Decompression sickness during construction of the Great Belt Tunnel, Denmark.

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Andersen HL, Decompression sickness during construction of the Great Belt Tunnel, Denmark. Undersea Hyperb Med 2002; 29(3): 172-188 - Thirteen cases of decompression sickness (DCS) occurred during the construction of the 8-km long railway tunnel under the Great Belt in Denmark between January 1992 and February 1996. 320 compressed air workers were subjected to 9018 pressure exposures in four tunnel boring machines. Overall DCS incidence was 0.14%. Working pressures ranged between 0.25 bar (1.25 atm abs or 126.3 kPa) and 2.95 bar (3.91 atm abs or 396.3 kPa) and working times ranged between 2 minutes and 339 minutes. During the first 1798 pressure exposures 7 DCS cases occurred using French air decompression tables from 1974. The following 7220 exposures were then decompressed in accordance with the newly issued French air decompression tables of 1992. After changing schedules 6 DCS cases occurred and DCS incidence was reduced to 0.08%. Two of the first seven DCS cases had permanent residual symptoms after recompression treatment. All DCS cases, except one, occurred among the 30 % of exposures that imposed the greatest decompression stress. DCS incidence among these exposures was 0.42%.

compressed air work, decompression sickness, French air decompression tables, decompression stress, DCS.

INTRODUCTION

The construction of the twin bored railway tunnel under the Great Belt Eastern Channel was the first major tunnel project in Denmark using compressed air workers (CAW). The 8-km long and 75 m deep tunnel was built using compressed air work over a four-year period between January 1992 and February 1996. To minimize the risk of decompression sickness (DCS) the French air decompression tables for compressed air workers were chosen for the project. Workers were hired from several different countries including Denmark to operate four tunnel-boring machines (TBM) in the compressed air environment. Experienced diving supervisors from the Danish offshore industry handled the decompression procedures and supervised the health and safety of CAW. Air pressure was required in the work chamber at the cutterhead of the TBM during the manned interventions in order to inspect and repair the cutting tools of the TBM.

A minimum of four men conducted every manned intervention in the work chamber of the TBM. One team leader and two workers were compressed in the personnel lock adjacent to the work chamber while one supervisor stayed outside to handle the decompression procedures. Two of the three men in the personnel lock crawled into the work chamber while one stayed in the lock as a tender in radio contact with the outside supervisor. The working time ranges for pressure exposures in the personnel locks and work chambers of the TBMs were between 2 minutes and 339 minutes.

There was a minimum rest period of 48 hours after 7 consecutive days of work. Repeated interventions within 12 hours rarely occurred. The pressure ranges for exposures in the TBM were between 0.25 bar (1.25 atm abs or 126.3 kPa) and 2.95 bar (3.91 atm abs or 396.3 kPa). In addition 53 pressure tests were made in the hyperbaric treatment chamber outside the tunnel at site at maximum pressure 4.8 bar (5.74 atm abs or 581.3 kPa). All CAW were instructed to stay in the vicinity of the hyperbaric treatment chamber at site for a 2 to 3 hour "bends watch" after decompression. The diving supervisor was contacted if any symptoms of illness occurred. Logbook data and history of the last pressure exposure was noted in a DCS examination report by the diving supervisor, who also performed a physical examination of the CAW involving a standardized neurological examination. If decompression sickness was suspected the diving supervisor made the decision to start recompression treatment and recompressed the CAW to 1.8 bar (2.8 atm abs or 281.3 kPA) breathing 100% oxygen in the hyperbaric treatment chamber. The Diving Medical Officer on call was then contacted for further advice.

The 1974 edition of the French decompression tables was used during the first nine months of the tunnel project. In addition, acclimatization exposures were used during this period in the form of one non-working pressure exposure at the current working pressure for CAW personnel who had not been exposed for some time. After the occurrence of the first 7 DCS cases, a "safety factor" was added in July 1992 to the decompressions in the form of one time-step up in the 1974 tables. The decompressions were changed, in September 1992, to follow the newly modified edition of the French air decompression tables issued in June 1992. This change mainly resulted in extensions of the decompression times. The acclimatization exposures and the "safety factor" were according to the logbooks not used after the change of schedule. Extra decompression time was added in both schedules by a one pressure-step up in the table if the temperature in the work chamber exceeded 27 degrees Celsius.

All applicants accepted as compressed air workers had to fulfill the requirements of a medical examination equal to the standards of diving medical examinations. Long bone X-rays were taken in order to diagnose pre-existing osteonecrosis. There was no follow-up regarding dysbaric osteonecrosis. The medical examination reports were not made available to the author.

Thirteen DCS cases in all received recompression treatment. Ten DCS cases received treatment in the hyperbaric treatment chamber at site, where they -after an initial examination- received recompression treatment conducted by the diving supervisor after consultation with the Diving Medical Officer on call. The remaining three DCS cases received recompression treatment in the Naval hyperbaric treatment chamber in Copenhagen. 16 CAW reported symptoms of illness to the diving supervisor that did not lead to recompression treatment since the symptoms were interpreted by the diving supervisor as not being related to decompression sickness.

METHOD

This study is a retrospective evaluation made after the completion of the tunnel. A/S EM.Z.SVITZER kindly made all logbooks, manuals and DCS examination reports available. The logbooks contained information of name of the CAW, date, working pressure (noted as gauge pressure: bar), working time, decompression time, entering time, exit time, total time and decompression tables used for all manned interventions throughout the project. All 13 DCS cases were documented in the DCS reports made by the diving supervisor. The Diving Medical Officer on call from the Danish Naval Technical School, Diving Course, also made medical notes regarding 10 of these DCS cases. Medical notes for the three remaining DCS cases recompressed on site were not made. The distinction between Type 1 and Type 2 DCS in some cases was initially not made clearly. The author interpreted therefore in some, but not all, cases this distinction after evaluation of the DCS examination reports and medical notes.

Due to the relatively small number of DCS cases, most of the results are presented in a descriptive manner. However, multiple linear regression analysis has been used to determine statistical correlations between data of work pressure, work time and DCS.

A total of 9018 pressure exposures by 320 compressed air workers were included in this study. All recorded exposures in the four TBMs as well as the pressure tests and acclimatization exposures in the hyperbaric treatment chamber were included in the study. 112 decompressions were excluded because the interventions were aborted, mostly due to middle ear equalization problems at low pressure after a short time in the personnel lock. 21 pressure tests in the hyperbaric treatment chamber of 5 workers were excluded; they eventually did not work as CAW in the TBM. Insufficient information in the logbooks led to the exclusion of 7 logbook sheets. 13 DCS cases were included in this study. Included as DCS cases were all compressed air workers in the tunnel project with symptoms of illness after decompression from a pressure exposure that received recompression treatment. The DCS case exclusion criterion was defined as the decision not to start or complete a recompression treatment of a CAW reporting symptoms of illness. Pressure values presented in the following are noted as in the original logbook notation: gauge pressure, but are also converted into absolute pressures noted in brackets.

RESULTS

Of CAW in this study, 50% were exposed to working pressure in the TBM 24 times or less and 25% were exposed less than10 times. Only 25% were exposed more than 42 times. The maximum number of pressure exposures was 94. The majority of the exposures (78%) were between 1.0 bar (2.0 atm abs or 201.3 kPa) and 2.0 bar (3.0 atm abs or 301.3 kPa) working pressure. Only 15% were above 2.0 bar (3.0 atm abs or 301.3 kPa) and 7% were below 1.0 bar (2.0 atm abs or 201.3 kPa). 1798 pressure exposures (20%) were decompressed according to the French 1974 decompression tables and 7220 pressure exposures (80%) were decompressed according to the 1992 tables. 2665 pressure exposures (30%) were below the no-decompression limit according to the French tables of 1992, while 6353 pressure exposures (70%) needed stage decompression.

Only 13 out of 320 CAW or 4% of the work force were treated for DCS. The overall DCS rate was 0.14% (13/ 9018). The DCS rate after pressure exposures above or equal to 1.0 bar (2.0 atm abs or 201.3 kPa) was 0.16%(13/8381). No DCS cases occurred after pressure exposures below 1.0 bar (2.0 atm abs or 201.3 kPa). One DCS case occurred after a pressure exposure of 203min at 1.0 bar (2.0 atm abs or 201.3 kPa) only 8 minutes from the no-decompression limit. The DCS incidence after exposures that needed stage decompression was 0.19% (12/6353). To investigate the relationship between DCS and the variables of pressure and working time, a multiple logistic regression analysis was performed that showed correlation between pressure and DCS (multiple logistic regression: P= 0.02). The same tendency was seen between working time and DCS but cases were too few to show statistical significance (multiple logistic regression: P=0.22).

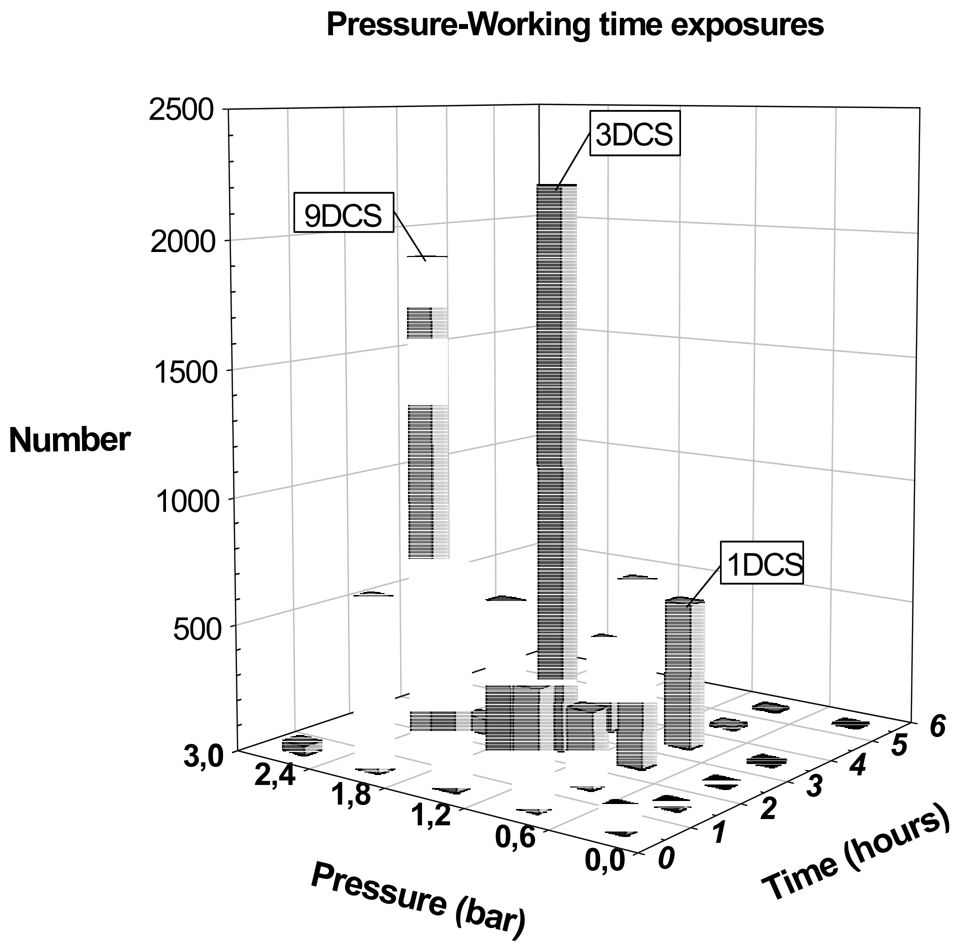

Figure 1. Number of exposures in intervals of gauge pressure 0.6 bar and time 1 hour. The number of DCS cases is indicated in the pressure/time interval where they appeared. The 53 test exposures at 4.8 bar in the hyperbaric treatment chamber are not shown.

The relationship between DCS and the variables of pressure and working time is also presented in Table 1.

Pressure/Time	0 –1 hours	1 - 2 hours	2 - 3 hours	3 - 4 hours	4-5 hours	5-6 hours	DCS %	Sample size
0-0.6 bar	84	13	7	8	0	3		115
0.6-1.2 bar	456	297	720	**(1)** 574	11	4	0,05%	2062
1.2-1.8 bar	844	645	**(3)** 2209	366	0	0	0,07%	4064
1.8 -2.4 bar	667	**(9)** 1932	59	0	0	0	0,43%	2058
2.4-3.0 bar	37	29	0	0	0	0		66
4.8 bar	53	0	0	0	0	0		53
All > 1 bar							0.16%	8381
All pressures							0.14%	9018

Table 1. Total exposures, DCS numbers and incidence in relation to gauge pressure and working time exposures. The numbers of exposures are listed in intervals of 0.6 bar working pressure and working times of 1 hour. Numbers of DCS cases in the intervals are indicated in brackets.

The first seven DCS cases in the project occurred within three days. Six of these DCS cases occurred on the same day in three consecutive shifts. Three DCS cases in the first shift two in the next and one in the last. All seven CAW were exposed to the same working pressure at 1.9 bar (2.9 atm abs or 291.3 kPa), and almost the same working time around 1 hour and 50 minutes. They were decompressed according to the same table 2.0 bar (3.0 atm abs or 301.3 kPa) pressure and 2 hours working time using the French 1974 decompression tables. Nine DCS cases occurred among "new-starters" within the first 5 pressure exposures. Four DCS cases occurred within only 1-2 exposures following 10 days to several months of absence. All DCS cases in the project occurred among CAW personnel exposed, within a maximum of five consecutive days of work, to working pressure in the TBM.

The distribution of pressure exposures and DCS cases before and after September 1992 is presented in Tables 2 and 3.

Pressure/ time	0-1hours	1-2 hours	2-3 hours	3-4 hours	DCS%	Sample size
0-0.6 bar	45	0	0	0		45
0.6-1.2 bar	162	175	419	31		787
1.2-1.8 bar	102	244	221	2		569
1.8-2.4 bar	123	**(7)** 267	7	0	1.85%	397
All > 1 bar					0.42%	1655
All					0.39%	1798

Table 2. Exposures decompressed using the French tables 1974 (max. pressure 2.2 bar (3.2atm abs or 321.3 kPa)

Pressure/Time	0-1hours	1-2 hours	2-3 hours	3-4 hours	4-5 hours	5-6 hours	DCS%	Sample size
0-0.6 bar	39	13	7	4	4	3		70
0.6-1.2 bar	294	122	301	**(1)** 543	11	4	0.07%	1275
1.2-1.8 bar	742	401	**(3)** 1988	364	0	0	0.08%	3495
1.8-2.4 bar	544	**(2)** 1665	52	0	0	0	0.09%	2261
2.4-3.0 bar	37	29	0	0	0	0		66
4.8 bar	53	0	0	0	0	0		53
All > 1 bar							0.09%	6726
All							0.08%	7220

Table 3. Exposures decompressed using the French tables 1992 (max. pressure 4.8 bar (5.74 atm abs or 581.3 kPa)

CLINICAL PRESENTATION

Six DCS cases had only mild Type 1 symptoms of joint pain or skin rash. Five DCS cases had serious neurological Type 2 symptoms. Two cases had apparently only mild, unclear symptoms of DCS such as headache and dizziness or tingling in hands and feet without neurological deficits. Some DCS cases had symptoms of both type 1 and type 2 DCS. Two DCS cases developed permanent residual symptoms. No CAW was subjected to DCS more than once. 16 CAW reported symptoms of illness to the diving supervisor that was not interpreted as DCS. The symptoms reported were mostly muscle and joint pain or headache and tiredness interpreted as strains or related other conditions than DCS. These individuals therefore did not receive recompression treatment. Although one of these CAW reported symptoms of illness to the diving supervisor, no action was taken to start recompression treatment. Upon later consultation at the local hospital, he was brought to the Navy recompression chamber in Copenhagen and received recompression treatment (DCS case no 13).

DCS Type 1 Symptom: Site: No:

Joint pain: Knee 3
Elbow 3
Ankle 1
Jaw 1

Skin rash: 2

DCS Type 2 Symptom: No:

Paraesthesia 3 Sensory loss 2
Unusual fatigue 2
Muscle weakness 2
Staggers 1
Cognitive deficits 1
Dizziness 1

Table 4. Independent listing of all DCS symptoms

In all DCS cases, the first symptoms appeared within 12 hours after completing decompression. Only two DCS cases reported symptoms of DCS less than 1 hour from decompression. One DCS case [Case 11]had symptoms of influenza and fevers the previous few days and did not report mild Type 1 DCS symptoms after an intervention in the TBM work chamber at 1.0 bar (2.0 atm abs or 201.3 kPa). However, after the following intervention the next day (also at 1 bar work pressure), the symptoms were reinforced. In three DCS cases symptoms were reported 4-5 days after completing decompression. The remaining DCS patients all reported symptoms within 24 hours. Most of them (six patients) reported symptoms between 1 hour and 2 ½ hours after completing decompression.

All recompression treatments started according to the US Navy Table 6. Eleven patients had full relief of symptoms. Two of these patients were recompressed with extensions one with extensions at 1.8 bar (2.8 atm abs or 281.3 kPa) the other patient was recompressed following US Navy Table 6A shortly after reaching the initial start of table 6 at 1.8 bar (2.8 atm abs or 281.3 kPa). The treatment of the two patients that developed permanent residual symptoms was more extensive. One was recompressed following US Navy Table 4 using oxygen shortly after the start of a US Navy Table 6. The other received repeated recompression treatments according to US Navy Table 6, the first time with extensions and the second time as Table 6A, then twice without extensions before deciding to stop further treatments because no progress was observed. In seven of the 13 DCS cases, the individual stopped working as a CAW immediately after recompression treatment. The remaining six DCS individuals were exposed to working pressure exposures between 5 and 55 times after successful recompression treatment.

Table 5. Brief case presentations

Case 1:	Date 6-7-92	Age 26.
	Work pressure 1.9 bar	working time 1 h 51 min.
	Table used:	2.0 bar at 2 hours, table 1974: 60 min deco.
	20 min. after deco:	1 symptom: Pain in left knee.
		2 symptom: Pain in left ankle.
	Time to report after deco:	1 h 40min.
	Time to treatment:	1 h 40 min: US Navy Table 6.
		Full relief. Type 1 DCS.
	Heavy alcohol consumption over 3 days before pressure exposure.	
Case 2:	Date 9-7-92	Age 27.
	Work pressure 1.9 bar	working time 1 h 50 min.
	Table used:	2.0 bar at 2 hours table 1974: 67 min deco.
	1 h 30 min after deco:	1 symptom: pain in right knee.

	Time to report after deco:	1h 30min.
	Time to treatment:	2 hours: US Navy Table 6.
		Full relief. Type 1 DCS.
Case 3:	Date 9-7-92	Age 36
	Work pressure 1.9 bar	working time 1 h 44 min.
	Table used:	2.0 bar at 2 hours table 1974: 70min deco.
	45 min after deco:	1 symptom: Tingling in hands and feet.
	1-2 hours after deco:	2 symptom: Pain in right femur and knee.
	Time to report after deco:	2 hours
	Time to treatment:	2 h 30min:US Navy Table 4.
		Residual symptoms, pain in right femur and minor muscular atrophy at the lower 1/3 of femur. Type 2 DCS.
		Permanently unfit.
Case 4:	Date 9-7-92	Age 46
	Work pressure 1.9 bar	working time 1 h 50 min.
	Table used:	2.0 bar at 2 hours table 1974: 67 min deco.
	10 hours after deco:	1 symptom: headache, heat and tightness in neck and shoulders. Unusual fatigue.
		Numbness and weakness of right arm and both hands.
		2 symptom: Disoriented and confused. Decreased short time memory and concentration difficulty.
	Time to report after deco:	21 h 30min.
	Time to treatment:	22 hours US Navy Table 6+, 6A, and 6 x 2, (4 times)

		Residual neuro-psychological problems. And right side hemiparesis. Type 2 DCS.
		Permanently unfit.
Case 5:	Date 9-7-92	Age 46
	Work pressure 1.9 bar	working time 1 h 50 min.
	Table used:	2.0 bar at 2 hours table1974: 67min deco.
	5 hours after deco:	1 symptom: Tingling in hands and feet.
	Time to report after deco:	12 hours but was uncertain. Examined by a neurologist but no deficit was detected. Decided to wait and see. But symptoms remained the same.
	Time to treatment:	26 hours: US Navy Table 6
		Full relief. Type (?) DCS
Case 6:	Date 9-7-92	Age 28
	Work pressure 1.9 bar	working time 1 h 54 min.
	Table used:	2.0 bar at 2 hours, table1974: 62 min deco.
	2 hours after deco:	1 symptom: Headache and dizziness.
	Time to report after deco:	4.5 days
	Time to treatment:	4.5 days: US Navy Table 6
		Full relief. Type (?) DCS
Case 7:	Date 9-7-92	age ?
	Work pressure 1.9 bar	working time 1 h 54 min.
	Table used:	2.0 bar at 2 hours, table 1974: 62 min.
	A few min after deco:	1 symptom: Headache and pain in left ear and temporomandibular joint.
		2 symptoms: staggers.

	Time to report after deco:	4.5 days
	Time to treatment:	4.5 days: US Navy Table 6A
		Full relief. Type 2 DCS
Case 8:	Date 23-1-93	Age 24
	Work pressure 1.6 bar:	working time 2 h 25 min
	Table used:	1.65 bar at 2 h 30 min, table1992: 62min deco.
	15 min after deco:	1 symptom: Loss of upward movement in right Wrist. (Muscle weakness?).
	Time to report after deco:	20 min
	Time to treatment:	40 min: US Navy Table 6+ extensions
		Full relief. Type 2 DCS
Case 9:	Date 24-1-93	Age 24
	Work pressure 1.6 bar:	working time 2 h 39 min.
	Table used:	1.65 bar at 3 hours, table 1992: 77 min deco.
	2 hours after deco:	1 symptom: pain in elbow.
	Time to report after deco:	2 h 30min.
	Time to treatment:	3 hours: US Navy Table 6
		Full relief. Type 1 DCS
Case 10:	Date 27-1-93	Age 25
	Work pressure 1.6 bar	working time 2 h 18 min.
	Table used:	1.65 bar at 2h 30 min, table 1992: 59 min deco.
	2 hours after deco:	1 symptom: Itchy skin rash on abdomen
	Time to report after deco:	2 h 10min
	Time to treatment:	6 hours: US Navy Table 6
		Full relief. Type 1 DCS

Case 11:	Date 1-3-93	Age 35
	Work pressure 1 bar	working time. 3 h 23 min.
	Table used:	1.2 bar at 3 h 30 min, table 1992: 25 min deco.
	6 hours after deco:	1 symptom: Pain in left elbow.
	Time to report after deco:	not reported
Date 2-3-93:	Work pressure 1 bar	working time 1 h 11 min
	Table used:	1.2 bar at 1 h 30 min. French table 1992
	Under working pressure.	2 symptom: feeling dizzy and unwell
	3 min after deco:	3 symptom: Pain in left elbow and failed “sharp/blunt” test on left forearm
	Time to treatment:	1 h 30 min: US Navy Table 6 Full relief. Type 1 DCS
	Other symptoms:	Influenza with fever past few days.

Case 12:	Date 25-7-93	Age 24
	Work pressure 2.05 bar	working time 1 h 50 min.
	Table used:	2.1 bar at 2 hours; table1992: 96 min deco.
	1 hour after deco	1 symptom: skin rash and ache over left Shoulder
	Time to report after deco:	1 hour
	Time to treatment:	2 hours: US Navy Table 6 Full relief. Type 1 DCS

Case 13:	Date 11-8-93	Age 42
	Work pressure 2.35 bar	working time 1 h 25 min.

Table used:	2.4 bar at 2 hours, table 1992: 133 min deco
12 hours after deco:	1 symptom: pain in right shoulder and elbow, tingling in feet and unusual fatigue.
	2 Symptom: decreased sensibility of left back and left posterior femur on examination
Time to report after deco:	5 days (to local hospital)
Time to treatment:	5 days: US Navy Table 6
	Full relief. Type 2 DCS

DISCUSSION

Several reports and evaluations exist of tunnel projects from USA, England, Hong Kong, Singapore, Brazil and Germany using the Washington State-, Blackpool- or German tables with and without oxygen decompression (1,2,3,4,5,6,7,8,9,10,11,12,13). Many of these differ with respect to working conditions and risk factors involved. Overall DCS incidences from exposures above 1.0 bar (2.0 atm abs or 201.3 kPa) from most of these projects vary between 0.2% and 2%. All studies show increasing DCS incidence with increasing working pressure and time. Accepting the weakness of comparisons between different studies, the French air decompression tables in the Great Belt tunnel project have performed very well when comparing the overall DCS incidences. The two groups of data sampled in the Great Belt tunnel project before and after changing decompression tables present a possibility for a more detailed comparison of the effectiveness of DCS prevention between the French decompression tables of 1974 and 1992. Comparing the DCS incidences before and after the change of schedules in September 1992, an improvement is observed that indicates a reduction in the frequency of DCS. There were, however, only few DCS cases in this project. A cluster of cases occurred, seven DCS cases in three days (54% of all cases), six of these on the same day. Considering also the 16 CAW reporting symptoms of illness after a pressure exposure and after the change of schedule, but not receiving recompression treatment, the comparison between the two schedules becomes uncertain and must therefore be viewed with caution. Taking these things into account, there is no certain evidence in this retrospective evaluation that there was a difference in the frequency of DCS between the two schedules.

The first 7 DCS cases that occurred in three days indicate that other factors were involved than those related to the decompression tables. However, evaluation of logbooks, medical notes and DCS examination reports revealed no single factor that could fully explain this coincidence. The temperature in the work chamber was noted to be 21-22 C and could be of influence. Information from the diving supervisors indicate that the CAW personnel subjected to DCS sat in a cramped position because too much gear was brought in to the personnel lock and personnel were leaning against the cold walls of the personnel lock during decompression. Such a position is not optimal for tissue perfusion and could also be of influence. Seeing a fellow CAW being treated for DCS for the first time might have created some nervousness among some of the CAW resulting in recompression treatment merely on suspicion when unclear symptoms of DCS were presented. Dehydration is a commonly known DCS risk factor (5). Alcohol consumption and days of fever will most often cause some degree of dehydration. But to what extent this has played a role in two of the DCS cases is unclear. The author speculates that a combination of a relatively high level of hyperbaric stress along with a mixture of the risk factors and circumstances mentioned above is the most likely explanation for the occurrence of this cluster of DCS cases.

16 CAW reported symptoms of illness to the diving supervisor who interpreted the symptoms as being unrelated to DCS. But had the CAW under other circumstances been examined by a diving medical officer and given the benefit of doubt, the symptoms might have resulted in recompression treatment in some of these cases. DCS case 13 is an indication of such a diagnostic discrepancy. Most of the 16 cases occurred after pressure exposures with a level of hyperbaric stress as high as those cases that received recompression treatment as illustrated in Fig 2.

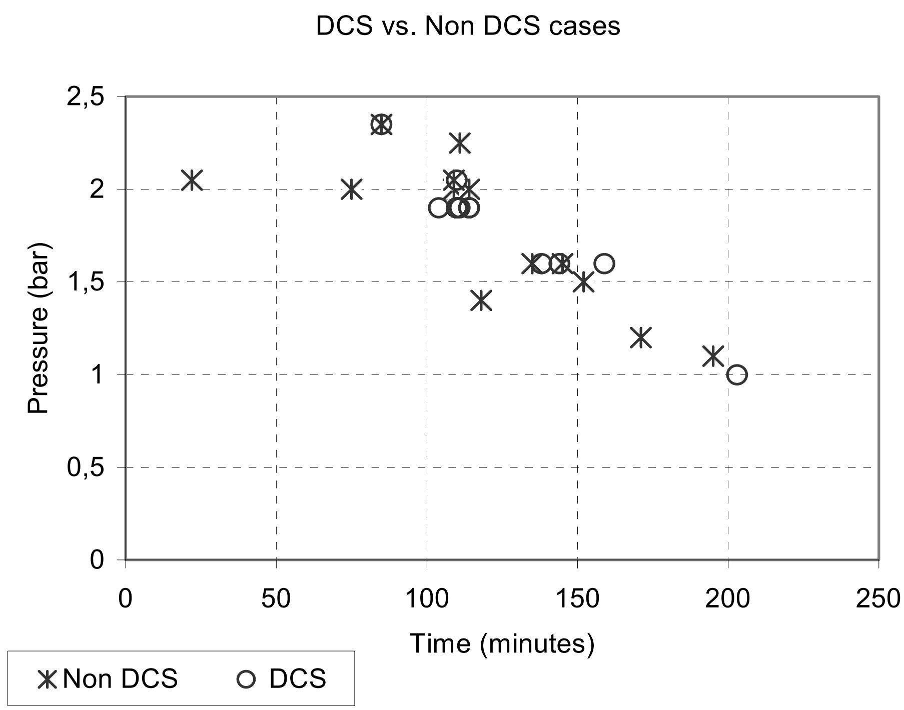

Figure 2. Pressure exposures of all CAW reporting symptoms of illness (the two cases of symptoms after a training session using oxygen are omitted)

All of the 16 non-DCS cases occurred after the change of decompression schedule. Two CAW reported symptoms after a training session breathing oxygen at 1.8 bar (2.8 atm abs or 281.3 kPa), no time was noted and these exposures are therefore not in the figure.

Underreporting of DCS symptoms affect the DCS rate (1). Fear of redundancy can be one reason for this. Underreporting is difficult to evaluate retrospectively, but indications of this problem are found among some of the DCS cases in this tunnel project. One individual did not report, or ignored the first symptoms of DCS and went to work the day after, but the symptoms were reinforced. Another tried to ignore DCS symptoms for 5 days before reporting the symptoms to the diving supervisor. Two others came forward after 4 days and reported symptoms of DCS to the diving supervisor shortly after five of their fellow workers were treated for DCS. Selection of CAW personnel did not have a major effect on DCS rates after the change of decompression tables since only 8.7% of the work force reported symptoms of illness; of these, 4% were subjected to DCS, and only 4 of these individuals stopped working after recompression treatment.

Although DCS cases were few in this tunnel project, some cases were of neurological Type 2 DCS. Permanent neurological residual symptoms after recompression treatment are unusual in tunnel projects and have not been reported in other tunnel or caisson projects of recent date. The two cases reported in this tunnel project occurred during the first part of the project among the first seven cases. Repeated examinations and tests were made to establish the nature and extent of these residual physical deficits and the conclusions were that the deficits were due
to DCS. But pre-employed data were limited in the medical notes and earlier incidences could have been of influence. All CAW were on the other hand considered fit and without physical deficits before employment according to the standards of the diving medical examination.

Age is a commonly known DCS risk factor (5,6,16,17). Unfortunately no records of age for CAW in the project were available, but the age of those treated for DCS is known in all but one case. There was a tendency of DCS symptoms being more severe and involving neurological symptoms for those older than 35 years of age. Symptoms of neurological Type 2 DCS was also of a more severe nature before the change of schedule. This is also reflected in the profile of the recompression treatment that these cases received. However, given the few DCS cases and without demographic data for all CAW it is not possible to relate this observation as an explanation to a significant higher risk of DCS before the change of schedule.

Pressure and time influence the severity of the hyperbaric stress from a sub-saturation exposure and thus the risk of DCS. This is well known and the tendency was also present in the Great Belt tunnel project. All DCS cases except one occurred among the 30% of exposures that imposed the greatest decompression stress according to the French air decompression tables of 1992. These exposures were decompressed more than 70 minutes for pressures equal or greater than 1.8 bar (2.8 ATA or 281.3 kPa) or decompressed more than 50 minutes for pressures less than 1.8 bar (2.8 ATA or 281.3 kPa). The one DCS case that fell below this level had influenza and fever a few days prior to the intervention and was therefore perhaps in a special risk category. The DCS incidence above this level was 0.42%. The DCS incidence below this level was 0.016%.

T.G. Shields and W.B. Lee have proposed to use the Decompression Penalty Index (DP Index) as a more accurate expression of the hyperbaric stress from a pressure exposure. They define the DP index as the exact decompression penalty to any continuum of depth and time calculated from the USN standard air diving table and thus eliminating the “rounding up” factor. A 20-minute DP index was recommended as a safety limit based on a large survey of 25740 professional dives and 79 DCS cases using different decompression schedules in the UK sector of the North Sea (15). The 20-minute DP index derived from the US Navy standard air tables is very close to the level that separate the 30% exposures that imposed the greatest decompression stress according to the French 1992 decompression tables in the Great Belt tunnel project as illustrated in Figure 2. This supports the indication that for exposures below this arbitrary level of decompression stress in the Great Belt tunnel project the risk of DCS was extremely low and that the risk above the level were significantly higher. The increase of DCS risk is probably some sort of continuum not separated by definite thresholds. But the DCS cases were too few to detect a closer pattern of risk increase related to the frequency increase observed in the Great Belt tunnel project using the French decompression tables. In addition, no DCS Type 2 cases, and extremely few DCS Type 1 cases, are so far described below this level of hyperbaric stress in any of the published results from tunnel or caisson projects of recent date.

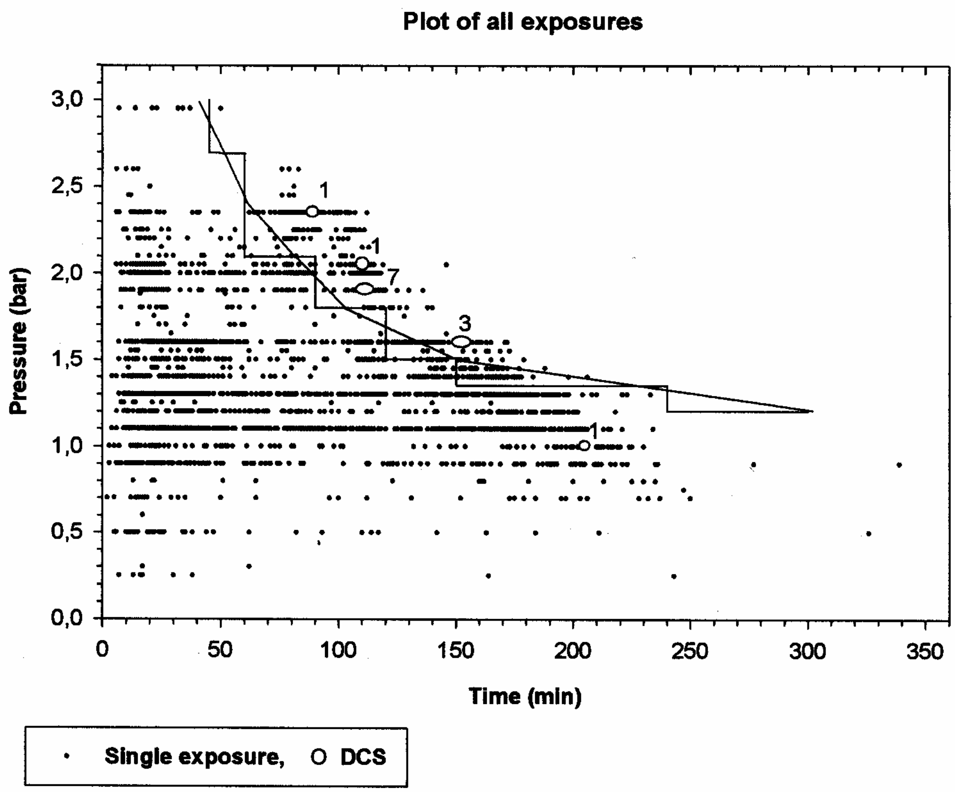

Figure 3 – Plot of all exposures against gauge pressure and working time. DCS cases are marked with circles and the number of cases indicated next to the circle. The smooth line indicates the 20-minute DP index according to US Navy standard air tables. The stepwise lines indicates the level in the French 1992 decompression tables with a DP index of more than 50 minutes for exposure below 1.8 bar and more than 70 minutes for exposure above or equal to 1.8 bar.

CONCLUSION

As in other tunnel projects, the incidence of DCS increased with the level of hyperbaric stress in the Great Belt tunnel project. All except one DCS case in the Great Belt tunnel project occurred among the 30% of exposures that imposed the greatest decompression stress. The DCS incidence among these exposures was 0.42% (12 DCS cases). The DCS incidence among the remaining 70% of the exposures was on the other hand very low, 0.016% (1 DCS case). Most of the CAW that reported symptoms of illness after a pressure exposure, but not treated for DCS had been exposed to a level of hyperbaric stress as high as the DCS cases. Under other circumstances, some of these might have been treated as DCS cases and the DCS incidences would have been slightly higher. Overall DCS incidence was 0.14% (13/9018). This is a very low incidence compared to other tunnel projects of this size. The DCS incidence would still be low still low, had all CAW reporting symptoms of illness been treated as DCS cases. Two patients had permanent neurological residual symptoms after recompression treatment. This is unusual in modern caisson or tunnel work. No clear explanation for this is evident in the material available, and the lack of pre-employment and demographic data allows no certain conclusions to be made of a higher DCS severity risk before the change of schedule in September 1992. Regarding the period of the tunnel project from when the French air decompression tables of 1992 were used, the overall DCS incidence during this part of the tunnel project was considerably lower (0.08% or 6/7220) compared to the first part, when the 1974 tables were used (0.39% or 7/1798). The occurrence of a cluster of DCS cases before the change of schedule, combined with the uncertainty of the 16 non-DCS cases occurring after the change of schedule, deems it uncertain whether there was any change in the frequency of DCS between the two schedules.

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