Statistical Investigation of Working Pressure and Decompression Sickness at Compressed-air Works

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Abstract

Recently compressed-air engineering work mostly employs pneumatic caisson method and tends to use higher working pressures in accordance with mechanization of shield works. Under the circumstances, the present author totaled results of five years'surveys on development of decompression sickness (DCS) and compared the results with former research findings. For this comparison, the control data was chosen among those which had been comprised by the same procedures as ours (Mano & Shibayama, 1987).

It is commonly said that DCS could not be developed under a condition of working pressures less than 1.0 kg/cm^2. Although we experienced seven patients with DCS development under 1.0 kg/cm^2 of the pressure, no case was observed in the present survey conducted with a total of 12,503 exposures of compressed-air works. Total number of compressed-air works with over 1.0 kg/cm^2 pressures include: 3,822 more exposures found in 1986 or later than before 1986; 9,649 more exposures observed in 1985 or former with working pressures of 1.0-2.0 kg/cm^2; and, with higher pressures over 2.0 kg/cm^2, the number of the works showed rapid increase in 1986 or later (Table 1). This means that deep excavation works, which need higher working pressures than before, are becoming popular for today's compressed-air works. In other words, working circumstances became more strict in these years, therefore, more precise safety supervision should be required. When decompression control is carried out basing on the current decompression table, development rate of DCS increases in line with enlargement of working pressures. This was also observed in the present study.

Comparing onset rates of DCS during these five years with those observed before the years, the results of these five years show lower rates, based on the working pressures divided by each 1.0 kg/cm^2 group, than those seen before the five years (Table1). This supposedly indicates that more strict decompression control is carrying out today than before.

1. INTRODUCTION

In Japan, compressed-air was initially used for constructing bulkhead and quay wall in Dejima, Nagasaki prefecture during 1789-1800. Foundation work by Caisson method has started in earnest for constructing bridges, i. e. Eitai, Kiyosu and Kototoi, over the Sumida river in Tokyo as one of the metropolitan reconstruction works after the Great Earthquake of 1923 in Kanto area, when an American engineer A. H. Hughs and others took leadership for the works. From 1935 on, pneumatic method was actively employed to engineering works, the method became a peak utilization for the construction works related to the Tokyo Olympic in 1964, and, today, pneumatic method has been employed as a technically established method (Mano, 1992 a).

Pneumatic method accompanies with possible hazards due to compressed-air such as DCS but also has benefits like; a reliable method for foundation works, an effective countermeasure especially to cope with spring water and earth pressure, and few disturbance to the road traffic; which are essential conditions needed for engineering works in urban places.

Under these circumstances, pneumatic method was frequently used at underground shield works for water supply as well as waste water systems, electric power, telegraph, telephone and subway constructions, and, during approximately 1970-1984, compressed-air shield works, together with pneumatic caisson works, became a primary procedure among pneumatic work method.

But after the years, mechanization progressed to cope with slurry and balancing earth pressure at the cutting faces, and, from about 1985 on, compressed-air shield method was not employed except rare cases. While underground digging technique became excessively deep methods more and more, consequently, vertical shafts also could become deeper. As same as the innovation of shield method, caisson method was assessed in order to avoid influence of compressed-air to human bodies as an alternative method of pneumatic for works such as continuous walls. And, from 1985 on, pneumatic caisson seemed not being needed any more, whereas pneumatic caisson was re-evaluated as an economic as well as reliable method in approximately 1989 on. Consequently, excessively deep excavation works, which were decreased in incidents required, could not avoid but rely on pneumatic method resulting in higher working pressures for the excavation works.

Basing on the above, the authors investigated development rate of DCS in line with total numbers of workers divided by each 0.2 kg/cm^2 basis, treated the results obtained statistically, and conducted a dynamic survey on the DCS development ratio as well as yearly changes of working pressures. The authors carried out these investigations through our previous activities such as; visiting the scene of works, conducting security on safety and sanitary controls, researching actual conditions of total process of the work, and asking questionnaires concerned.

2. Methods

2.1. The authors investigated the actual conditions of fields under compressed-air works during 12 years, from 1979-1990. Dividing the 12 years into two groups, the former seven and the latter five years, basing on working pressure over 1.0 kg/cm^2, which could develop DCS and was grouped by each 0.2 kg/cm^2, we surveyed numbers of both the total workers and the onset cases of DCS.

2.2. It is specified in the law that compressed-air workers should undergo medical examination every six month. We analyzed the results of the medical examination especially on bone lesions in the results.

2.3. Tokyo Medical & Dental University has furnished hyperbaric treatment chamber for DCS since 1966, and we experienced medical cares of 175 patients with type II bends. The authors in the present study examined the results of the above experiences, and analyzed proportional changes between compressed-air workers and divers basing on three divided groups treated in 1970-1980, 1981-1985, and 1986-1990 (Table 4).

3. Results

3.1. Table 1 shows incidence of DCS divided by working pressures. Total number of the workers were 51,097, of which 38,594 workers were those labored withworking pressures 1.0 kg/cm^2

Table 1. Comparison of DCS incidence according to different working pressure

Working pressure (kg/cm^2)	1979～1985			1986～1990		
	Number of workers	Number of DCS	Incidence (%)	Number of workers	Number of DCS	Incidence (%)
～1.0	10,208	0		2,295	0	
～1.2	2,032	2		539	0	
～1.4	2,768	2		590	0	
～1.6	2,152	5	0.16 (15/9,649)	935	0	0.10 (4/3,822)
～1.8	1,714	4		800	1	
～2.0	983	2		958	3	
～2.2	743	9		2,479	11	
～2.4	489	16		1,485	9	
～2.6	665	9	1.37 (49/3,586)	1,493	19	0.86 (191/20,945)
～2.8	1,287	11		3,827	6	
～3.0	402	4		11,661	136	
～3.2	212	9		124	0	
～3.4	57	0		16	1	
～3.6	25	0	3.06 (9/294)	36	2	2.26 (5/221)
～3.8	0	0		11	0	
～4.0	0	0		34	2	
4.1～	0	0		77	1	1.30 (1/77)
Total	23,737	73	0.31	27,360	191	0.70
1.0 k or more	13,529	73	0.54	25,065	191	0.76

or over. of 38,594, DCS were observed in 264 workers corresponding to 0.68% (264/38,594) of DCS incidence.

DCS incidences in the either groups increased as working pressures became higher. Comparing working pressures employed in the former seven years and in the latter five years, works under high-pressure increased more in the latter period than in the former years. But, on the contrary, DCS incidence disclosed a significantly low in the latter period ($p<0.001$).

3.2. Table 2 shows results of medical examination especially on bone lesion.

Compressed-air workers, 2,696, and divers, 1,509 (total: 4,205), were examined by x-ray at A-P positions on the both side joints of the shoulder, hip and knee, and the findings were analyzed basing on the classification by Walder (1975). Total number of the cases showing any of bone lesion findings were 546, of which type A with higher malignancy were 12 corresponding to 2.2%. While type B were 114 cases (20.9%) and the rest, type C were 420 cases (76.9%). But, considering that the type C had few correlation with compressed-air works, an actual cases with bone lesion included the both types of A and B, 126 cases in total, corresponding to 3.0% (126/4,205) of the incidence. Results by the lesional site, as seen in Table 3, onsets at the hip joints were the most corresponding to 73.3%.

Table 2. Results of medical examination on divers and compressed air workers

	Number of check up (persons)	Age	Number of bone x-p (persons)	Age	Rate	Number of abnormal view	Age	Inci-dence
《Compressed air workers》								
Staff	2,747	34.3	2,384	34.5	86.8	263	34.8	11.0
Labours	807	36.6	312	35.2	38.7	35	36.2	11.2
《Divers》								
Fishermen	1,222	32.9	1,062	32.4	86.9	130	31.5	12.2
Engineering	356	29.5	328	29.7	92.1	34	29.8	10.4
Rescue	124	27.1	111	27.1	89.5	2	27.5	1.8
Sport	113	20.2	2	24.5	1.8	1	30	50.0
Instructor	6	37.5	6	37.5	100.0	0	–	0.0
Total	5,375	33.6	4,205	33.4	78.2	465	33.6	11.1

Table 3. Site of bone lesion

	Shoulder joints			Hip joints			Knee joints			Total
	L	R	B	L	R	B	L	R	B	
Type A	0	1	1	3	2	2	0	0	0	12 (2.2%)
Type B	8	8	7	30	23	6	12	3	2	114 (20.9%)
Type C	20	40	2	107	167	26	11	17	1	420 (76.9%)
Total	28	49	20	140	192	68	23	20	6	546 (100.0%)
Rate	97	(17.7%)		400	(73.3%)		49	(9.0%)		

*3.3.*Table 4 shows a classification of occupations of patients with DCS and Arterial Gas Embolism (AGE), who were treated in the University hospital during 20 years from 1970 to 1990, into two groups, compressed-air workers and divers.

Ratios of compressed-air workers corresponds to 78.9% (120/152 patients) during 1970-1980, 37.4% (34/91 patients during 1981-1985, and extremely decreased to, 14.7% (19/129 patients) during 1986-1990.

3.4. Survey on medical examination

For the purpose of surveying actual states of the medical examination of compressed-air workers, the authors in the present study obtained copies of the table of test items for the examination carried out at each field, analyzed the items and showed the results in Table 5. In each working field, the medical examination was carried out by institutes concerned. But, when we surveyed the items examined by medical institutes, we found that only 68.4% of the test items regulated by the compressed-air rule, Para.1 of Art. 38, were satisfied.

In other words, measurement of blood pressure was exceptionally conducted in medical examinations at all working fields, but other test items were not necessarily carried out at each working field. This possibly means that institutes concerned do not acknowledge the

Table 4. Comparison of DCS & AGE number between compressed air workers and divers

	1970～'80			1981～'85			1986～'90			Total
	Type of DCS I	Type of DCS II	AGE	Type of DCS I	Type of DCS II	AGE	Type of DCS I	Type of DCS II	AGE	
Caisson workers	37	40	0	4	10	0	5	8	0	104 (27.4%)
Shield workers	24	19	1	15	5	0	3	3	0	70 (18.5%)
Total number of compressed air workers	61	59		19	15		8	11		
	120 (78.9%)		1	34 (37.4%)		0	19 (14.7%)		0	174 (45.9%)
Fishermen divers	2	8	0	16	14	1	42	17	0	100 (26.4%)
Other professional divers	8	8	2	2	8	0	8	10	0	46 (12.1%)
Leisure divers	3	3	0	9	8	2	19	14	1	59 (15.6%)
	(4.0%)			(18.7%)			(25.6%)			
Total number of divers	13	19		27	30		69	41		
	32 (21.1%)		2	57 (62.6%)		3	110 (85.3%)		1	205 (54.1%)
Total	74	78		46	45		77	52		
	152 (100%)		3	91 (100%)		3	129 (100%)		1	379 (100%)

test items needed for medical examination of compressed-air workers.

Under these circumstances, in which every working field obtained medical examination for compressed-air works, it may be said that a big task will be left for further study.

4. Discussion

4.1. Compressed-air works include different ways of procedures in either pneumatic caisson or shield methods.

Pneumatic caisson works proceed vertically into underground, e.g. for foundation work of bridges, whereas, shield works horizontally excavate underground, e.g. for the subway constructions. With these conditions, hyperbaric exposures to the workers increase as the caisson works proceed, while, under shield works, the exposures keep approximately constant levels from the beginning to the completion of the works.

As seen in Table 1, a peak of the working pressure from 1979 to 1985 corresponds to 1.2 -1.4 kg/cm^2, and principal works were carried out with 1.8 kg/cm^2 or less. This means that shield works were mostly employed during the years, although caisson works were also used together with caisson method. The reason why another peak of the working pressure is

Table 5. Test items of medical examination for compressed air workers

	Test at employment	Regulation 38		Fields of pneumatic caisson (12 fields)		Fields of compressed shield (7 fields)		Total (19 fields)	
		Item 1	Item 2	Number of fields	Rate of taking tests	Number of fields	Rate of taking tests	Number of fields	Rate of taking tests
Height	●			7	58.3	1	14.3	8	42.1
Weight	●			7	58.3	1	14.3	8	42.1
Eye sight	●			6	50.0	1	14.3	7	36.8
Color blindness	●			3	25.0	1	14.3	4	21.1
Disease history	●	●		9	75.0	5	71.4	14	73.7
Working history	●	●		6	50.0	2	28.6	8	42.1
Self-knowledge symptom	●	●		9	75.0	7	100.0	16	84.2
Symptom Motion function	●	●		9	75.0	6	85.7	15	79.0
Breast x-p	●			8	66.7	3	42.9	11	57.9
Bone x-p			●	0	–	0	–	0	–
Medical exam				4	33.3	1	14.3	5	26.3
Eardrum		●		4	33.3	6	85.7	10	52.6
Hearing ability	●	●		10	83.3	6	85.7	16	84.2
Blood pressure	●	●		12	100.0	7	100.0	19	100.0
ECG			●	5	41.7	3	42.9	8	42.1
Blood chemistry				1	8.3	0	–	1	5.3
Pulmonary volume		●		11	91.7	6	85.7	16	84.2
Pulmonary function			●	2	16.7	4	57.1	6	31.6
Urine Sugar	●	●		11	91.7	7	100.0	17	89.5
Urine Protein	●	●		11	91.7	7	100.0	17	89.5
Urine Blood				0	–	0	–	0	–
Urine PH				0	–	0	–	0	–
BSG				2	16.7	0	–	2	10.5
Other test				3	25.0	2	28.6	5	26.3
Working condition		●		1	8.3	2	28.6	3	15.8
Notice		●		3	25.0	2	28.6	5	26.3
Rate of sufficiency (%)	64.8	68.4	24.6						

observed at 2.8-3.0 kg/cm^2 in Table 1 is that an effort has reportedly been done to keep the earth pressures not to exceed 3.0 kg/cm^2. The Safety and Hygiene Law for Labor in Japan prescribes that works over 3.0 kg/cm^2 of working pressures are especially dangerous and such works in any constructions should be previously applied to the Minister of Labor of this country. This makes companies undertaking the works do the best efforts to keep the maximum working pressure at 3.0 kg/cm^2 or less. For example, they try to decrease groundwater levels by installing deep wells, or make an effort not to increase working pressures by improving soil with a chemical dosing method (grout method).

While compressed-air shield method was technically improved resulting in the earth pressure balance method with pressure exposure only at cutting faces, by which atmospheric pressures can be allowed to expose on workers in shield tunnels. Under these circumstances, compressed-air method works rapidly decreased in number in 1980s, and, from approximately 1986 on, the method was hardly employed to constructions concerned. Consequently, data on working pressures from 1986 to 1990, which we investigated in the present study, corresponded to those observed under pneumatic caisson works. In these data, working pressures during 2.8-3.0 kg/cm^2 are frequently seen in numbers of hyperbaric pressure exposure. This is supposedly because companies concerned likely refrain from the application to the Ministry of Labor.

Apart from the above, it is a general tendency that DCS develops according to enlargement of working pressures. This is primarily because of the standard decompression table itself.

Current decompression table has been compiled taking consideration of: working efficiency and a risk suffering from DCS, both of which have essentially inharmonious characteristics; a favorable working efficiency with a minimum risk mentioned; method improvement based on experiences concerned; and establishment of currently used standard table of decompression which was approved by the Ministry of Labor. It has been widely known that as working pressures increase the time required for decompression is prolonged resulting in a reduction of working efficiency. And in case that compressed-air works are carried out basing on current decompression table in either Japan or in Europe and U. S. A., the higher working pressures go, the more cases with DCS increase, resulting in expanded onset rates of DCS in line with enlargement of working pressures. This is conceivably a natural result.

As seen in Table 1, incidences of DCS significantly increased in the former seven years than in the latter five years. This suggests that the work control is becoming strict and safer decompression control is being employed.

4.2. Compressed-air workers in Japan should undergo a specific medical examination every six month. This is provided by the Law, and items of the examination are those shown in Table 5. Number of the medical examinations conducted so for is indicated in Table 2 including 3,554 workers of compressed-air constructions (mean age, 34.9 years). Of the 3,554 workers 2696 cases underwent X-ray examinations at the bone greater joints (shoulder, hip and knee), while 1,509 of the 1,821 divers did the same bone X-ray examinations.

Results of X-ray examination were classified by criteria of Walder (1975). The results showed 12 cases of type A, a type of articular surface disturbances of bore lesion, of which four cases underwent artificial capital replacement approved by the labor accident. Type B was observed in 114, although type C was seen in 233 cases, cases of this type C are currently excluded from the bone lesion of compressed-air works or dive. So, it will be needed to follow chiefly types A and B.

Developments of bone lesion were mostly found at hip joint, e.g. 73% of the lesions were seen at hip joints of articular surfaces, capitals and necks of the femoral bones. According to Walder (1975) bone lesions were observed in an approximately similar incidence in the sites of femoral capital such as shoulder, hip and knee joints. This supposedly due to working conditions of people laboring under pneumatic caisson method. It was separately reported that bone lesions were developed over 50% of shell-fishery helmet divers. In our own survey on divers working for fishery, salvage procedure and engineering showed a tendency of almost the same incidence with bone lesion as observed with compressed-air workers (Tabel 2). Based on the findings above it can be concluded that such a high incidence of bone lesion is observed limitedly in the group with shell-fishery helmet divers in Kyushu district.

4.3. The university has been treating DCS since 1966 and has experienced over 175 cases of severe DCS, i.e. type II. Of patients, who visited our hospital for the treatment of DCS, ratios of compressed-air workers are shown in Table 4. Patients of the disease visiting the hospital disclose a tendency showing a rapid increase with divers for leisuring purposes while to disclose a fast decrease with compressed-air workers. These findings are supposedly due to a synergistic effect due to the facts that: scuba diving created a boom in 1980s in Japan, just like another new turn in which owners of any sort of certificated cards (C-card) amounted to 630,000 today in Japan, growing in a manner of geometric progression, from only 10,000 persons in 1980; whereas,

1) number of compressed-air shield works showed a sharp decrease in 1980s and were hardly seen in 1986 on,

2) number of pneumatic caisson works also reduced, and

3) in case of employing pneumatic caisson works, much more severe control for safety should be taken.

These changes above rapidly under went in compressed-air engineering works in Japan. Although pneumatic caisson works is decreasing in incident, in case of conducting the works, the depths of excavation show a tendency becoming deeper. Consequently much more strict countermeasures to DCS are required. While caisson works are being intended to conduct with worker less method and mechanization, and in case of methods with workers it is needed to use helium as an artificial air. It becomes an era that we should presume pneumatic caisson works under the pressures up to 7.0 kg/cm^2 for which safety control should also be studied.

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