LEADING ARTICLE

SINGAPORE MASS RAPID TRANSIT PROJECT

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INTRODUCTION

The idea of a Singapore Mass Rapid Transit (SMRT) system first surfaced in early 1970 when the State and City Planning Study examined land use and transportation in the light of the Government's development 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 railbased 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 its Diving and Hyperbaric Medical Centre (DHMC) 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 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 Decompression Tables were used by contractors. The manpower and doctors from DHMC enabled a comprehensive management and documentation of all medical cases treated.

The Singapore MRT system comprises 41 stations along a 65.8 km route. 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 PTE LTD (BOC)	– CONTRACT 105
KAJIMA-KEPPEL JOINT VENTURE (KKJV)	– CONTRACT 107
TAISEI-SHIMIZU-MARUBENI CONSORTIUM (TSM)	– CONTRACT 108
OHBAYASHI-GUMI/OKUMURA JOINT VENTURE (OOJV)	– CONTRACT 109
NISHIMATSU-LUM CHANG JOINT VENTURE (NLJV)	– CONTRACT 301

A total of about 20 km were underground tunnels of which about 11 km were constructed using compressed air. In addition, the MRT Gammon – Antara Koh Joint Venture, Industrial Health Division, Ministry of Labour and Singapore Fire Service also used the services of the centre.

BACKGROUND

In Singapore, compressed air was first used on a very small scale in sewage tunneling in 1982. In 1984, compressed air tunneling began on the SMRT project.

The idea of using compressed air to displace ground water from a working tunnel was first mentioned in 1691 by Denis Papin. 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).

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, the other significant health hazards of work in the compressed air environment are decompression sickness (DCS), pulmonary barotrauma and dysbaric osteonecrosis (DO). 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 (CAWs), divers, medical workers in hyperbaric environment and aviators are similarly susceptible to DCS and DO.

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DECOMPRESSION SICKNESS

Although the symptoms of DCS were first described by Triger (2) in 1841, it was only later that Pol and Watelle (1854) noted these afflictions occurring only in workers leaving the tunnel and not whilst entering or remaining in the compressed air environment (3). Signs and symptoms of DCS like painful joints, disturbances of the cardiovascular, respiratory and nervous systems were described. They rightly recommended recompression as a therapeutic modality but it was left to others to develop proper decompression schedules and therapeutic tables.

The reduction in ambient pressure causes the dissolved nitrogen to form nitrogen bubbles in tissues. The exact mechanism of bubble formation, even after 100 years of research, is still unclear. Theories of bubble formation like 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 (4) observed bubbles in tissue and blood samples of animals decompressed in hypobaric chambers. Bert (5), in a series of experiments with goats and other small animals in 1878, established the role of nitrogen bubbles in DCS. Many workers (6-8) 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 (9) indicate that nitrogen bubbles are the causative agents in DCS.

Further studies since the 1930's have found that bubble-blood interactions occurring in-vivo 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 in 1937 (10) and End in 1938 (11) 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 the bubbles produced changes in the blood and tissues with both morphological and metabolic consequences. These included alteration in platelets function, changes in the blood and plasma levels of enzymes, and catecholamine, lipids, proteins and coagulability of blood. Leitch and Hallenbeck showed that the pathology may also be caused by arterial gas embolism leading to peripheral vascular obstruction by gas bubbles (12). Involved cord segments showed varying degrees of haemorrhage and occasional vascular congestion. Microscopic petechiae were present in both the grey and white matter. These appearances were compatible with hypoxia or embolic episodes. Thorsen et al in 1987 (13) have shown 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 (DO). In 1911, Bassoe (14), in a paper to the Chicago Neurological Society, described chronic joint pain and stiffness in 11 out of 161 caisson workers. Bornstein and Plate in 1912, also described 3 cases of joint disease among some 500 bends cases associated with the construction of the Elbe Tunnel at Hamburg (15). Bassoe in 1913 suggested a relationship between initial joint "bends" and subsequent development of bone atrophy.

This condition is included in this paper as many workers consider DO as a chronic form of DCS. The aetiological basis of both diseases are similar. DO 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. DO has been known to occur with a single exposure to pressure. In 1931, five survivors of the submarine 'Poseidon', which sunk in the China Sea, spent 2 to 3 hours at 38 metres before escaping. Three of the five subsequently developed DO.

DO 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 DO occurs as a result of bone infarction caused by occlusion of capillaries by nitrogen bubbles or by secondary platelets plugs. Once blockage occurs, the osteocytes in the affected bone die if the ischaemia is not reversed within 12 hours. Common sites for DO are the head, neck and shaft of long bones, especially in the femur, tibia and humerus. DO is seen radiologically about 4 months after the initial insult. Severe cases of DO may have marked sclerosis and collapse of the bony trabeculae, resulting in disruption of the joint.

COMPRESSED AIR WORK IN THE UNITED STATES

Compressed air was first used in 1869 during the construction of a railroad bridge over the Pee Dee river between Wilmington to Colombia. In the same year, the foundations of the bridge over the Mississippi at St. Louis were built using compressed air (16). Decompression schedules used in the 1879 Hudson River Project (17) required men to work at 32 psig (2.18 bar) 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 psig, the men worked in shifts of 3 hours with 3 hour rest intervals. Workers working between 40 psig (2.72 bar) and 42 psig (2.82 bar) spent 3 hours on shift with a 3 hour rest interval between shifts at normal pressure. There was an attempt by the New York State Department of Health and Port Authority to minimize disabilities arising from DO.

FL Keays, 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 (18). 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 (19) 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. This was an attempt by the New York State Department of Health and the Port Authority to minimize disabilities arising from DO.

In 1961, Dr Leon Sealey (20), Medical Consultant to the Municipality of Metropolitan Seattle and Metropolitan Engineers organized a committee to formulate decompression tables regulating work in compressed air in connection with the major sewage tunnel project through Seattle. The new tables were subsequently adopted by Michigan, New York and California. It was later observed that these new tables again failed to prevent disabling DO in CAWs. Kindwall et al (21) re-examined the current Occupational Safety and Health Agency (OSHA) decompression schedules and concluded that these tables permitted the development of DO 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 were adopted. An oxygen version of this table was also designed to reduce the decompression times considerably.

COMPRESSED AIR WORK IN ENGLAND

Caissons were first used in Britain by Hughes (1851) during the construction of the foundations of a bridge at Rochester in Kent (22) and shortly afterwards by Brunel for the Saltash bridge between Devon and Cornwall. DCS and DO were a great problems for caisson work as well as diving and in 1906, the British Admiralty appointed a committee which included JS Haldane to develop safe decompression schedules (23). In 1907, Haldane described the now classic principle 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 CAWs working for varying periods up to 50 psig, 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 (24) and were subsequently adopted in the Compressed Air Special Regulation of the Ministry of Labour (United Kingdom), which came into force in 1958 (25).

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 (26). 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. One of the more recent large scale tunneling projects requiring compressed air, was undertaken in Hong Kong for the Mass Transit Railway, using the Blackpool Tables (27).

SINGAPORE EXPERIENCE

A total of 2,392 workers were screened at DHMC for fitness to work in compressed air. 1,737 (72.6%) were found fit and went on to work in the project. They were employed as manual workers, semi-skilled or skilled workers, or as supervisors and inspectors. In addition to these CAWs, firemen from the Singapore Fire Service, staff from the Ministry of Labour and the MRT Corporation were also screened for exposure to the hyperbaric environment.

188,538 man decompressions were carried out during the entire project. This produced 164 cases of DCS. 160 of these were of the milder type I category. The other 4 were of the more severe type II category, classified after Golding et al (28). All recovered completely after treatment with no disability. This gave us a DCS incidence rate of 0.087% which is very favourable compared to the major compressed air works done the world over since 1914. This low incidence of DCS and its associated disability in the MRT Project can be attributed to following factors:

1. Implementation of legislation to control compressed air works.
2. Sound training of the medical staff, CAWs and man-lock attendants.
3. Proper selection of the CAWs, weeding out those who had medical problems that would predispose them to DCS or other dysbaric illnesses.
4. Strict use of appropriate decompression tables at the man-locks.
5. Accurate diagnosis and prompt treatment of DCS.

The experience that we have gained through providing medical support for the compressed air works in the MRT Project has stood us in good stead in the field of Hyperbaric Medicine in Singapore. This is however a fast changing field which will be influenced in part by future changes in tunneling support techniques.

THE FUTURE

The future of compressed air tunneling will see the use of oxygen for decompression. Oxygen decompression was suggested as early as 1874 by Paul Bert (5), and Ham and Hill (29). The advantages of oxygen decompression include a reduction of the incidence of DCS and DO. In addition, Decompression schedules can be shortened appreciably and this will make it economically attractive for the Construction Industry. However, the benefits will have to be weighed against the disadvantages of oxygen decompression. Manlocks 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. All flammable articles cannot be brought into the chambers. Proper usage of the masks for oxygen breathing during decompression will have to be ensured if DCS is to be avoided. The workers may develop complications of CNS oxygen toxicity, and a doctor will have to be at the manlock to supervise the decompression. The Japanese have had bad experiences with oxygen decompression, as fire and deaths had occurred in their manlocks.

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 OSHA Decompression Schedules

(21). Oxygen Tables are currently being used by the French and German for decompression from tunneling work, but these have not been widely adopted elsewhere. The 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 CAW 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 tunneling may be another method which may be adopted for the future.

REFERENCES

1. Snell EH: Compressed Air Illness, or So-called Caisson Disease. London: HK Lewis, 1896.
2. Triger E: Memoire sur un appareil a air comprime, pour le pencement des puits de mines et antre travaux, sour les eaux et dans les sables submerges. C R Acad Sc, Paris 1841; 13: 884-96.
3. Pol B, Watelle TJJ. 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: 241-79
4. Boyle R. New pneumatical observations about respiration. Phil Trans R Soc 1670; 5: 2011-31.
5. Bert P. High pressure. In: Barometric pressure (1878). Trans. by Hitchcock MA, Hitchcock FA., Columbus, Ohio: College Book Co, 1943; republished by Undersea Med Soc Inc, 1978.
6. Gramenitskii PM, Savich AA: Results of experimental analysis of decompression air embolism. In: The Effects of Gas Embolism and Pressure on Body Functions III. Brestkin MP. Washington DC: US Dept of Commerce, 1965: 47-56.
7. Leverett SD, Bitter HL, McIver RG: Studies in Decompression Sickness; Circulatory and Respiratory Changes Assoicated with Decompression Sickness in Anesthetised Dogs. Report SAM-TDR-63.7. USAF School of Aerospace Medicine, 1963.
8. McIver RG, Fife WPP, Ikels KG (1965): Experimental Decompression Sickness from Hyperbaric Nitrous Oxide Anesthesia. Report SAM-TR-65-47. USAF School of Aerospace Medicine, 1965.
9. Spencer MP, Johanson DC, Campbell SD: Safe decompression with the Doppler ultrasound blood bubble detector. In: Underwater Physiology; Proc Vth Symp. Underwater Physiology. Ed. CJ Lambertsen, Bethesda, Md: Fedn Am Socs Exp Biol, 1975: 311-25.
10. Swindle PF: Occlusion of blood vessels by agglutinated red cells, mainly as seen in tadpoles and very young kangaroos. Am J Physiol 1937; 120:59-74.
11. End E: The use of new equipment and helium gas in a world record dive. J Ind Hyg 1938; 20: 511-30.
12. Leitch DR, Hallenbeck JM: Pressure in the treatment of spinal cord decompression sickness. Undersea Biomed Res Vol 12 No 3, 291-305.
13. Thorsen T, Daleen H, Bjerkvig R, Holmsen H: Transmission and scanning electron microscopy of Nitrogen microbubble-activated human platelets in vitro. Undersea Biomedical Research 1987; 14: 45-58.
14. Bassoe P: Compressed air disease. J Nerv Ment Dis 1911; 38: 368-9.
15. Bornstein A, Plate E: (1911-12): Uber chronische Gelenkveranderugnen, entstanden durch Presslufterkrankung. Fortschr Geb RontgStrahl; 18: 197-206:
16. Woodward CM: A History of the St. Louis Bridge. St Louis: Jones, 1881.
17. Jacobs CM: The Hudson River Tunnels of the Hudson and Manhattan Railroad Company. Min Proc Instn Civ Engrs 1910; 181: 169-257.
18. Keays FL: Compressed air illness. Am Labor Legislation. Rev 1912; 2: 192-205.
19. Thorne IJ: Caisson Disease: Observation and report of 300 cases at the Queens Midtown Tunnel Project, JAMA 1941; 117: 585-8.
20. Sealey JL: Safe Exit from the Hyperbaric Environment – Medical Experience with Pressurized Tunnel Operations. J Occup Med 1969; 11: 273-5.
21. Kindwall EP, Nellen J, Spiegelhoff, DR: Aspetic Necrosis in Compressed Air Tunnel Workers Using Current Decompression Schedules. J Occup Med 1982; 24: 741-5.
22. 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: 353-69.
23. Boycott AE, Damant GCC, Haldane JS. Prevention of compressed air illness. J Industr Hyg 1908; 8: 342-443.
24. Paton WDM, Walder DN: (1954): Compressed Air Illness - An Investigation during the Construction of the Tyne Tunnel, 1948-1950. Spec Report, Ser No 281, Medical Research Council, London.
25. Ministry of Labour and National Service (1958) Work in Compressed Air Special Regulations (SI No 61). HMSO, London.
26. Blackpool Tables (1973) In Medical Code of Practice for Workers in Compressed Air. Construction Industry Research and Information Association Report 44. 1st edn 1972.
27. Lam TH, Yau KP: Manifestations and treatment of 793 cases of decompression sickness in a compressed air tunneling project in Hong Kong. Undersea Biomedical Research 1988; 15: 314-88.
28. Golding FC, Griffiths P, Hempleman HV, Paton WDM, Walder DN: Decompression sickness during construction of the Dartford Tunnel. Br J Ind Med 1960; 17: 167-80.
29. Ham C, Hill L: Oxygen inhalation as a means to prevent caisson and divers' sickness. J Physiol 1905; 33: vii-viii.