than 10 air dives per year and concentrate on saturation diving. Others specialize in air diving operations and may perform more than 60 air dives per year (figure 2).

The diving methods.

Air table possibilities depend on the diving methods used. SCUBA diving is restricted to shallow and short dives. Surface supplied diving constitutes the majority of commercial dives, the divers being generally deployed using a basket or a wet bell. TUP diving allows a better control of the depth and a higher comfort of the diver but remains marginal because of the cost of mobilization of bell diving gear.

Table 1: 1990 Comex air diving activity sorted according to the diving methods.

Diving method	SCUBA diving	Surface supplied diving	TUP diving
Number of dives	1426	10584	61
Percentage	12%	87.5%	0.5%

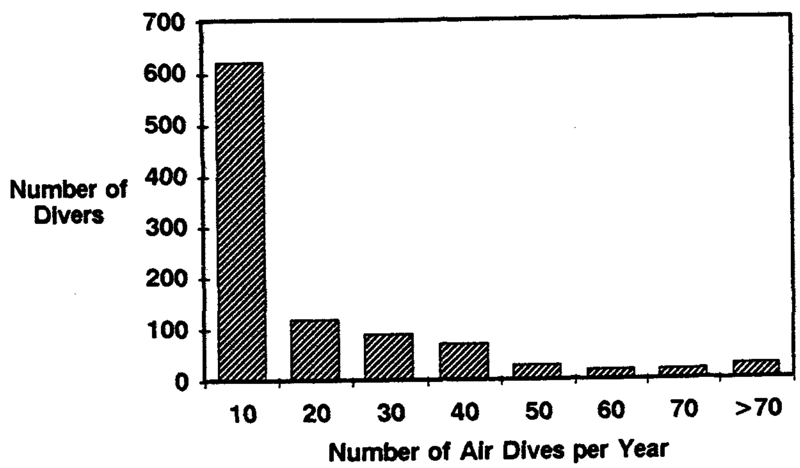

Figure 2. Chart of the number of air dives carried out each year by the Comex divers.

The decompression procedures.

In France, the risk of Type II DCS following sur-D tables was soon recognized and surface decompression was banned by the 1974 French regulations. Surface decompression has been rehabilitated in the 1990 French regulations but Comex has kept a tradition of in-water decompression while the rest of the diving contractors use mostly sur-D tables. Generally, in-water decompression is used in warm waters such as in West Africa, Middle East and Far East while surface decompression is preferred in the North Sea.

The repetitive tables.

Repetitive diving represents only a small fraction of the Comex diving activity. The supervisors prefer to organize the job with one long dive per day rather than two short ones. This allows rotation of the various functions in the team (diver, tender, stand-by diver). It must also be admitted that the repetitive decompression times are longer and difficult to fit within the 12 hour shift.

Table 2 : 1990 Comex air diving activity sorted according to single and repetitive dives.

Decompression method	single dives	repetitive dives
Number of dives	11,486	585
Percentage	95%	5%

Repetitive diving is sometimes required for operational reasons, such as tidal diving. This is the case for instance in the southern North Sea or in Argentina where three tides per day and strong currents make diving only possible during the short slack water periods when the tide turns. The problem was addressed in the Guidance Note No. 048 of the U.K. Association of Diving Contractors with special attention to the personnel level.

Results and Discussion

Yo-yo diving.

Yo-yo diving is unfortunately a common practice, even though it has always been recognized as a dangerous procedure in diving manuals. Although yo-yo diving may be suspected as a contributing factor in any serious DCS, it is interesting to study its influence on DCS occurring in the air no-stop decompression area. This permits elimination of the possible role of the decompression table.

The Comex data base holds records of 4 Type II DCS for such exposures, 3 of them having a recognized history of pressure changes and the last one a too rapid ascent to the surface, as presented in the table below.

Table 3. Case history of 4 Type II DCS occurrences with the air no-stop decompression exposures.

Case	Max. Depth	Bottom Time	Comments
1	12 m	89 min	Inspection work, several ascents to the surface. Paralysis of the face. Symptom reported 40 h after the end of the dive.
2	9 m	212 min	Work on a riser clamp, heavy swell (3m). Vertigo and nausea. Symptoms reported 30 min after the end of dive.
3	33m	15 min	SCUBA diving, too rapid ascent to the surface. Visual problems, pins and needles. Symptoms reported 2 h after the end of the dive.
4	21 m	30 min	Inspection work, several depth changes. Vertigo, pins and needles. Symptoms reported 20 min after the end of dive.

These cases indicate a strong correlation between yo-yo diving and the risk of Type II DCS in the no-stop decompression exposures. Such DCS cannot be accounted by the tissue gas load model - the tissue gas load is minor and does not even require a decompression stop - but are simply explained by the arterial bubbles model.

Similar cases have been compiled by T. Shields in the DOE report. A total of 6 Type II DCS are mentioned for no-stop decompressions recorded between 1982 to 1988. No information is provided on the dive profile of these accidents.

This is the problem of the investigation of Type II DCS because the diving supervisors usually do not report the pressure changes in the dive logs. It is also the limit of computer data bases collecting the information contained in the diving reports. They are unable to consider the eventual pressure changes and thus correlation of Type II DCS and dive profiles. The alternative would be to work on information recorded continuously with electronic dive loggers, but these devices remain expensive and very demanding in computer power for processing records.

Surface decompression diving.

There is one case where the pressure variation can be documented without a dive recorder, *i.e.* surface decompression. In surface decompression the ascent to the surface is built into the dive procedure. The surface interval is of course variable but we know that it is restricted to 5 minutes in the U.S. Navy procedures and to 3 minutes in the Comex tables. Surface decompression is an interesting opportunity to test the predictions of the arterial bubble model by comparing sur-D tables with tables using a continuous ascent to the surface, such as in-water or TUP decompressions.

The comparison is made between the two methods in Table 4. The first source of information is the DOE report and the data are extracted from the 1982 to 1986 operations. The second source is data from the Comex data base on air dives recorded from 1976 to 1983 (Imbert and Bontoux, 1986). Both have been combined for the in-water and TUP decompressions in the last column. The limit of such a comparison is that the safety performances of a table much depend on the exposures selected and it must be verified that the partition of the exposures was the same in sur-D, in-water and TUP dives considered in the test. This appears to be an acceptable assumption considering the various exposure patterns expressed using the "Prt index" (Pressure x square root of time) defined by Dr. T. Shields in the DOE report (Fig.3).

Table 4. Comparison of performances of sur-D and in-water or TUP tables from different sources.

Source	DOE report sur-D 1982-86	DOE report in-water and TUP 1982-86	Comex in-water and TUP 1977-86	Combined DOE + Comex in-water and TUP
Number of dives All exposures	49,742	11,867	31,196	43,063
Number of Type I	152	25	118	143
Percentage	0.30%	0.21%	0.38%	0.33%
Number of Type II	89	5	4	9
Percentage	0.18%	0.04%	0.01%	0.02%

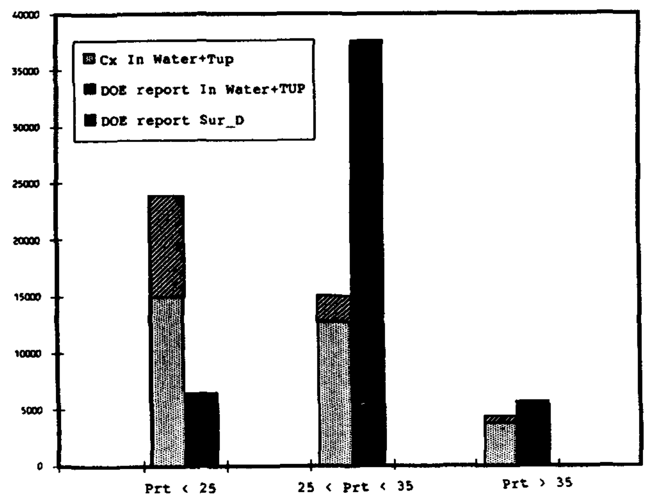

Figure 3: Comparison of exposures patterns of the DOE report surface decompression dives and the combined DOE report/Comex in-water and TUP decompression dives presented in Table 4. The exposures are categorized according to the Prt index (Pressure x square root of time) defined by Dr. T. Shields in the DOE report.

First, it can be noted that the Type I DCS rates appear to be similar for sur-D and in-water or TUP decompressions. Second, it appears that the sur-D have a significantly ($p < 10^{-6}$) higher rate of Type II DCS than in-water or TUP decompressions. This is much in favor of the arterial bubbles model that recommends continuous ascent to the surface. There is also some doubt that the few Type II DCS recorded with in-water or TUP decompression might be associated with some pressure changes or yo-yo diving but this cannot be demonstrated with present data bases.

These results show the limit of the Dr. T. Shields' approach in the DOE report. The limiting line drawn in the pressure versus time diagrams permits the separation of Type I DCS but certainly not Type II, because of their different mechanism. The exception is surface decompression, where the pressure change is integrated into the procedure and thus, well documented. In this case it is justified to expect to define a frontier between high and low Type II DCS risk exposures and this is effectively observed for sur-D tables in the DOE report. It would be interesting to know how this frontier is defined for diving companies that use 15m recompression for sur-D. However, such a limit does not apply to in-water decompressions, where the pressure variations are random. The results thus support the DSM limiting exposures for surface decompressions, but not for in-water decompressions. In any case, if in-water decompressions were to be restricted, as they have shown to be safer, their limit should be more permissive.

Repetitive diving.

There is a second case where the pressure variations are defined in the procedures, that is repetitive diving. In repetitive diving a recompression occurs at the beginning of the second dive, after a surface interval that may vary from 0 to 12 hours. The 12-hour surface interval is considered by the U.S. Navy manual sufficient for the divers to clear any effect from the previous dive. The Comex 1974 tables used to consider an 8-hour surface interval for a single dive but this was changed to 12 hours in the last revision to align with the U.S. standards, purely for political considerations. Table 5 below presents data from the Comex data base on repetitive dives performed from 1977 to 1986.

Table 5. Safety of 1974 Comex air repetitive tables sorted according to the surface interval.

Interval	6:00	4:00	3:00	2:00	1:30	1:00	0:30	0:00
Number of dives	2688	1371	321	254	110	287	343	140
Number of Type I	4	5	2	1	1	4	1	0
Percentage	0.15%	0.36%	0.62%	0.39%	0.90%	1.39%	0.29%	0%
Number of Type II	0	0	0	0	0	0	0	0
Percentage	0%	0%	0%	0%	0%	0%	0%	0%

According to the arterial bubble model, the problems in repetitive diving are expected to happen with short surface intervals. However, the data collected in this area are insufficient to draw any conclusions. The longer surface intervals only, and especially the 6-hour surface interval, can support a statistical analysis. These repetitive tables have only produced Type I DCS, and their rate of incidence does not significantly differ from the one for single dives.

This data confirms the importance of the time factor. It seems that the number of available bubbles supposed to be able to pass the lung filter significantly decreases as the time passes. It appears that, after 6 hours, the recompression following the beginning of the second dive no longer produces arterial bubbles.

Split-level diving.

Split-level diving tables have been regularly used since their introduction and approximately 1,000 man-exposures have been recorded, all with in-water decompression. The way the Comex procedures are conducted, starting with the deeper level first, is unlikely to produce pressure changes with dramatic consequences. Effectively, no problem of decompression of any type has been reported with these tables.

Conclusion

Two models have been used, the tissue gas load model used by Dr. T. Shields in the DOE report and the arterial bubbles model, to analyze short and/or repetitive recompressions in commercial air diving procedures.

The arterial bubbles model successfully permitted correlation of Type II DCS occurrences with depth changes or recompressions. The contributing effect was found significant in yo-yo diving and surface decompression diving. In repetitive diving, the available data indicate that the risk of Type II decreases as the surface interval increases. No problem of any type was encountered with the Comex split-level tables.

This work shows the limit of Dr. T. Shields' approach in the DOE report. The pressure versus time diagrams can effectively describe the Type II DCS partition when the pressure variations are built into the procedures as for surface decompression, but not when they are random as with the in-water decompression. The arterial bubble model thus supports the limits imposed by the DOE for surface decompressions but not for in-water decompressions. In any case, if in-water decompressions were to be restricted, the data collected show that the limits should be more permissive.

This work permits to recall, after the 1990 EUBS workshop at Amsterdam, that future improvements in decompression safety will have to rely on accurate dive profile recording based on electronic dive recorders and the associated computer treatment capacity.

Finally, the study allows to draw an immediate practical conclusion. The highly random process involved in the generation of the arterial bubbles makes table designers desperate to ever find a model for such events. If no table can be produced to prevent Type II, the divers will have to learn to avoid depth changes and pressure variations. This new philosophy could be summarized as follows:

- use the right table to avoid Type I and,
- use the right procedures to avoid Type II.

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