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MEDICAL SUPPORT OF COMPRESSED AIR TUNNELLING IN THE SINGAPORE MASS RAPID TRANSIT PROJECT

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Summary

The Mass Rapid Transit System in Singapore has been a unique experience for the many who have worked in its development. The Republic of Singapore Navy, it was given the exciting task of providing medical support to the compressed air phase of the project. Decompression sickness (DCS) is a recognised occupational hazard faced by compressed air workers, divers and aviators. In the Singapore Mass Rapid Transit Project (MRT), 11 km of underground tunnels were built using compressed air. This report deals with the planning and the set up of the medical support infrastructure in support of the contract. It also highlights the findings obtained during the medical examination. Medical problems faced by workers in the project are discussed.

Introduction

Let me first pay tribute to Major (Dr) Vijayan, Captain (Dr) Wong Ted Min and a team of National Service doctors, nursing officers, and medical orderlies who have contributed to the successful completion of the Singapore Mass Rapid Transit Project.

Some of you may wonder why a tiny place like Singapore needs a Mass Rapid Transit system. Singapore is an island 24 miles (38.4 km) East to West and 16 miles (25.6 km) North to South, about 400 square miles in area. No longer do people live in kampongs as they did in the 1960s and 1970s. 75% to 80% of people are housed in flats in high rise buildings. It is so built up that it is a concrete jungle choked with cars. Already we have 3 million tourists a year and they are building a second international airport at Changi, with the second terminal to open in 1990. We had to have tunnels going underneath the city to transport residents and tourists because there is not sufficient road space on top for more cars. We chose to have trains running in the tunnels rather than cars.

Use of caissons and tunnelling in compressed air

Denys Papin first mentioned the idea of using compressed air to displace ground water from a working tunnel in 1691.[1]

In 1830 the English engineer, Cochrane (later Lord Dundonald) took out a patent for using compressed air to keep water back from tunnels.[1] However, it was left to the celebrated French engineer, Triger, to solve the practical problems. In 1839, Triger was able to successfully sink a tunnel into quicksand to reach a bed of coal at Haye-Longne.[2]

COMPRESSED AIR WORK IN THE UNITED STATES

In the United States of America compressed air was first used in 1869 during the construction of a railroad bridge over the Pee Dee river between Wilmington and Colombia. In the same year, the foundations of the bridge over the Mississippi at St. Louis were built using compressed air.[3] Decompression schedules used in the 1879 Hudson River Project required men to work at 32 psig (2.18 Bar gauge) for 8 hours out of 24, taking half an hour for lunch at the working pressure or at a slightly reduced pressure. At pressures higher than 32 psi (2.18 Bar gauge), the men worked in shifts of 3 hours with 3 hour rest intervals. Workers working between 40 psig (2.72 Bar gauge) and 42 psig (2.82 Bar gauge) spent 3 hours on shift with a 3 hour rest interval between shifts at normal pressure.[4] There was a high incidence of DCS in this project because the workers decompressed at the same rate regardless of the duration or pressures they were exposed to.

F.L. Keays[5], Medical Director for the contractor in charge of the construction of the East River Tunnels for the Pennsylvania Railroad in 1909, reported 3,692 cases of DCS arising out of 557,000 decompressions, with 20 deaths. The New York Tables (1912), which were a revision of the decompression tables used in the Hudson River Project, were formulated in connection with the Public Service Commission Tunnel Project. These tables were revised in 1922. However, the 1922 Tables were inadequate and Thorne[6] reported 300 cases of DCS. The New York Tables 1955-57 used in the Lincoln Tunnel Operation were yet another revision of the 1922 Tables, in an attempt by the New York State Department of Health and the Port Authority to minimise disabilities arising from dysbaric osteonecrosis.[6]

In 1961, Dr Leon Sealey, Medical Consultant to the Municipality of Metropolitan Seattle and Metropolitan Engineers, organised a committee to formulate decompression tables regulating work in compressed air in connection with the major sewage tunnel project through Seattle.[7] The new tables were subsequently adopted by the States of Michigan, New York and California. It was later observed that these new tables again failed to prevent disabling dysbaric osteonecrosis in compressed air workers. Kindwall et al[8] re-examined the current Occupational Safety and

Health Agency (OSHA) decompression schedules and concluded that these tables permitted the development of dysbaric osteonecrosis when used in the recommended pressure ranges. Until the development of a new set of schedules, an interim set of decompression schedules, with longer decompression times was adopted. An oxygen version of this table was also designed to reduce the decompression times considerably.

COMPRESSED AIR WORK IN ENGLAND

In 1852 caissons were first used in Britain by Hughes during the construction of the foundations of a bridge at Rochester in Kent[9] and shortly afterwards by Brunel for the Saltash bridge between Devon and Cornwall. DCS and dysbaric osteonecrosis were great problems for diving as well as for caisson work and in 1906 the British Admiralty appointed a committee which included J.S. Haldane to develop safe decompression schedules[10]. In 1907, Haldane described the now classic principles of staged decompression. Based on his experiments, he believed the pressures could be reduced in a 2:1 ratio without bubble formation. The decompression schedules described were used to some extent by tunnel and caisson workers, but it later became apparent that the 2:1 ratio proposed was too rapid for prolonged and high exposures to pressure.

In 1935, a British committee appointed by the Institution of Civil Engineers developed a set of decompression tables for compressed air workers working for varying periods up to 50 psig (3.4 Bar gauge), using the principle of staged decompression. These tables were widely used until new decompression tables were compiled by the Compressed Air Committee of the Institution of Civil Engineers and the Ministry of Labour (United Kingdom). These tables were first used in 1948 in the construction of a tunnel under the River Tyne and were subsequently adopted in the Compressed Air Special Regulation of the Ministry of Labour (United Kingdom), which came into force in 1958.[11]

At about the same time, new tables were produced based on Hempleman's theory on "Diffusion-Limited Gas Uptake" of tissues. The new tables were first used in Blackpool in 1966. The Blackpool Tables, with the code of practice prepared by the Medical Research Council Decompression Sickness Panel and published by the Construction Industry Research and Information Association (CIRIA), is the currently accepted standard governing compressed air work in the United Kingdom[12]. One of the more recent large scale tunnelling projects requiring compressed air, was undertaken in Hong Kong for the Mass Transit Railway, using the Blackpool Tables.

Hazards in compressed air work

With the advent of compressed air work, more and more medical problems were encountered. Besides the usual hazards of noise, dust, vibration and construction related accidents faced by construction workers everywhere, other significant health hazards of work in the compressed air environment are decompression sickness (DCS), pulmonary barotrauma and dysbaric osteonecrosis. DCS, also known as bends, caisson disease, compressed air illness or dysbarism, is a condition which results when there is an overly abrupt and extensive reduction in environmental pressure. Compressed air workers, divers, medical workers in hyperbaric environments and aviators are similarly susceptible to DCS and dysbaric osteonecrosis.

Although the symptoms of DCS were first described by Triger[2] in 1841, it was only in 1854 that Pol and Watelle[13] noted these afflictions occurring only in workers leaving the tunnel and not whilst entering or remaining in the compressed air environment. Signs and symptoms of DCS with painful joints or with disturbances of the cardiovascular, respiratory and nervous system were described. They rightly recommended recompression as a therapeutic modality but it was left to others to develop proper decompression schedules and therapeutic tables.

Pathogenesis

DECOMPRESSION SICKNESS

A reduction in ambient pressure causes dissolved nitrogen to form nitrogen bubbles in tissues. The exact mechanism of bubble formation, even after 100 years of research, is still unclear. Various theories of bubble formation, de novo nucleation, supersaturation, tribonucleation and in vivo cavitation, have been suggested as possible causative factors of the bubbles implicated in decompression sickness.

As early as 1670, Boyle[14] observed bubbles in tissue and blood samples of animals decompressed in hypobaric chambers. Paul Bert[15], in a series of experiments with goats and other small animals, established the role of nitrogen bubbles in DCS. Many other workers[16-18] showed that gas bubbles arose both intravascularly and within tissues. Intravascular bubble formation can lead to embolisation and mechanical obstruction of blood vessels. This was the earliest proposed mechanism explaining the observed symptoms and the findings of ischaemic changes in the various organs. The fact that bubbles can be detected by histology, direct observation with an operating microscope and by doppler ultrasonography[19], indicate that nitrogen bubbles are the causative agents in DCS.

Further studies since the 1930s have found that bubble-blood interactions occur in vivo and may account for some of the clinically observed symptoms like inflammation around joints and relapsed symptoms, and biochemical changes in the blood. Concurrent work done by Swindle[20] and End[21] showed sludging of red cells with the formation of emboli and petechial infarcts in spinal cord and brain in DCS. Subsequent work done by numerous researchers have shown that bubbles produced changes in the blood and tissues with both morphological and metabolic consequences. These include alteration in platelet function, changes in the coagulability of blood and in catecholamine, plasma lipid, plasma protein and enzyme levels. Leitch and Hallenbeck[22] showed that the pathology may also be caused by arterial gas embolism leading to peripheral vascular obstruction by gas. Cord segments involved showed varying degrees of haemorrhage and occasionally vascular congestion. Microscopic petechiae were present in both the grey and white matter. These appearances were compatible with hypoxia or embolic episodes. In 1987 Thorsen et al[23] showed, with the help of scanning electron microscopy, activation of human platelets by nitrogen micro bubbles.

DYSBARIC OSTEONECROSIS

The other hazard of compressed air work is that of dysbaric osteonecrosis. Bassoe[24], in a paper to the Chicago Neurological Society, described chronic joint pain and stiffness in 11 out of 161 caisson workers. Bornstein and Plate[25], also described 3 cases of joint disease among some 500 bends cases associated with the construction of the Elbe Tunnel at Hamburg. Bassoe suggested a relationship between initial joint "bends" and subsequent development of bone atrophy.

This condition is included in this paper as many workers consider dysbaric osteonecrosis as a chronic form of DCS. The aetiological basis of this disease is similar. Dysbaric osteonecrosis has been observed following caisson work at a pressure as low as 17 psig (<12 msw), and also for as short an exposure as 7 hours at 3.38 ATA.

Dysbaric osteonecrosis may appear several months, or even years, following inadequate decompression from compressed air environment. The victims may or may not have had a past history of DCS. It has been proposed that dysbaric osteonecrosis occurs as a result of bone infarction caused by occlusion of capillaries by nitrogen bubbles or sludge-formed elements of the blood. Once blockage occurs, the osteocytes in the affected bone die if the ischaemia is not reversed within 12 hours. Common sites for dysbaric osteonecrosis are the head, neck and shaft of long bones, especially in the femur, tibia and humerus. Dysbaric osteonecrosis is seen radiologically about 4 months after the initial insult. Severe cases of dysbaric osteonecrosis may have marked sclerosis and collapse of the bony trabeculae, resulting in disruption of the overlying joint.

Use of compressed air tunnelling in Singapore

In Singapore, compressed air work was first used in sewage tunnelling in 1982. In 1984, compressed air tunnelling began on the Singapore Mass Rapid Transit (MRT) project.

The idea of a Singapore Mass Rapid Transit system first surfaced in the early 1970s when the State and City Planning Study examined land use and transportation in the light of the Government's developmental policies. This study, completed in 1971, confirmed that it would be physically impossible and environmentally unacceptable to build roads to accommodate the demands placed by the automobile.

Thus the Mass Transit Study (MTS) was carried out in 3 phases from 1972 to 1980. In the meantime, an MRT review team from Harvard headed by the late Kenneth Hanson, studied the transportation needs and recommended an all bus network. This proposal was later examined in the Comprehensive Traffic Study (CTS) in 1981 which confirmed previous forecasts that an all bus system would not provide comparable service to a rail network.

In 1982, the Government finally announced its decision to go ahead with the MRT Project. The Protem Committee of the MRT Project subsequently approached the Republic of Singapore Navy (RSN) in August 1982 to assist in providing the overall medical support for the project. The RSN was chosen as it had the experience and facilities to examine and treat divers and compressed air workers.

In 1984 the Ministry of Defence gave approval to the request from Mass Rapid Transit Corporation (MRTC) for the Diving and Hyperbaric Medical Centre (DHMC) to provide the medical support for the compressed air phase of the project. DHMC assisted the Ministry of Labour, in 1984, to draft regulations pertaining to compressed air work. The regulations were adopted by MRTC and the Blackpool Tables were used by the contractors. The manpower and doctors from DHMC enable a comprehensive management and documentation of DCS cases treated.

The Singapore MRT system comprises 41 stations along a 65.8 km route. A total of about 20 km were underground tunnels of which about 11 km were constructed using compressed air. Compressed air was used by 6 contractors for tunnel construction from 21 September 1984 to 17 April 1987. Six contracts were drawn up with the contractors to formalise the agreement to provide medical support. These contracts were:

Tobishima-Takenaka Joint Venture (TTJV)
Contract 104
Bocotra Construction Pty. Ltd (BOC)
Contract 105
Kajima-Keppel Joint Venture (KKJV)
Contract 107
Taisei-Shimizu-Marubeni Consortium (TSM)
Contract 108
Ohbayashi-Gum/Okumura Joint Venture (OOJV)
Contract 109

Nishimatsu-Lum Chang Joint Venture (NLJV)
Contract 301

In addition, the Mass Rapid Transit Corporation, Gammon-Antara Koh Joint Venture, the Industrial Health Division, Ministry of Labour and the Singapore Fire Service have also used the services of the centre.

Methods employed in the construction of the MRT tunnels

The MRT tracks run underground in the central business district. Two construction methods were employed:

TUNNELLING

This method was chosen for construction of the MRT tunnels across the central business district as it minimises the disruption to traffic flow. When the tunnel was below the water table or the soil was unstable compressed air tunnelling was employed. Non compressed air tunnelling was employed in soil and rock which was above the water table. Tunnelling involved the use of various shields. The Full Faced Mechanised Shield consists of a steel cylinder which precisely fits the diameter of the tunnel. The cutting face rotates and removes the earth from the face of the tunnel. As each section is completed, the shield is moved forward by powerful hydraulic rams. Prefabricated concrete liners are then placed inside the tunnel. The shield supports the tunnel face and protects the men working inside. Other variations of this method that were utilised were the Greathead Shield, the Semi-Mechanised Shield and the Fully Closed Shield and the New Austrian Tunnelling Method.

Jet grouting was used to stiffen the soft marine clay encountered in the Kallang region where the tunnels had to go. This process involved the drilling of holes into the ground to a certain depth. The grout, a mixture of cement, chemicals and water, was injected into the soil through high pressure jets which extend horizontally out of the drilling shaft into the surrounding ground. The displaced soil was pumped to the surface and carried away in sludge trucks. This process reduces the surface settlement of the ground and makes the ground more uniform.

CUT AND COVER

This method is a 3 step process. An excavation is first made, then the tunnels are laid in place and finally covered over. This method is much cheaper than bored tunnelling especially if the depth of the tunnels are less than 10 metres below ground level, but it has the disadvantages of noise, dust and disruption to traffic.

For the construction of the tunnel across the Singapore River and Marina Bay, a special method of cut and cover was used with the help of cofferdams. Sheet piles were driven into the river bed on either side of the proposed tunnel line, creating a dammed up central portion, the coffer dam. The water trapped between the two walls was pumped out and a cut and cover method was employed to construct this tunnel.

Planning phase

A study team, led by myself, was sent overseas to study the medical support concept that existed in various countries.

In planning for medical support, we realised that there were two main hazards in tunnelling operations. These were:

1. The hazards of exposure to hyperbaric and closed environments; and
2. The general hazards of tunnelling, industrial and construction work.

Thus our objectives were:

(a) To assist in the preparation of proper legislation for tunnel worksites and compressed air workers.
(b) To provide a comprehensive medical examination for all compressed air workers.
(c) To provide training of personnel working with compressed air.
(d) To provide preventive care and medical treatment to all personnel working in the compressed air environment.
(e) To supervise and cultivate safe work habits and to perform safety inspections and ensure all regulations were adhered to.
(f) To be prepared for all emergencies with the establishment of a 24 hour emergency service with doctors, medics and ambulance service in readiness to meet the exigencies.
(g) To centralise all documentation and data collection so as to expedite data processing and information retrieval.

Preparation

Legislation was incorporated to ensure the safe conduct of construction and tunnelling. Besides the building code which the contractors had to comply with, they had to ensure that all potential compressed air workers underwent a medical examination at DHMC prior to commencement of work in compressed air. The compressed air workers had to attend training courses and be aware of the dangers of working inside the tunnels.

Legislation also detailed the need for medical selection of compressed air workers, periodic clearance, chest and long bone X-rays, training and proper medical certification of compressed air workers. Regulations pertaining to use of compression facilities by man-lock and medical-lock attendants were also included.

The preparatory phase included the establishment of DHMC as the key Medical Operations Centre and various satellite Medical Centres in the various worksites which provided local cover for the compressed air operations.

Diving and Hyperbaric Medical Centre

DHMC was subdivided into the Clinical and Medical Selection Department, the Operations Room and the Therapeutic Centre. More medical officers were recruited through the Ministry of Defence and were put through a Ministry of Labour approved course to enable them to examine and treat dysbaric osteonecrosis with dysbaric illnesses and to certify them fit for compressed air work.

The senior medical orderlies from DHMC, who were experienced in dealing with diving cases, were also put through the Manlock and Medical Lock Supervisor's course. This enabled them to conduct training for compressed air workers seeking work as medical and manlock attendants.

A new, larger and more advanced hyperbaric chamber was purchased and installed at DHMC to support the treatment of cases of decompression sickness. Medical drugs and various other equipment were also purchased to assist in the therapy and health care of the compressed air workers, e.g.. spirometer and audiometer.

An operational set up with 24 hour manning was established to enable the recall of duty medical personnel at any time of the day to treat cases requiring recompression. Pagers were issued and emergency contact numbers were disseminated to all the worksite offices to facilitate the recall of personnel to the site of the decompression incident. The Operations Room also held the medical records of all the personnel examined for clearance to work in compressed air. It also served as the centre for monitoring the appointments for periodic medical clearance, X-rays, blood and other investigations. Data was collected from the various tunnels, with regard to tunnel pressures, temperatures, humidity, periodic inspections for noise, oxygen, carbon dioxide, carbon monoxide and other contaminant levels. These data were stored in a microcomputer and monthly progress reports were compiled and sent to the relevant authorities.

Medical arrangements at the various worksites

To ensure safety and to provide emergency medical support to compressed air workers, a medical centre was established at each of the sites under the supervision of DHMC. Medical and emergency equipment were in readiness at the centres to cater to exigencies. The set up of the medical centre included a consultation room with couch, drugs, equipment including audiogram, vitalograph and resuscitation equipment. A double lock medical recompression chamber (RCC) was mandatory at worksites which had to work with pressure exceeding 1 Bar gauge. These RCCs were equipped with emergency backup power supply. These were housed in an enclosed area.

Charts of tunnel pressures, humidity, temperatures, gas contents, shift timetables, and various safety/warning messages were also put up in the medial centre. A trained medical officer was present daily when the tunnels were pressurised above 1 Bar gauge. At all times, there was a medical lock attendant on duty to administer immediate medical treatment to workers suffering from pressure related diseases.

Medical Selection

Medical selection of compressed air workers started in April 1984 with the commencement of compressed air work at the Shan Road worksite.

Compressed air workers were divided into those who engaged in manual labour doing shifts of specified duration, supervisory personnel and those with special skills (e.g.. electricians, pyrotechnic experts), who were usually non-shift employees. In addition the men of the Fire Service and Industrial Health Division also had to be examined for suitability to enter into compressed air.

Fitness to work in Compressed Air

The labourers were usually young. Enforcing stringent criteria on age, degree of body fat and freedom from pulmonary and ENT pathology was not a problem. However, the experienced supervisors were usually older and they harboured the usual physical impediments of this age group. In addition, if these supervisors had previous experience with compressed air, they would also have a greater risk of having dysbaric osteonecrosis of the long bones.

Paton and Walder[26] showed that men over 40 had a greater risk of DCS. Age restrictions were imposed. The compressed air workers had to be fit individuals of 18 to 40. Those over 40 were cleared on a case to case basis with stress testing to ensure their fitness as well as the limitations of their exposure to compressed air.

Nitrogen is 5 times more soluble in fat than in water. A man whose body weight comprises 30% fat will have 2,000 ml more nitrogen than a lean man who had only 10% body fat for every 1 atmosphere change in pressure. This predisposes the obese to a greater risk of decompression sickness on account of the large amount of nitrogen gas released from the tissues during decompression. Therefore, compressed air workers were required to be lean individuals of less than 20% body fat, as measured by the skin fold method. Individuals who were between 20 and 24% body fat were given limitations on the duration and pressure at which they could work.

A comprehensive history was taken to exclude any conditions, especially asthma or ENT conditions, which could place the worker at greater risk of getting barotrauma. Experienced compressed air workers were also screened for past histories of decompression sickness as well as problems of dysbaric osteonecrosis.

The height, weight and body fat were measured. The workers were examined for any ENT condition which might predispose them to sinus, or aural barotrauma. They were assessed on their cardiovascular health and an audiometric examination was performed.

Investigations included their full blood count, urine testing, eyesight testing, serum lipids and cholesterol, chest and long bone X-rays. Stress testing on a bicycle ergometer was required for a worker over the age of 40.

Entrapment of air under pressure within the lungs due to secondary lung pathology can result in serious pulmonary embolism. Congenital cysts, scar tissues, vesicles and emphysematous bullae are possible sites of air entrapment. Many physicians feel that the stethoscope is not efficient in the detection of small lesions. The routine examination, therefore, included spirometry and the measurement of peak expiratory velocity or equivalent quantitative tests of pulmonary function. Chest X-rays were taken prior to commencement of work in compressed air and were repeated yearly. The workers were also given a recompression chamber run to ensure that they were able to equalise the pressure in their ears, sinuses and lungs.

A total of 2,392 potential compressed air workers were seen for pre-employment medical examination. Out of these, 1,737 (72.5%) passed and 655 (27.4%) failed the medical examinations.

Among the failures, ear problems stood out as the commonest cause, accounting for 43.5%. These included perforations of the tympanic membranes and chronic infection of the ears. Heart and lung problems together contributed 31% to the failures. Common pulmonary conditions were asthma and pulmonary tuberculosis. Hypertension and valvular heart conditions were the common cardiovascular problems.

It is interesting to note that 3 cases were rejected because of dysbaric osteonecrosis. All these 3 cases had previously worked in compressed air in other parts of the world. Other causes that disqualified candidates from compressed air work can be seen in Table 1.

TABLE 1

REASONS FOR FAILING MEDICAL EXAMINATION

Condition	**Number Failed**	**%**
Ear	285	43.5
Cardiovascular	102	15.5
Respiratory	102	15.5
Chamber Test	36	5.5
Nose	32	4.9
Sinus	19	2.9
Endocrine	14	2.2
Musculoskeletal	10	1.5
Dysbaric Osteonecrosis	4	0.6
Others	51	7.8
Total	**655**	**100.0**

Training of various personnel

To provide medical coverage at all the worksites daily, doctors, nursing staff and medical orderlies had to be trained in management of compressed air illnesses. Training was also administered to man-lock and medical-lock attendants who had the great responsibility of looking after workers who worked in the compressed air tunnels. Other lectures had to be given to safety officers, firemen, ambulance officers, industrial health nurses and compressed air workers on the medical aspects and hazards of compressed air exposure. Some of these courses were administered and approved by the National Productivity Board but the training of the personnel was done by DHMC. The courses conducted are shown in Table 2.

TABLE 2

COURSES CONDUCTED BY DHMC

Courses	**Number**	**Number Trained**
Medical-lock Attendants' Instructors (MRT) Course	1	5
Medical-lock Attendant Course	7	36
Man-lock Attendant Course	10	51
Medical-Lock Conversion Course	1	5
MRT Construction Safety	7	55
Compressed Air Course for SAF Medical Officers	3	23
Safety Officer's Course	3	45

Prevention and health care

ROUTINE MEDICAL CONSULTATION

The fluctuation of pressures during entry and exit from the tunnels can potentially cause injury to the air cavities of the body. In particular, the sinuses, middle ear, lung and even air cavities in the teeth can be affected.

In order to prevent compressed air workers from suffering from these pressure related problems or barotrauma, consultation at the worksite was made available. This facilitated early treatment of colds and coughs which may occlude the airways and sinuses of these workers thus predisposing to barotrauma. It was noted that the high humidity in the confined working chamber and dampness from the soil caused more respiratory tract infections than usual.

There were problems of high humidity (almost 100%) and high temperatures (approaching 40 degrees on some occasions) which caused workers to suffer from dehydration, heat exhaustion and an increased risk of decompression sickness. There were also many cases of dermatological problems related to the humid and hot environment.

Regular periodic follow-ups were made compulsory for all compressed air workers. New starter clearance was also conducted at the worksite. This ensured that all compressed air workers remained fit and that any problems were tackled early on.

MONITORING OF WORKSITE AND TUNNEL SAFETY

The medical officer at the worksite was required to monitor the tunnel pressures and the man-lock register daily. The tunnel pressures were recorded on barographs and daily checks were performed to ensure that appropriate decompression was carried out by the man-lock attendant for the workers on the man-lock register. Immediate action was taken to ensure workers did not exceed the Blackpool Tables, which required compressed air workers to spend at least 12 hours at ground level between shifts.

All man-lock attendants had to abide with the proper decompression procedures. They were fined when wrong decompression schedules were used. Those compressed air workers in the man-locks found tampering with the emergency exhaust valves to release themselves early, were also fined.

An MO inspected the worksite and inside the tunnels fortnightly to ensure that there were no unsafe work practices and to reduce the number of accidents occurring through carelessness or ignorance.

Inspection of the man-locks revealed that some man-lock chambers leaked, especially during the last 0.3 bar of pressure. This was due to poor seals and bad alignment of the doors. This problem was further compounded as some man-locks were not level. This was a problem as it meant that the workers were suddenly decompressed when the doors opened unexpectedly. As there was a real danger that the compressed air workers would get DCS, measures were taken by the contractor to modify the chamber doors by including various locking devices to hold the doors shut until decompression was completed. Leaks which required rectification were also found at some of the piping.

With the high humidity and temperatures in some of the tunnels, the contractors were told to install water coolers inside the tunnels to prevent dehydration in the compressed air workers.

Cigarette butts were found on some occasions within the compressed air tunnels, which was alarming. The high partial pressure of oxygen in the tunnel air can cause fires or explosions, especially with naked flames. Immediate action was taken to notify the contractors and engineers to stop such unsafe practices.

However, in spite of the checks, two major accidents still occurred in Contracts 104 and 105 when runaway railway cars smashed into the mud-lock doors of the tunnel causing an explosive decompression. At Contract 105, (tunnel pressure 1.88 bar gauge), 15 men suffered from aural and sinus barotrauma and 4 men had to be treated at DHMC. At Contract 104, (pressure 1.45 bar gauge), all the 15 men inside the tunnel had to be treated simultaneously for DCS at DHMC.

There was a problem with ammonia fumes produced by jet grouting of the tunnel face causing a disruption of the ammonia equilibrium in the soil. This caused the ammonia level to rise to 36 ppm at one stage, resulting in some workers complaining of irritation of the throat, smarting and tearing of the eyes. The problem eventually controlled when the company took steps to wash the tunnel face and to spray the soil with mild acids.

Decompression Sickness

Of special interest in the entire project was the management and treatment of decompression sickness suffered by the compressed air workers.

The population at risk of suffering from DCS was a cohort of 1737 workers who were a multinational lot. There were Thai, Korean, Japanese, Chinese, Indian, Malay and Caucasian workers of various age groups. Both shift and non-shift workers were involved in the contract. The non-shift workers included engineers, supervisors, electricians and fitters who entered the tunnel to perform tasks. They spent variable times in the tunnel and had to be decompressed accordingly.

TABLE 3

SITE OF TYPE I SYMPTOMS

Site	**Pain**	**Skin Rashes**	**Lymphatic Manifestations**
Head	-	1 (Macular Rash)	-
Shoulder	19	-	-
Elbow	16	-	-
Wrist	2	-	-
Abdomen	-	2 (Papular Rash)	-
		1 (Marbling Rash)	1
Inguinal Region	-	-	1
Hip	4	-	-
Knee	108	-	-
Lower Leg	-	1 (Itchy, Macular)	-
Ankle	5	-	-
Total	**154**	**5**	**2**

For ease of reporting and presentation, the cases of DCS were classified into two types after Golding et al.[27]

Type I (mild) Symptoms and signs were mild and present as musculoskeletal pain or swelling due to lymphatic obstruction and skin involvement.

Type II (serious) Symptoms and signs were severe and attributable to disorders of the nervous, pulmonary and cardiovascular systems.

Various factors were analysed including the host characteristics, duration of onset, age, length of exposure, pressure, number of episodes of DCS, overall incidence, relationship to shift-work and physical environment of the worksite, treatment methods and outcome.

Data on the incidence of dysbaric osteonecrosis was obtained by review of the long bone X-ray reports performed yearly as required by legislation. Factors with regard to pressures of exposure and other host characteristics like obesity, race and number of episodes of DCS were analysed.

SYMPTOMATOLOGY

There were 164 cases of DCS. 160 were of the milder Type I category while 4 were of the more serious Type II category.

Type I

The commonest presentation of Type I DCS in this series was pain (154 cases or 96.3%). The commonest site of pain was around the joints. 84 cases (55%) presented with monoarticular pain while 70 cases (45%) presented with polyarticular pain. In 76% of the cases the joints of the lower limb were involved. The knee joint was the commonest joint involved (108 cases) followed by the shoulder joint and the elbow joint (Table 3).

The characteristic nature of the pain noted was that it was deep joint pain, aggravated by movement. There was also a limitation of the range of joint movement.

There were 5 cases (3.1%) of cutaneous DCS. Two cases presented with papular rashes over the abdomen. Two cases had macular rashes, over the forehead and over both shins respectively. One case presented with a marbling rash over the abdomen. One case of lymphatic DCS was seen involving the inguinal lymphatics and presenting as swelling of the penile skin (Table 4).

Type II

Table 5 illustrates the clinical presentation of the 4 Type II cases seen in the MRT project. Three of them were exposed to compressed air for periods exceeding 8 hours. All of them presented within 2 hours of decompression. Case number 4 developed pulmonary DCS following an explosive decompression of the tunnel when a runaway locomotive smashed open the mud-lock door.

ONSET OF SYMPTOMS

94.5% of the Type I and II cases developed symptoms within 12 hours of decompression (Table 6).

TABLE 4

CLINICAL PRESENTATION OF TYPE I DCS

Symptomatology	No. of Cases
Pain:	
Deep Pain	133
Superficial	7
Constant	24
Throbbing	5
Radiation of Pain	3
Limitation of Movement	16
Rashes:	
Erythematous, Papular, Itchy	2
Erythematous, Macular, Itchy	2
Marbling Rash over abdomen	1
Lymphatic Swelling	2
Itching	5
Warmth Around Joints	8
Numbness	16

EPISODES OF DCS

Of 1,737 people who worked in compressed air from September 1984 to April 1987, 136 (7.83%) suffered from DCS. Of these 136 men, 114 (83.5%) suffered from a single episode of DCS while 22 (16.2%) had two or more episodes of DCS. Table 7 shows the distribution of DCS episodes amongst the 136 affected. The maximum number of episodes of DCS in any one man was 4.

INCIDENCE WITH PRESSURE AND DURATION OF EXPOSURE

A total of 188,538 man decompressions were performed in the MRT project. There were 160 cases of mild (Type I) DCS and 4 cases of severe (Type II) DCS, giving the overall incidence of DCS at 0.087%. There were 64,059 man decompressions over 1 Bar gauge, with 154 cases of DCS, giving an incident rate of 0.240%.

A study of the compressed air exposure time of the 164 cases showed that the majority, 125 cases (76.3%), occurred after exposure times exceeding 8 hours as seen in Table 8.

TABLE 5

CLINICAL PRESENTATION OF TYPE II DCS

Case Number	Working Pr (Bar)	Exposure Time	Onset of Symptoms Following Decompression	Clinical Presentation	Treatment
1 (N S)	1.75	8 hrs 5 mins	1/2 < 1 hr	Pain - left knee and hip joints. Loss of sensation L3, 4 bilateral. BP 110/70. 2 previous episodes of Type 1 DCS.	CIRIA 2
2 (A Y)	1.53	8 hrs 23 mins	1/2 < 1 hr	Pain - right knee. Loss of sensation to pinprick over right half of body.	CIRIA 2
3 (K P)	1.45	8 hrs 32 mins	1/2 < 2 hrs	Felt weak & giddy 70 min after leaving manlock. Noted to be staggering & vomiting but no nystagmus, visual or auditory symptoms. BP 110/70. Relapsed with giddiness and low BP of 90/50 & vomiting on sitting.	CIRIA 2 and TABLE 62
4 (I H)	1.4	6 hrs 25 mins	< 1/2 hr	Sudden decompression accident. Pain - Both knees. Aural barotrauma bilateral. Chest pain & dyspnoea. BP 140/80 Pulse 84.	TABLE 62

TABLE 6

ONSET OF SYMPTOMS OF DECOMPRESSION SICKNESS

Time	**< 1 Hr**	**1 < 4 Hrs**	**4 < 6 Hrs**	**6 < 12 Hrs**	**12 < 24 Hrs**	**> 24 hrs**	**Total**
Number of Type I	32	68	32	19	1	8	**160**
Number of Type II	3	1	0	0	0	0	**4**

TABLE 7

NUMBER OF EPISODES OF DCS

No. of Episodes of DCS	1	2	3	4	Total
No. of Men Affected	114	17	4	1	136
Percentage of Men Affected	83.8	12.5	2.9	0.8	100%

TABLE 8

INCIDENCE OF DCS WITH PRESSURE AND DURATION OF EXPOSURE

Maximum Working Pressure (Bars Gauge)	**DCS Type**	**Decompression Sickness Incidence In % (brackets show absolute figures)**			**DCS Incidence (by Type of DCS %)**	**Total Incidence %**
		< 4 Hours	**4-8 Hours**	**> 8 Hours**		
</1 Bar	Type I	0.00 (0)	0.00 (0)	0.027 (10)	0.008 (10)	**0.008%**
	Type II	0.00 (0)	0.00 (0)	0.00 (0)	0	
No. of Man-Decompressions.		60,976	27,080	36,423	12,4479	
1-2 Bar	Type I	0.016 (4)	0.310 (32)	0.359 (98)	0.215 (134)	**0.221%**
	Type II	0.00 (0)	0.001 (1)	0.011 (3)	0.006 (4)	
No. of Man-Decompressions.		24,596	10,423	2,7331	62,350	
2-3 Bar	Type I	0.00 (0)	1.786 (2)	1.724 (14)	0.936 (16)	**0.936%**
	Type II	0.00 (0)	0.00 (0)	0.00 (0)	0.00 (0)	
No. of Man-Decompressions.		785	112	812	1,709	
TOTAL	**Type I**	**0.005 (4)**	**0.090 (34)**	**0.193 (122)**	**0.085**	**0.087%**

The incidence of DCS at less than 1 Bar gauge exposures was 0.008%. There were 10 cases in 124,479 man decompressions. This unexpected finding will be discussed in another paper.

The incidence of DCS at pressures between 1 to 2 Bar gauge was 0.218% with 138 cases in 62,350 exposures. Between 1-2 Bar, for durations less than 4 hours, the results again were significantly lower (p < 10-6) than the mean values. At exposure times of greater than 4 hours however, the number of cases of DCS observed were significantly higher than the expected values for the exposures of longer than 4 hours duration (both p values < 10-6) (Table 8).

The incidence of DCS occurring at pressures greater than 2 Bar gauge was 0.936%, with 16 cases in 1,709 exposures. Above 2 Bar gauge pressure, with duration of exposure less than 4 hours, there were no significant variations between the observed and the expected number of DCS cases. However, the observed increase in the number of cases of DCS was statistically significant for exposures between 4-8 hours (p < 0.03) and exposures greater than 8 hours (p < 10-6) (Table 8).

INCIDENCE OF DCS AND HEAT AND HUMIDITY

The incidence of DCS did not appear to correlate significantly with the observed high temperatures and humidity of some tunnels. The highest temperatures were recorded at Contract 105, where temperatures reached a high of 42 degrees. Most tunnels had relatively high humidity above 80%. At Contracts 107 and 108, there were occasions where humidity reached 100% .

DCS AND OBESITY

Few of the compressed air workers were obese. However, there were 3 cases of DCS amongst the 26 personnel who had more than 30% body fat during initial medical clearance (Table 9).

DCS AND OCCUPATION

The distribution of cases among the various occupations is shown in Table 10.

INCIDENCE OF DCS BY CONTRACTS

The maximum working pressure in the various contracts varied, the lowest being 1.43 Bar gauge in Contract 105, and the highest, 2.35 Bar gauge in Contract 301. The incidence of DCS by contracts is given in Table 11.

SHIFT-WORK

The incidence of DCS was evenly distributed among the 3 shifts.

DCS BY RACE

There appeared to be a slightly higher incidence of DCS occurring in the Malay population as compared to the other races. However, in view of the small number of man decompressions undertaken by this group of compressed air workers compared with the other groups, the findings were not significant (p > 1.0) (Table 12).

Treatment

Treatment primarily consisted of recompression with supportive drug therapy. Recompression in most instances were carried out at the medical-locks of the various work-sites. Following the recompression therapy, 100% surface oxygen was administered ensuring no relapse of symptoms (Table 13).

The CIRIA air therapeutic tables were used in most (73.9%) of the cases. The CIRIA table for Type 1 DCS involves returning the patient to the original working pressure, then a stepwise 0.1 Bar decompression every two minutes. When the pressure has been reduced to half the working pressure the rate of ascent is reduced to 0.1 Bar every 25 minutes. The table for Type II DCS involves returning to the original working pressure. If the symptoms are not relieved at this pressure, pressure is increased in increments of 0.1 Bar. Normally with an extra 0.6-0.7 Bar the patient loses his symptoms. He is then held at that pressure for 15 to 30 minutes before pressure is reduced by 0.1 Bar every 25 minutes. The patient is held at 1 Bar gauge for 6 hours and then decompressed at 0.1 Bar every 45 minutes. There is a 90 minute hold at 0.5 bar gauge after which decompression is continued at the same rate. The CIRIA tables were used as not all the medical-locks at the work-sites were equipped with built-in oxygen breathing systems. In resistant and relapsed cases, Workman and Goodman oxygen therapeutic tables were used by bringing oxygen breathing apparatus into the chamber or by transporting the patient to DHMC.

Of the 164 cases treated, 4 (2.44%) cases relapsed after the first treatment and had to be treated with hyperbaric oxygen. None of the 39 (23.78%) cases treated with hyperbaric oxygen had a relapse (Table 13).

Dysbaric osteonecrosis

Of the 1,737 compressed air workers who were certified fit to work in compressed air, 32 had previous type B dysbaric osteonecrosis lesions while 11 had other benign lesions such as bone islands. The compressed air workers with type B dysbaric osteonecrosis were allowed to work in compressed air, with exposure limited to not more than 2 Bar gauge. Follow up yearly long bone X-rays showed no new

TABLE 9

DCS AND PERCENTAGE OF BODY FAT

Percentage of Body Fat	Number of DCS Cases	Number of Man Decompressions	Incidence
< 20 %	156	181,813	0.086%
24 - 30 %	5	5,586	0.090 %
> 30 %	3	1,139	0.262%
Total	**164**	**188,538**	**0.087%**

TABLE 10

INCIDENCE OF DCS BY OCCUPATION

Occupation	Number of DCS cases	Number of Man-Decompressions	% Incidence
Compressed air worker	110	110,943	0.099
Engineer	15	51,050	0.029
Supervisor	23	12,883	0.179
Others	16	13,701	0.117

TABLE 11

INCIDENCE OF DCS BY CONTRACT

Contract	Maximum Pressure (Bar)	Number of DCS cases			Number of Man Decompressions		Incidence of DCS					
							Overall %			Over 1 Bar %		
		Type I	Type II	Total	Total	Above 1 Bar	Type I	Type II	Total	Type I	Type II	Total
104	1.50	36	1	37	79,363	39,064	0.045	0.001	0.046	0.092	0.002	0.094
105	1.43	3	0	3	27,976	937	0.011	0.0	0.011	0.320	0	0.320
107	1.60	31	0	31	8,757	2,679	0.354	0.0	0.354	1.157	0	1.157
108	1.95	26	1	27	19,520	6,666	0.133	0.005	0.138	0.390	0.015	0.405
109	1.50	28	2	30	38,110	5,550	0.073	0.005	0.078	0.505	0.036	0.541
301	2.35	36	0	36	14,812	9,163	0.019	0.0	0.019	1.746	0.044	1.790
TOTAL	**-**	**160**	**4**	**164**	**188,538**	**64,059**	**0.085**	**0.002**	**0.087**	**0.250**	**0.006**	**0.256**

TABLE 12

INCIDENCE OF DCS BY RACE

Race	Number of DCS cases	No. of Man-Decompressions	% Incidence
Chinese	39	45,008	0.0867%
Malay	14	15,849	0.0884%
Indian	34	39,064	0.0870%
Japanese	20	23,035	0.0868%
Korean	18	20,539	0.0876%
Thai	35	40,239	0.0870%
Caucasian	4	4,804	0.0834%
Total	**164**	**188,538**	**0.0870%**

TABLE 13

TREATMENT USED

Recompression Table	Contracts 104	105	107	108	109	301	Total
CIRIA 1	35	-	26	21	19	14	115
CIRIA 2	1	-	1	2	(2)	-	4(2)
TABLE 61	-	3	4	3	9	1	20
TABLE 62	(1)	-	-	-	-	18	18(1)
CIRIA 1 followed by Table 61	-	-	-	-	-	1	1
CIRIA 1 and 2 followed by Table 62	-	-	-	(1)	-	2	2(1)
Total	**37**	**3**	**31**	**27**	**30**	**36**	**160(4)**

Numbers in brackets denote cases of Type II DCS. There were 160 cases of Type I and 4 cases of Type II DCS

cases of dysbaric osteonecrosis and those compressed air workers who had pre-existing dysbaric osteonecrosis did not have any further change seen. Only 643 compressed air workers had exit long bone X-rays done at the end of their contract (Table 14).

Incidence of DCS in Singapore

The incidence of DCS in the Singapore MRT project was low when compared with compressed air work done elsewhere in the world. (Table 15)

The main reason for the low incidence is the generally low pressures that were used. The highest pressures were at Contract 301, which had a maximum tunnel pressure of 2.35 Bar gauge.

64.63% of our 164 cases of DCS occurred with exposures exceeding 8 hours. A higher incidence of DCS was also noted with increasing pressures (Table 8). This was observed with the incidence of DCS rising from a low of 0.008% to 1.61% for exposures exceeding 8 hours. With the increase in duration of exposure, there was an overall increase in the DCS incidence. For exposures greater than 2

TABLE 14

ABNORMAL LONG BONE X-RAYS OF COMPRESSED AIR WORKERS

	Abnormal Entry Long Bone X-rays		Abnormal Exit Long Bone X-rays	
Contract	**Type B**	**Benign Orthopaedic Conditions**	**Type B**	**Benign Orthopaedic Conditions**
MRT Task Force*	1	2	1	2
109	0	0	0	0
108	0	0	0	0
104	0	0	0	0
107	2	2	0	0
MRTC	8	0	3	0
105	2	1	0	0
301	19	6	5	6
Total	**32**	**11**	****9**	****8**

** Only 643 compressed air workers had done their exit Long Bone X-rays.
* MRT Task Force comprised firemen from the Singapore Fire Service.

TABLE 15

COMPARISON OF VARIOUS COMPRESSED AIR CONTRACTS

Contract	**Period of Compressed Air (Months)**	**Total No. of workers**	**Maximum Pressure (Bar)**	**No. of Man-Decomp.**	**No. of DCS Cases (Over-all)**	**DCS Incid. Over-all**	**DCS Incid. (>1 Bar)**
East River Tunnel New York 1914-21	84	-	3.26	1,360,000	680	0.05%	-
Howrah Bridge India 1938	6	509	2.72	12,400	353	2.8%	-
Lincoln Tunnel NY 1955-56	18	704	2.31	138,000	44	0.03%	0.07%
Dartford Tunnel 1957-59	24	1200	1.90	122,000	685	0.56%	0.97%
Blackwall Tunnel 1960-64	44	1536	2.65	8,100	863	1.1%	1.09%
Tyne Road Tunnel 1960-64	38	650	2.86	44,800	711	1.6%	1.74%
Hong Kong Islandline 1982-85	36	3966	2.85	443,430	2003	0.46%	0.52%
Singapore MRT 1984-87	**31**	**1737**	**2.35**	**188,538**	**164**	**0.087%**	**0.26%**

Bar absolute, due to the exigencies of the project, we had to increase the decompression time as the Blackpool Tables do not indicate decompression times for exposures greater than 8 hours. This had in a way, prevented more cases of DCS from occurring.

The higher incidence of DCS noted at the extremes of exposure indicate that far greater risks are associated with long exposures with the use of the Blackpool Tables in spite of adequacy of control. It is likely that with longer working hours, the workers have absorbed grater amounts of gases and have also been subjected to greater stresses involving the use of vibrating tools and lifting heavy loads over long distances in the tunnels. The cumulative factors resulted in the development of DCS in some men who appeared to be more susceptible to developing DCS than their peers who had been similarly exposed to the same pressures and performed the same type of work.

The overall incidence of the 4 cases of Type II DCS was 0.002% compared with 1 case (0.001%) reported by Lam's Hong Kong MTR series out of 93,509 man decompressions[28]. Three of the Type II cases developed DCS after more than 8 hours exposure at 1.45 Bar and above. The fourth case developed DCS soon after suffering from sudden decompression, when the mud-lock doors were smashed open by the runaway rail cars. Three out of four developed symptoms within 1 hour of decompression, while the fourth case had symptoms within 2 hours of decompression.

The incidence of DCS among the obese compressed air workers was higher than in the other compressed air workers. Nitrogen had been shown to be 5 times more soluble in fat than in lean tissues like muscle. With long exposures, it is expected that there is near saturation of the fatty tissue by nitrogen in the obese person. This results in a 5 times greater gas load during decompression. Therefore it was not surprising that despite conditionally passing the obese compressed air workers and allowing them to work at a limited exposure time and pressure, they still had a significantly higher incidence of DCS.

The supervisor category of personnel had an overall greater incidence of DCS when compared with the other categories of workers. This is related to the nature of work and the fact that supervisors were generally of an older age group. They were required to enter and exit from the tunnels up to five times a day, increasing their risk of DCS. The compressed air workers, in comparison, although were performing heavier work, exited only once per shift.

The incidence of DCS among the various races were fairly similar, with exception of the Caucasians, who had a lower DCS incidence. This is due to the fact that the Caucasians held specialist appointments like engineers and inspectors and had short exposure times in the course of their work.

Reasons for low incidence

MEDICAL STANDARDS

No compromise was made with regard to the selection of men working in compressed air. Workers who were susceptible to DCS were certified unfit or conditionally cleared to work in compressed air. This included the obese (> 24% body fat by skinfold measurement), those with a high incidence of DCS in the past and compressed air workers with established dysbaric osteonecrosis. The obese (over 24% body fat), and those with Type B dysbaric osteonecrosis were given a conditional clearance. They were allowed to work at a limited pressure and for a limited duration.

TRAINING

The man-lock attendants were required to attend certification courses conducted by DHMC in conjunction with the National Productivity Board and Ministry of Labour. In addition, all compressed air workers were thoroughly briefed on the safety aspects of compressed air work. They were taught the importance of proper decompression and the signs and symptoms of early DCS. Some compressed air workers found tampering with the emergency exhaust valves in the man-locks to release themselves early, were disciplined. The strict control of the decompression procedure paid off and prevented DCS occurring due to negligence.

LEGISLATION AND CONTROL OF DECOMPRESSION PRACTICE

The legislative framework determined the requirement for the control of the time of exposure. In addition, we believed that a period of acclimatisation for new starters did much to reduce the incidents of DCS. This was incorporated in the legislation for all new compressed air workers as well as those who have been away for more than 12 consecutive days. Paton and Walder[26] noted a high incidence of DCS in newly introduced workers, but with acclimatisation, the incidence fell. As a result of the regulations, we did not see any cases of DCS in new starters.

The Blackpool Tables, designed by Hempleman, were well tested in the UK and Hong Kong with a DCS incidence rate of less than 2%. For exposures less than 1 Bar gauge, compressed air workers were decompressed to the surface at a rate of not exceeding 0.4 bar/min. However, in the Singapore MRT project, a stop at 0.2 Bar gauge for 5 minutes was included into the regulations. This stop was included to reduce the rate of ascent further as we believed that it would have been to risky to ascend immediately to the surface after more than 10 hours of exposure.

Compressed air workers exposed to pressures more than 1 Bar gauge had to follow the decompression schedules according to the Blackpool Tables. These tables required compressed air workers to remain at the surface for at least 12 hours in every 24 hours. This was because at the end of decompression, residual nitrogen still remains in the body. This will accumulate without an adequate rest period at atmospheric pressure.

Multiple entries into the compressed air tunnels were allowed for the supervisors. By law, they were allowed to enter the chambers only 5 times in a 24 hour period at pressures not greater than 2 bar gauge, for not more than half an hour on any one occasion and with a minimum surface interval at normal pressure of more than 1.5 hours.

There were instances where compressed air workers were exposed to compressed air exceeding the time limits imposed by the Blackpool Tables, either by misinformation or the exigencies of work. This posed a problem of decompression as the Blackpool Tables were calculated with a maximum of 8 hours exposure. In order for them to work at these long hours, extension of the Tables were required and additional stops had to be included as a safety measure. The incidence of DCS in the extended part of the Tables was lower than the incidence following decompression with the Blackpool Tables.

Clinical presentation

The commonest presentation of Type I DCS in our series was that of joint pain (Table 3). This occurred in 96.3% of cases with 76% of cases having pain in the lower limbs. Pain was mostly around the joints of the long bones. 84 cases (55%) presented with monoarticular pain while 70 cases (45%) presented with polyarticular pain. 76% had pain in their lower limbs compared with 87.82% reported Lam in the Hong Kong MTR project.[28] The knee was most commonly affected in our series (108 cases or 70.1%), followed by the shoulder joint (19 cases or 12.3%) and the elbow (16 cases or 10.4%).

A detailed analysis of the onset of symptoms revealed that 82.9% of cases had symptoms within 6 hours of decompression, with 95.1% of cases presenting before 24 hours. This is comparable with Lam's Hong Kong MTR series with 93.6% presenting within 6 hours.[28]

There were 5 cases of Type 1 DCS presenting as rashes. These cases proved difficult to diagnose. Recompression confirmed the assessment. Two cases presented as swelling of the lymphatics, one of who had lymphatic swelling over the inguinal region which also subsided with recompression. In the Hong Kong series, 4 cases had skin mottling, 39 had non-specific symptoms of headache, nausea and vomiting. The other 94.6% (749) cases presented with joint pains.

Treatment

Early recognition of symptoms and prompt treatment was ensured by making it compulsory for compressed air workers to remain at the worksite for 2 hours following decompression from the tunnel. This probably accounted for the fairly low relapse rate of 2.44% (4 cases). By comparison, 8.2% (64 cases) required a second treatment and 11 (1.4%) required a third treatment in the Hong Kong series.

Adjuvant therapy including fluid replacement was used. Fluids included Dextran in addition to Normal Saline and Hartmann's Solution. Aspirin was not given to the compressed air workers because of the possibility of masking the symptoms.

The objective in fluid therapy was to replace depleted blood volume, to restore haematocrit and to prevent blood sludging and to improve tissue perfusion. It is common to find that patients with acute DCS have reduced blood volumes, and many animal studies have confirmed this finding. Dextran has advantages for restoring intravascular fluid lost by increased capillary permeability during DCS[29], although there are those who are more concerned with the potential of Dextran for creating an acute volume overload and further lung congestion. Our experiences with Type 1 DCS and delayed Type II DCS has shown us that judicious use of Dextran, especially in the young, robust compressed air workers or fisherman divers, reaped benefits in the improvement of symptoms in our patients. We advocate the combined use of fluid therapy with colloids and crystalloids, aspirin, dexamethasone and recompression therapy in DCS therapy.

Accidents

Two major accidents occurred in Contracts 104 (Bocotra at Orchard Road) and 105 (TTJV at Novena Station) when runaway rail cars smashed the mud-lock doors of the tunnel causing an explosive decompression. At Contract 105, (tunnel pressure : 0.88 Bar gauge), 15 men suffered from aural and sinus barotrauma and 4 had to be admitted and treated at DHMC.

At Contract 104, the tunnel pressure was 1.45 Bar gauge. There were 15 men inside the tunnel while 2 men were working around the mud-lock. The men had been working for seven and a half hours. Five men developed symptoms of DCS and the operations centre at DHMC was thrown into full alert. Ambulances were sent to the site and doctors were deployed to three recompression chambers treating the patients simultaneously. One of the workers working around the man-lock was thrown 10 metres by the out-rushing air. He was evacuated to hospital with head and body injuries. The number of cases of DCS would have been less (159 instead of 164) except for this accident.

The future

The future of compressed air tunnelling will see the use of oxygen for decompression. Oxygen decompression was suggested as early as 1878 by Paul Bert[15], and 1905 by Ham and Hill[30]. The advantages that oxygen decompression offer are reduction of the decompression times and perhaps a lower DCS rate. Oxygen tables are available for decompression and, while they reduce the amount of time spent decompressing, they have inherent disadvantages. Man-locks will have to be modified to incorporate oxygen built-in breathing systems (BIBS) and an oxygen overboard dump. This will incur increased costs. High pressure oxygen, being a fire hazard, will require special care during the decompression. No flammable articles can be brought into the chambers. Proper use of the masks for oxygen breathing during decompression will have to be ensured if DCS was to be avoided. The workers may develop CNS oxygen toxicity, and a doctor will have to be at the man-lock to supervise the decompression. The Japanese have had bad experiences with oxygen decompression, as fire and deaths have occurred in their man-locks.

The Blackpool Tables and the current American OSHA tables are still not perfect. Kindwall et al are currently evaluating the use of oxygen tables to supersede the current United States Occupational Health and Safety Agency (OSHA) Decompression Schedules. Oxygen tables are currently being used by the French and Germans for decompression from tunnelling work, but these have not been widely adopted elsewhere. These tables adopt profiles similar to those of dive tables, but incorporate oxygen in order to shorten the decompression times.

Automation and robotics may be featured more prominently in future, where tunnels may be dug using unmanned devices. Alternatively, the compressed air worker may adopt a lightweight armoured suit as used by the deep sea diver, where the worker can remain at 1 atmosphere pressure and perform tasks without the need for decompression. Saturation compressed air tunnelling could be another method which may be adopted for the future.

Conclusion

Decompression sickness is a preventable condition in compressed air work. The prevention of this illness is to a large extent dependent on the recognition of the hazards involved and in the application of recognised medical and environmental control measures. The DCS incidence of 0.087% in the Singapore experience was low and the medical team involved in the project can look back at the months of compressed air work with much satisfaction. The attention to detail during planning and the adoption of strict medical standards in selection of men and in safety control ensured that no case of DCS ever occurred out of ignorance or poor compliance with safety regulations. The preventive measures undertaken enabled a fairly good safety record to be achieved.

REFERENCES

1 Snell E.H. Compressed air illness, or so-called caisson disease. London: H.K. Lewis, 1896

2 Triger E. Memoire sur unappareil a air comprime, pour le pencement des puits de mines et autre travaux, sous les eaux et dans les sables submerges. *C.R. Acad. Sci.* Paris, 1841; 13: 884-896.

3 Woodward C.M. A history of the St. Louis Bridge. St. Louis: Jones, 1881

4 Jacobs C.M. The Hudson River tunnels of the Hudson and Manhattan Railroad Company. *Min Proc Instn Civ Engrs* 1910; 181: 169-257.

5 Keays F.L. Compressed air illness. *Am. Labor Legislation. Rev*. 1912; 2: 192-205.

6 Thorne I.J. Caisson Disease: Observation and report of 300 cases at the Queens Midtown Tunnel Project, *JAMA* (Aug. 23) 1941; 117: 585-588.

7 Sealey J.L. Safe exit from the hyperbaric environment - Medical experience with pressurised tunnel operations. *J Occup Med* 1969; 11(5): 273-275.

8 Kindwall E.P, Nellen J and Spiegelhoff D.R. Aspetic necrosis in compressed air tunnel wworkers using current decompression schedules. *J Occup Med* 1982; 24: (10) 741-745.

9 Hughes J. The pneumatic method adopted in constructing the foundation of the new bridge over the Medway at Rochester. *Min Proc Instn Civ Engrs* 1851; 10: 353-369.

10 Boycott A.E, Damant G.C.C, and Haldane J.S. (). Prevention of compressed air illness. *J Industr Hyg* 1908; 8: 342-443.

11 Ministry of Labour and National Service (). Work in Compressed Air Special Regulations (S.I. No. 61). London.: HMSO, 1958

12 Medical code of practice for workers in compressed air. Construction Industry Research and Information Association Report 44. 1st edn 1972.

13 Pol B and Watelle T.J.J. Memoire sur les effects de la compression de l'air appliquee au creusement des puits a houille. *Ann Hyg Publ* (Paris), 2nd Series,1854; 1: 241-279.

14 Boyle R. New pneumatical observations about respiration. *Phil Trans R Soc* 1670; 5: 2011-2031.

15 Bert P. Barometric pressure, 1878. Trans. by Hitchcock M.A and Hitchcock F.A. Columbus, Ohio: College Book Company, 1943; republished by Undersea Med Soc Inc, 1978.

16 Gramenitski P.M and Savich A.A. Results of experimental analysis of decompression air embolism. In The effects of gas embolism and pressure on body functions III. Ed. Brestkin M.P. 47-56. Washington, D.C.: US Dept. of Commerce, 1965;

17 Leverett S.D, Bitter H.L and McIver R.G. Studies in decompression sickness; circulatory and respiratory changes associated with decompression sickness in anesthetised dogs. Report SAM-TDR-63.7. USAF School of Aerospace Medicine. 1963

18 McIver R.G, Fife W.P.P and Ikels K.G. Experimental Decompression Sickness from Hyperbaric Nitrous Oxide Anesthesia. Report SAM-TR-65-47. USAF School of Aerospace Medicine. 1965

19 Spencer M.P, Johanson D.C and Campbell S.D. Safe decompression with the Doppler ultrasound blood bubble detector. In Underwater Physiology; Proc Vth Symp Underwater Physiology, 311-325. Ed. C.J. Lambertsen. Bethesda, Maryland: Fedn Am Socs Exp Biol, 1975

20 Swindle P.F. Occlusion of blood vessels by agglutinated red cells, mainly as seen in tadpoles and very young kangaroos. *Am J Physiol* 1937;120: 59-74.

21 End E. The use of new equipment and helium gas in a world record dive. *J Ind Hyg* 1938; 20: 511-530.

22 Leitch D.R., Hallenbeck J.M. Pressure in the treatment of spinal cord decompression sickness. Undersea Biomed Res, 1985; 12: (3) 291-305.

23 Thorsen T, Daleen H, Bjerkvig R and Holmsen H. Transmission and scanning electron microscopy of nitrogen microbubble-activated human platelets in vitro. *Undersea* Biomed Res 1987; 14: (1) 45-58.

24 Bassoe P. . Compressed air disease. *J Nerv Ment Dis* 1911; 38: 368-369.

25 Bornstein A and Plate E. . Uber chronische Gelenkveranderugnen, entstanden durch Presslufterkrankung. *Fortschr Geb Rontg Strahl* 1911-12; 18: 197-206.

26. Paton,W.D.M, Walder D.N. (). Compressed air illness: An investigation during the construction of the Tyne Tunnel, 1948-1950. Spec Report, No. 281. London: Medical Research Council, 1954

27 Golding F.C, Griffiths P, Hempleman H.V, Paton W.D.M and Walder D.N. Decompression sickness during construction of the Dartford Tunnel. *Br J Ind Med* 1960; 17: 167-180.

28 Lam T.H. and Yau K.P. Manifestations and treatment of 793 cases of decompression sickness in a compressed air tunnelling project in Hong Kong. *Undersea Biomed Res* 1988; 15: (5) 377-388.

29 Cockett A.T.K and Nakamura R.M. Treatment of decompression sickness employing low molecular weight dextran. *Review of Subaquatic Physiology and Hyperbaric Medicine* 1968; I: 133

30 Ham C and Hill L. Oxygen inhalation as a means to prevent caisson and divers' sickness. *J Physiol* 1905-06; 33: vii-viii .

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PROJECT STICKYBEAK

This project seeks to document all types and severities of diving-related accidents. Information,which is treated as being CONFIDENTIAL in regards to identifying details, may be sent to:

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ASSESSMENT OF THE PNEUPAC HC HYPERBARIC VENTILATOR

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Introduction

The PneuPac HC Hyperbaric Ventilator (Figure 1) has been specifically designed to ventilate patients within hyperbaric chambers over a range of pressures up to 10 ATA (atmospheres absolute). It is a standard pneumatically controlled, time-cycled ventilator providing independent control of inspiratory time, inspiratory flow rate and expiratory time. The range of these parameters has been significantly extended to allow compensation for the changes in ventilator performance with different chamber pressures.[1] Following the manufacturer's advice, we carried out calibration of the PneuPac HC ventilator to derive a series of calibration tables for its clinical use.

Description of PneuPac HC ventilator

The HC Ventilator consists of a pneumatic control module operating a remote patient valve housed in the patient connection block. These are linked by a small diameter flexible hose which can be separated to allow sterilisation of the patient valve. The control module is operated from compressed air, oxygen or a helium/O_2 mixture which is delivered from a regulator within the chamber, set at 400-1000 kPa gauge pressure. A simple schematic diagram of the PneuPac HC is shown in Figure 2.

The control module has three control knobs; one each for the inspiratory and expiratory times which are each arbitrarily graduated from one to nine, and an inspiratory flow control which completes eight and a half revolutions between its minimum and maximum settings. As well, there is an on/off switch and a pressure gauge. All moving parts of the control module are manufactured to require no lubrication or maintenance.

On connecting the ventilator to the gas supply and switching on, the spool in valve B is initially biased to allow the gas to flow from port 1 to port 2 from where it will flow to the inspiratory timer valve C and to valve F and thence to the patient valve.

The inspiratory time knob restricts the gas flow into the inspiratory timer cartridge C which then fixes the rate of pressure rise within C. At a predetermined pressure, a piston within C moves to allow gas to flow to port 4 of valve B which in turn switches the spool of valve B to the expiratory position. Now the gas flow is directed from port 1 to port 3 and thence to the expiratory timer cartridge D which behaves in a similar way to the inspiratory cartridge. During expiration, a non-return valve within C opens to release the pressure within this cartridge. The expiratory time knob is