HSE
Health & Safety
Executive

Human Factors in Decompression Sickness in Compressed Air Workers in the United Kingdom 1986-2000

A Case-Control Study and Analysis using the HSE Decompression Database

Prepared by **North Sea Medical Centre** for
the Health and Safety Executive 2003

RESEARCH REPORT 171

Human Factors in Decompression Sickness in Compressed Air Workers in the United Kingdom 1986-2000

A Case-Control Study and Analysis using the HSE Decompression Database

Dr Andrew P Colvin
North Sea Medical Centre
3 Lowestoft Road
Gorleston-on-Sea
Great Yarmouth
Norfolk
NR31 6SG

This study follows the recommendation of the CIRIA reports (Results of the Analysis of Compressed Air Records in the Decompression Sickness Central Registry, Project Report 6. London: CIRIA 1992) that a full case-control study of acute Decompression Sickness (DCS) be conducted on compressed air workers in the United Kingdom.

The report describes a case-control study of UK compressed air workers in which subjects with repetitive DCS during a single compressed air project were matched to two control groups. Further to this an analysis of the Health and Safety Executive (HSE) Decompression Database 1986-2000 was undertaken to examine the relative contribution of those workers with repetitive DCS to the overall number of DCS episodes in the UK during the study period.

It is recognised within the tunnelling industry (and is the personal experience of the author) that some individuals are apparently ‘bend prone’ and others apparently ‘bend proof’, often with no clear link between bend vulnerability and age, obesity or lifestyle. This despite the fact that individual risk factors are often quoted in anecdotal or historical medical reports concerning compressed air work. This analysis examines whether a correlation could exist with human factors and seeks to determine if repetitive DCS could be associated with any particular compressed air contract or project characteristics.

This report and the work it describes were funded by the Health and Safety Executive (HSE). Its contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

HSE BOOKS

First published 2003

ISBN 0 7176 2771 3

CONTENTS

ABSTRACT

Aims

To determine if personal characteristics (individual or human factors) in compressed air workers can be associated with repetitive episodes of Decompression Sickness (DCS).

To determine the distribution of repetitive Decompression Sickness (DCS) in the compressed air workforce in the United Kingdom for the period 1986-2000.

Design

A case control study of UK compressed air workers in which subjects with repetitive DCS during a single compressed air project were matched to two control groups.

An analysis of the Health and Safety Executive (HSE) Decompression Database 1986-2000 was undertaken to examine the relative contribution of those workers with repetitive DCS to the overall number of DCS episodes during the study period and to determine if repetitive DCS could be associated with any particular contract characteristics (not all compressed air contracts during the study period contained workers with multiple episodes of DCS).

Study Population and Setting

All compressed air workers in the HSE Decompression Database during the period 1986-2000 were identified.

Subjects

The “cases” were 62 compressed air workers selected from the study population with 2 or more episodes of decompression sickness confirmed during a single compressed air contract.

Two separate groups of control subjects were identified from the study population, i.e. those with no episodes of DCS (zero bend controls) and those with a single episode of DCS during a single compressed air contract (single bend controls). All controls were matched to the cases by compressed air contract, equivalent pressure exposure and occupation.

Methodology

Personal history and clinical examination findings were collated on all subjects from the contemporaneous clinical records of the pre-employment or initial compressed air medical examination held by the Contract Medical Adviser. Non-personal data (i.e. pressure/exposure data including reported DCS episodes) was collated from the HSE Decompression Database as reported by the Compressed Air Contractor to the Health and Safety Executive.

A total of 62 cases, 71 single bend controls and 130 zero bend controls were included in the study.

52 fully matched sets consisting of 52 cases matched with two zero bend controls and one single bend control were the basis for initial analysis. Subsequently comparisons between cases and control groups were undertaken using a variety of statistical analysis, the most important being conditional logistic regression.

Results

4% of the workforce in the HSE Decompression Database 1986-2000 suffered 50% of the episodes of DCS requiring therapeutic recompression.

No significant differences were found between those with multiple bends (cases), single bends or zero bends when analysing the various personal characteristics assessed during the initial or pre-employment compressed air medical examination. There is some evidence to suggest that a survivor or “healthy worker” effect is operating in the compressed air workforce with regard to susceptibility to DCS.

Those contracts likely to produce repetitive DCS in some workers often had an average pressure greater than 1 bar gauge/ 201 kPa absolute, greater number of compressed air workers being exposed and longer shift lengths (greater than 6 hours at pressures below 1.5 bar gauge/ 251 kPa absolute or greater than 4 hours at pressures over 1.5 bar gauge/ 251 kPa absolute).

Conclusions

This study did not find any differences in the personal characteristics of compressed air workers with multiple, single or zero episodes of DCS when matched by contract, occupation and pressure exposure. This negative finding contradicts long-standing associations with age and obesity often reported in the literature based on historical and often anecdotal reports. "Bend prone" compressed air workers do exist but this study suggests that the history and clinical examination (and tests) undertaken at the routine pre-employment compressed air medical examination will not reveal them.

If individual or human factors causing, or associated with, susceptibility to DCS could be identified then a significant reduction in episodes of DCS in the compressed air workforce could occur. This study suggests that different methodology or clinical examination will be required to achieve this however.

1. THE STUDY

This study will compare the personal characteristics of the identified cases with a control group of workers matched from the same contract or project population and with similar pressure exposure and occupation to determine if the “bend prone” group of tunnellers can be differentiated from the control group in terms of key personal characteristics or human factors already identified by previous studies as being potential risk factors. It will also compare the personal characteristics of a group of tunnellers matched to the “cases” of those who have suffered a single episode of DCS.

This study will also include a simple analysis of the HSE Decompression Database 1986-2000 which contains the exposure records of 2160 compressed air workers with 371 reported episodes of DCS from 110,354 exposures.

1.1 REASONS FOR THE STUDY

Compressed air workers (commonly referred to as tunnellers or caisson workers) have a relatively high incidence of DCS in comparison to divers and hyperbaric health care workers. (1 & 2) This may be due to the use of air decompression schedules which are recognised by some authorities as providing an inadequate decompression for the typical duration of exposure. (3) It has been recognised for many years that an important determinant of risk in DCS is the maximum pressure and duration of time that the worker is exposed. (4 & 5) It is also recognised however that DCS does not occur on a completely random basis and that more episodes than expected will occur in some individual workers. Although such factors as age, obesity, previous DCS, occupation and compliance with acclimatisation procedures are recognised as potential risk factors (6), little is known about their relative importance when applied to individual compressed air workers. Previous studies of compressed air projects have shown that those workers who sustain multiple episodes of DCS (i.e. two or more episodes) during a single compressed air project or contract, although constituting a relatively small number of the workforce, may contribute to a significant proportion of the overall cases of DCS. (7) This relatively small group of workers not only contributes significantly to the overall project morbidity but may be at long-term risk of dysbaric osteonecrosis since previous episodes of DCS appear to be a risk factor for this condition. (8) In recent years the view that DCS may represent a multi-system multi-organ disease of which the symptoms may only be the tip of the clinical iceberg, also means this group of workers may be at increased risk of long-term central nervous system or other organ damage. (3 & 9)

Therefore the identification of personal characteristics or human factors that are associated with repetitive DCS could be valuable in reducing short-term (and possibly long-term) morbidity resulting from compressed air working. This knowledge would be of particular value to Contract Medical Advisers in assessing fitness to return to work of individual compressed air workers after a single episode of DCS during a contract.

1.2 POSSIBLE HUMAN FACTORS PREDISPOSING TO DCS

The following are the potential risk factors for DCS to be studied:-

History:
Age (years)
Smoking habit (smoker/non-smoker)
Alcohol consumption (alcohol units/week)
Previous compressed air work
Previous history of DCS

Clinical Examination
Findings:
Height (metres)
Weight (kilograms)
Skin fold thickness (millimetres)
Body Mass Index
Ponderal Index
Lung function (FEV1, FVC, PEFR)
Haematology test results (haemoglobin, white count, haematocrit)
Chest x-ray report

These are all routinely recorded at the pre-employment or initial compressed air medical examination under the supervision of the Contract Medical Adviser.

Body Mass Index is calculated by weight in kilogrammes divided by the square of height in metres. It has the highest correlation with skinfold thickness or body density. The higher the Body Mass Index, the more obese the individual – greater than 30 is moderate obesity, greater than 35 is severe obesity.

The Ponderal Index is another anthropometric measure of body mass. It is calculated by the cube root of body weight (in kilogrammes) times 100 divided by height (in centimetres). The lower the ponderal index, the more obese the individual. It is more closely correlated with skinfold thickness or body density than weight alone.

1.3 POSSIBLE CONFOUNDING FACTORS AND LIMITATIONS

Only in the last few years in compressed air work in the UK has there been reasonable confidence that possible symptoms of DCS will be recognised and reported by workers, assessed by a clinically competent person, and treated and recorded as a case of DCS. Until relatively recently DCS has been accepted by compressed air workers as part of the job and “minor” or non-neurological manifestations have been both commonly under-reported and under-treated, and therefore under-recorded. *(10, 11 & 12)*

The relatively small numbers of cases and the presence of potential multiple risk factors may make statistical analysis complex and difficult to interpret. Currently, there is no specific objective or definitive clinical means of diagnosing DCS nor determining its severity or likelihood of late or long-term health effects.

Contract or individual compressed air worker factors that influence reporting of DCS may act as confounders to this study, e.g. individual psychological or attitudinal factors in some workers may result in reporting bias. The way in which compressed air workers are managed on particular contracts after reporting possible symptoms of DCS or the prevalent ‘safety culture’ may influence not only reporting rates but also the Medical Lock Attendant’s subsequent actions and recording of clinical information.

This case control analysis is retrospective and therefore relies on contemporaneously recorded clinical data. In recent years some previously unrecognised personal factors that will not have been measured, e.g. patent foramen ovale and complement levels among others, could be potential confounders to this study.

It may be that while personal characteristics of the compressed air worker are important either singly or in combination, other as yet unidentified factors in the working environment confound their effects.

1.4 SIGNIFICANCE

There is surprisingly little information concerning potential individual or human risk factors for DCS in compressed air workers. Although it is well recognised within the field of hyperbaric medicine that pressure/time exposures are the main pre-disposing factors to DCS, more episodes than expected will occur in some individuals. It is known that potential individual risk factors for DCS in compressed air workers and other workers exposed to pressure exist. (6, 7 & 13) Since DCS is relatively common in compressed air work there is benefit from the investigation of personal characteristics to determine those risk factors which are most related to the incidence of DCS in individual tunnel workers. Such factors would be of particular importance to the sub-group of the compressed air workforce who are known to suffer repetitive episodes of DCS and who make a significant contribution to overall morbidity.

Much of the literature concerning compressed air work in the UK is now quite old and concerns civil engineering projects that are quite different in size, methodology and decompression procedures to those currently practised. The Decompression Sickness Central Registry held at the Newcastle-upon-Tyne University keeps extensive information from compressed air contracts but holds no new contract information since 1980. (14) Much of the data pre-dates the introduction of the Blackpool Tables which in recent years (from the implementation of the work in Compressed Air Regulations 1996 until 17 September 2001) were only used with considerable modification particularly at pressures greater than 2 bar and in the longer exposures. It was normal for much of the period during which these data (1964-1980) were collected for workers not to report what was regarded as “minor” manifestations of DCS. This makes meaningful interpretation of the clinical data problematical, particularly since the re-classification of DCS in 1990 by Francis and Smith (15) that has been widely accepted within the fields of hyperbaric medicine. Although the Decompression Sickness Central Registry was extensively analysed (14) only non-human factors were considered in relation to acute DCS. In fact the ‘Final Report’ of the Decompression Sickness Registry data in April 1991 recommends “that a full case/control study for acute DCS be undertaken”. (16)

Apart from the United Kingdom, no other country in the world has a National or Central Register of pressure exposures and/or clinical data for compressed air workers. (17) Although individual civil engineering projects may collate pressure exposure and clinical data, no “case-control” studies examining individual or personal characteristics of compressed air workers have been published – probably this is due to insufficient numbers to make such studies statistically viable. Due to changes in methodology and techniques in civil engineering and particularly in tunnelling, it is likely in future that most compressed air work will be utilised in small hand excavation projects or in tunnel boring machine inspection and maintenance. Both require only relatively short compressed air periods employing a comparatively small compressed air workforce to historical compressed air contracts. This means that for the foreseeable future it may take a considerable time to accumulate the exposure and clinical data required to conduct a similar case control study even should a Central Register be established.

Although this case control study examines air decompression techniques only, it is likely that any human factors increasing susceptibility to DCS (if these can be identified) will remain pertinent to compressed air work utilising oxygen or mixed gas decompression, thereby this work remains significant for the future. It is also likely that air only decompression techniques will continue to be employed in the UK (up to 1 bar gauge/201 kPa absolute) and abroad where cost, technical or safety considerations may exclude the utilisation of oxygen decompression.

In summary therefore, this case control study utilising the HSE Decompression Database offers a unique opportunity to identify human factors associated with susceptibility to DCS in compressed air workers in the UK Such factors (if identified) would be significant, not only in reducing short-term health effects (acute decompression sickness) resulting from compressed air work but also possibly for late or longer term illnesses (central nervous system pathology or dysbaric osteonecrosis) which may be associated with DCS.

This research project is the first attempt to utilise the data contained in the HSE Database 1986-2000 to assist in health risk analysis in compressed air work.

2. BACKGROUND AND LITERATURE REVIEW

2.1 HISTORY

2.1.1 Overview

The first civil engineering application of compressed air can be credited to the British Engineer, John Smeaton (1724-1792) in underwater construction. (18) Smeaton designed a form of diving bell for use in repairing the foundations of the Hexham Bridge in Northumberland. A later design in 1791 was applied in the Ramsgate Harbour works and used a partially submerged iron box, or caisson, supplied with continuous pumped air from a boat on the surface. Following Smeaton's death in October 1792 however there were few innovations in compressed air work for several decades. (19)

Compressed air in tunnel working was used in 1878 (20) following its first practical use described by Triger in 1839 for caisson work and published in 1845 which involved (more advanced) steam-powered pumps with a work chamber built to maintain the compressed air state. (21) With man being exposed to hyperbaric environments in compressed air for construction work and in the water for diving purposes, various medical conditions have been identified as being caused by decompression from a hyperbaric environment.

Since the mid to late 1800's the medical disorders arising from decompression are now well recognised (6, 22 & 23) and include:-

decompression sickness
pulmonary barotrauma and arterial gas embolism
dysbaric osteonecrosis
middle ear barotrauma

The aetiology and pathophysiology of DCS, arterial gas embolism and dysbaric osteonecrosis have attracted much scientific and medical interest although an exact understanding of the causative factors and nature of the conditions remains elusive.

The famous French Physiologist, Paul Bert, in 1878 (24) demonstrated in a most conclusive manner that DCS is primarily the result of inert gas bubbles (nitrogen in the case of compressed air divers and caisson workers) which had been dissolved according to Dalton's and Henry's Laws and then released into the gas phase in tissues and blood during or following decompression. Henry's Law (1803) states that the quantity of a gas dissolved by a liquid increases directly as the pressure. (25) This effect is obvious when one unscrews the top on a carbonated soft drink bottle causing a sudden reduction in pressure with bubble formation. Dalton's Law (1807) states that the quantity of a gas dissolved by a liquid from a mixture of gases depends on the partial pressure of that particular gas. DCS is thought to result from the mechanical, biochemical and immunological consequences of these nitrogen bubbles in the vascular and extra-vascular tissues. (6, 22 & 23) In order to prevent this occurrence within the tissues, compressed air workers are decompressed slowly in accordance with rates set out in established decompression tables or schedules. Previously in the UK the Blackpool Tables were approved by the Health and Safety Executive (HSE) (26) initially by individual request from contractors and latterly by blanket approval for all compressed air working. However in recent years efforts have been made to find more effective schedules in terms of health risks (incidence of decompression sickness and bone necrosis) and length of decompression in relation to a given pressure exposure (cost effectiveness). (1, 3 & 14)

“Oxygen decompression” is periods of breathing 100% oxygen through a mask or hood during decompression. This has been universally utilised by the international commercial diving industries since the 1960’s. It is generally accepted that it substantially reduces the risks of DCS and probably dysbaric osteonecrosis whilst significantly shortening the decompression time.

During the course of this project the HSE has issued an Addendum to the “Work in Compressed Air Regulations 1996 Guidance on Regulations”. This Addendum is titled “Guidance on Oxygen Decompression” (27) and effectively notifies disapproval of the use of the Blackpool Air Tables in the United Kingdom. This Addendum brings oxygen decompression (and the use of breathing mixtures other than compressed natural air) into routine use in the United Kingdom above 1.0 bar gauge/ 201 kPa absolute pressure. It permits air decompression only below 1.0 bar gauge/ 201 kPa absolute pressure with significantly increased decompression times in the pressure range 0.81 bar gauge/ 182 kPa absolute to 0.95 bar gauge/196kPa absolute. This change in the HSE approval of new decompression régimes (other than the air Blackpool Table) became effective on the 17th September 2001.

In the United Kingdom a major consideration in tunnel construction project planning is whether or not workers will have to be exposed to compressed air. Since this is costly and intrinsically hazardous to health, large projects with thousands of workers working in compressed air over several years are likely to be a thing of the past. However it is likely that for short lengths of tunnel under certain ground conditions below the water table and where de-watering techniques or tunnel boring machines are impracticable then men will have to work in compressed air. Increasingly men are exposed to pressurised environments for “maintenance” work on the front of Tunnel Boring Machines (TBM) which as the name suggests are mechanised boring excavators and so it would appear that one way or another workers will continue to be exposed to compressed air in the tunnel industry for the foreseeable future. The risks of DCS become greater particularly as pressure exceeds 1 bar gauge/ 201 kPa absolute, and beyond 3 bar gauge/ 401 kPa absolute there are few existing compressed air tables or procedures for performing the decompressions to the required safety standard whilst being commercially viable in terms of man ‘working time’ under pressure. (1 & 3)

Tunnel Boring Machines at present require periodic inspection or repair of the excavation tools/teeth on the front of the machines. Some types of machines under some ground conditions require compressed air, sometimes in a pressure range beyond 3 bar gauge/401kPa absolute. While the TBM is being inspected or repaired further progress cannot occur so the maintenance phase is often time critical and therefore delays are costly so there is the need to have effective decompression schedules in the higher pressure range. High DCS rates are disadvantageous not only to the individual employee but also from a management perspective in terms of loss of key personnel (often technically skilled) and potential delays in the maintenance period which are typically measured in hours or days. This combined with the relative ineffectiveness of air decompression as one approaches 3 bar gauge/ 401 kPa absolute pressure is the reason why oxygen decompression and mixed gas techniques are being developed and used worldwide in tunnelling projects. (3) Nonetheless it is still likely that under some operations air decompression will be utilised in projects where technical/safety issues and/or local/regional conditions (e.g. geographical, legislative or cost restrictions) combine to make the application of oxygen decompression impracticable or even hazardous. Thus, it is likely that air decompression will continue to play an important but probably more restricted role in compressed air tunnelling for the foreseeable future.

2.1.2 Decompression Sickness (DCS)

The term “decompression illness” has historically been used to refer to any medical disorder, illness or injury arising from decompression (see page 5). The term “decompression sickness” specifically refers to illness arising from the separation of gas from solution in the body which takes place in association with gas nuclei in blood or tissues. In recent years it has become commonplace for authors to refer to episodes of DCS as “decompression illness” or “acute decompression illness”. However, since many of the older references in this study use “DCS” to refer to illness arising from the separation of gas from solution in the body this term has been used throughout this paper for consistency.

Bubbles may develop in the body of the diver, aviator or caisson worker, whenever he is exposed to a reduction in environmental pressure (decompression), potentially causing symptoms of DCS. The colloquial term “bends” is commonly used instead of DCS but needs to be defined with care. It was originally used by the caisson workers building supporting piers for the Brooklyn Bridge in New York (1894). *(28)* It has been used for the various limb pains, paralysis and cramps that caisson workers encounter, but it also has come to be used for limb pain in the absence of any sign of central nervous system dysfunction. *(29)* In recent times the term has come to be used rather loosely by some authors and has included, for instance, the death of small animals after decompression. Thus some qualification is needed each time that the term is introduced – e.g. the musculo-skeletal type of DCS would be termed “limb bends”, of neurological type “neurological bend” and so on.

The first practical execution of compressed air in caisson work was in 1839 by M. Triger, a French Engineer, who sunk a shaft at Shalonnes through a layer of quicksand to reach an extensive bed of coal that was known to exist there. Triger reported this in a memoir presented by him in 1841 to the Académie des Sciences *(21)* and followed this with a second communication in 1845 *(30)* which is widely credited as the first written report of acute decompression sickness. The technique used by M. Triger was then used to open other coal mines in northern France, as reported by another French Engineer, M. Blavier, in 1846. *(31)* Compressed air was subsequently increasingly used as a method in civil engineering for the boring of shafts or wells and the fixing of piles for bridges.

The Physicians, Pol and Watelle *(32)* published the first medical report indicating the clinical features of DCS in 1854 with several illustrative case histories, including the observation that recompression could relieve the symptoms of DCS.

DCS remains the most important acute manifestation of the decompression disorders and it is relatively common in modern compressed air workers in comparison to divers, aviators or hyperbaric health care workers. Cases of DCS in the past have been classified into two types after Golding *et al* (1960). *(7)*

Type 1 (“pain only or simple”) - symptoms and signs are mild and present as musculo-skeletal pain, swelling due to lymphatic obstruction and skin involvement.

Type 2 (“serious”) - symptoms and signs are severe and attributable to disorder of the nervous, pulmonary and cardiovascular system.

This classification was further refined by Elliott and Kindwall (1982) and was widely used in both diving and tunnelling industries for many years.*(33)* In the early 1990s this categorisation of DCS was questioned on theoretical and practical grounds with regard to the pathophysiology of the condition, low diagnostic concordance between experienced hyperbaric physicians and the knowledge that it was found to be misleading or confusing with regard to appropriate hyperbaric treatment.(34) DCS is now therefore classified using purely descriptive terminology with regard to its presentation or manifestation and its evolution. (15)

It is increasingly accepted that DCS is a multi-level, multi-system disease and concern has been expressed for reported but, as yet, scientifically unconfirmed, long-term effects on the central nervous system in both compressed air tunnellers and commercial divers. (23) Any episode of DCS is now regarded as clinically important, even "minor" bend symptoms or "simple" pain only bends which historically have not always been reported or treated in compressed air workers. Gorman *et al* (35) have reported that patients suffering from apparent "Type 1" or "simple" DCS with negative neurological examinations were later found to have significant cognitive impairment, a 40% incidence of abnormal EEG findings and brain atrophy. Studies of long-term health effects on divers and tunnellers are few, however a mortality study by McCallum on divers did not find any support for detectable work-related ill-health causing increased mortality rates. (36)

The long-term historical incidence of DCS in compressed air workers in the United Kingdom runs around 2% of those exposed to pressures in the range 0.7 bar gauge/ 171 kPa absolute to 3.45 bar gauge/ 446 kPa absolute reported from HSE data. (1) Compressed air work differs from commercial diving in several important ways. Tunnel or caisson exposures are usually carried out at modest pressures rarely exceeding the equivalent of 50 p.s.i.g. (3.45 bar gauge/ 446 kPa absolute). Shift lengths however almost always range between 4-8 hours on a daily basis with 6-8 hours exposures in the past having been common. There is commercial incentive for Contractors to avoid extending decompression times unnecessarily since this will shorten productive working time for a given shift length. It is also obvious that the nature of the work and the working environment are fundamentally different for the compressed air worker and the commercial diver. Compressed air workers' bodies are not supported by water whilst working and in addition to supporting their own weight throughout the exposure, they must carry their tools and other equipment. The air in tunnels usually contains more contaminants and dust than are present in divers' air. When working at pressure, tunnellers are rarely chilled but are often exposed to heat from working, for example, at the back of tunnel boring machines or during concrete pours, whilst he may be chilled during decompression when the workers are seated in a dry chamber. Balldin *et al* showed in 1969 that there is a 30% diminished nitrogen elimination in those decompressing in the dry as opposed to those decompressing while immersed. (37) This different working environment must therefore have an influence on the relative risk of the dysbaric diseases, although surprisingly little high quality data are available regarding the efficacy of decompression tables used in tunnelling when compared to diving decompression schedules. This is perhaps surprising in view of the fact that compressed air work exposures in general terms in the past have been much more numerous than diving exposures, and are known to produce a higher incidence of DCS and dysbaric osteonecrosis in the workforce.

Most decompression schedules for compressed air workers have been extrapolated or based on naval diving schedules despite the fact that the Navy in general terms have very little experience with long duration air dives at shallow depths typical of the hyperbaric exposure of compressed air workers. There is now a respectable body of professional hyperbaric medical opinion, both in the United Kingdom and abroad, which believes that oxygen decompression appears to be the only viable method of decompression for tunnel workers on a daily basis in terms of health risk (incidence of DCS and dysbaric osteonecrosis) and commercial practicability. (1 & 3) There were until recently in the UK, however residual concerns relating to fire safety and oxygen toxicity as well as the general applicability of a more technically complex procedure to the tunnel industry. These concerns have now been addressed by the introduction of the detailed HSE Guidance on Oxygen Decompression. (27)

2.1.3 Factors associated with Decompression Sickness

Pressure exposure

Pol and Watelle concluded in 1854 following observations of miners working under compressed air in coal mines, that pressures up to 4½ atmospheres (readers unfamiliar with pressure units see : Appendix A "Units of Pressure" on page 57) were not in themselves harmful. It was the return to atmospheric or the normal ambient pressure which was dangerous with the risk of the development of DCS. The risk of DCS occurring was even then recognised as being related to the maximum pressure to which the workmen were exposed and the rapidity of the decompression. *(32)*

The use of compressed air as a method of sinking caissons became more widespread over the next 50 years and the above deductions were confirmed by many others. *(38)* By 1870 Dr. A. Jaminet *(39)* amongst others clearly understood from experience that the higher the pressure the greater the risk of DCS, that the length of decompression should be related to the maximum pressure and increased proportionately and that as the pressure rose so the working hours (i.e. pressure exposure) should be reduced in terms of duration and number of daily exposures.

In 1954 Paton and Walder reported a detailed investigation into DCS from data collected during the construction of the Tyne Pedestrian Tunnel in 1948-1950. *(13)* This project involved 376 individuals being exposed to compressed air with a total number of 40,000 compressions performed at greater than 18 lb/in^2 (1.2 bar gauge/ 221 kPa absolute) pressure. By convention at that time DCS was defined as those attacks of bends sufficiently severe to require therapeutic recompression. (This would exclude the vast majority of those suffering mild to moderate pain in the joints or type 1 symptoms of DCS which was accepted by the workforce {and their medical advisers} as being 'part of the job' and of little clinical significance.) They observed no cases of DCS below 18 lb/in^2 (1.2 bar gauge/ 221 kPa absolute).

They found no relationship between external climatic conditions (rainfall, humidity, wind velocity, temperature and sunshine) and the incidence of DCS in the workforce exposed to compressed air. They also could not find any relationship between arduous working conditions, although they accepted that the multiplicity factors involved made interpretation of this area complex.

Golding *et al* reported on DCS occurring during the construction of the first Dartford Tunnel (1957-1959) *(7)* which involved a total of 1,200 men on the contract with 122,000 compressions of which the vast majority were over 16 lb/in^2 (1.1 bar gauge/ 211 kPa absolute) pressure. Data was obtained which demonstrated that the risk of DCS increased significantly in exposures greater than 4 hours. The official decompression tables at that time assumed that 18 lb/in^2 (1.2 bar gauge/ 221 kPa absolute) represented a safe threshold below which the risk of DCS would be very low. This has since been proven to be untrue. The internal tunnel climatic conditions (air temperature, relative humidity and wind velocity) were measured and deemed to be quite independent of the external climatic conditions. However, no relationship could be demonstrated between the internal environment of the tunnel, which was found to be relatively constant in comparison to external climatic conditions, and the DCS rate. How in 1990 also studied tunnel temperature and humidity and again found no obvious relationship to DCS rate. *(40)*

It was recognised following these projects, and others, that differentiation should be given to "trivial" working pressures (i.e. those below 16 lb/in^2 or 1.1 bar gauge/ 211 kPa absolute) and those above 16 or 18 lb/in^2 (1.1 or 1.2 bar gauge/ 221 kPa absolute when attempting to compare the overall bend rates for compressed air work projects. The underlying assumption is that the working pressure affects the incidence of DCS. Tunnelling took place on two sides of the river on the Dartford Tunnel project with one side at much higher working pressure than the other and it was noted that the incidence of DCS was four times greater on the side with higher pressure. (7)

In more recent compressed air projects it has been confirmed many times that higher maximum working pressure and longer duration of exposure results in an increased rate of DCS. This particularly applies where the pressure is greater than 1.5 bar gauge/ 251 kPa absolute and the exposure is greater than 4 hours. (40, 41, 42, 43 & 44) This pressure related effect on the incidence of DCS in a compressed air workforce becomes very marked when using the Blackpool Tables at pressures greater than 2 bar gauge/ 301 kPa absolute and exposures of 8 hours or longer. (40 & 45)

Multiple daily exposures requiring multiple decompressions and therefore increased risk of bubble nuclei would be expected to lead to an increased risk of DCS and this has been shown to be the case. (40 & 45)

Decompression schedules

By the late 1870's Bert had made a clear distinction between the effects of compression and decompression in his landmark publication, La Pression Barométrique. (24) He showed that DCS was related to the appearance of nitrogen bubbles in the blood and tissues following rapid decompression, and that very slow decompression would prevent symptoms occurring. He considered that the severity of "post-decompression illness" (i.e. DCS) depended on the maximum pressure to which men had been exposed and to the rapidity of decompression. He suggested a steady rate of decompression from the working pressure so that decompression time was related to the working pressure instead of being a fixed duration. He believed that up to one atmosphere (gauge) pressure there appeared to be no ill-effects but that over 2 atmospheres gauge (or approximately 2.0 bar gauge) pressure serious illness could occur.

Historical Note: *Paul Berts experimental work based on reports and observations from the previous 30 years of compressed air projects published clear conclusions about the aetiology of DCS. His suggested rates of decompression (20 minutes per atmosphere) were similar to those subsequently proposed and used by Von Schrötter* ***(46)*** *almost 20 years later. He suggested those stricken after decompression should be therapeutically recompressed then slowly decompressed – an idea that was not utilised by industry until the Hudson River tunnel project was restarted in 1890 with a dramatic reduction in mortality and morbidity from DCS.* ***(32)*** *This along with his pioneering work on oxygen toxicity, is why Bert is generally accepted as being the initiator of a truly scientific approach to hyperbaric medicine and physiology.* ***(24)***

However, despite this knowledge, until the turn of this century men were habitually decompressed very rapidly, even after several hours at high pressure and severe symptoms, gross disablement and deaths were common. (46, 47 & 48) Compressed air work and military and civil diving activities increased until by the early years of 1900 there was considerable controversy regarding the speed and method by which divers and caisson workers should be decompressed, and the theoretical basis upon which decompression tables should or could be based.

The English Physiologist, John Scott Haldane and his collaborators, proposed his "Haldane" method in 1907 in a report to the Admiralty of the Deep Water Diving Committee. (49) This involved three assumptions. The first was that the body could be represented by five separate tissues having theoretical half times (i.e. the time for the tissue to become 50% denitrogenated) between 5 minutes and 75 minutes for nitrogen. The uptake and elimination of nitrogen gas in the body was therefore exponential and directly proportional in each tissue to the difference between ambient absolute pressure and gas tension in that tissue. Secondly,

it was found that divers could tolerate a rapid decompression producing a super-saturation of gas within tissues produce nitrogen bubbles yet not produce DCS on the basis of animal and human experiments. It was believed a 2:1 ratio of maximum depth to the first decompression stop, in pressure absolute, could be conducted in safety. Haldane then calculated ascent rates whereby the nitrogen pressures in each of the five hypothetical tissues never exceeded the environmental pressure by more than a 2:1 ratio – the so called "Critical Ratio Super-Saturation Hypothesis". He produced a protocol for his calculated decompression rates to be followed by periods of time or 'stops' at certain pressures – the 'staged decompression' method. Many of the current diving and caisson decompression tables have their basis in this work, albeit with further development and refinement often empirical in nature.
Sir Leonard Hill and his collaborators at the London Laboratory in 1912 suggested a different approach – the ◊ P concept, i.e. a constant pressure difference for the linear decompression of caisson workers. (48) Hill argued that a man can be decompressed by a fixed amount from his equivalent depth for saturation before bubbles form and he becomes at risk from DCS. Although Hill emphasised the close concordance between the results of his own experimental work and those of Haldane, he was concerned that the advantages of stage over continuous decompression might not be as great as Haldane had suggested. Linear decompression, as proposed by Sir Leonard Hill, was subsequently adopted by Behnke in 1937 as the basis for a decompression schedule and appeared to be effective. (50) However, undoubtedly this approach was largely overshadowed by the "Haldane" method of 'staged decompression' published a few years earlier which had almost immediate success in reducing mortality rates amongst divers and compressed air workers. The development of safer tables for compressed air work in civil engineering has continued since then in parallel with but independently from that of diving tables, the nature of the compressed air workmen's prolonged exposures creating some distinct problems.

In 1936 the Institute of Civil Engineers published a report giving guidance and decompression schedules for compressed air workers, however further progress was delayed until after the war. Subsequently in 1946 a Joint Committee of the Institution of Civil Engineers, The Ministry of Labour and the Medical Research Council was set up to consider revising the then existing unofficial Compressed Air Regulations in the United Kingdom in the light of advances in knowledge. The panel produced two reports and the conclusions they reached provided a provisional version of intended new Regulations. (51) The definitive Regulations appeared in 1958 as the "Work in Compressed Air Special Regulations 1958" (52) and included the now official new decompression tables thereafter called "The 1958 Table". By the 1960s it had become obvious that the British decompression procedures described in the 1958 Regulations were inadequate in that there was an unacceptable rate of decompression sickness (including occasional fatalities) and dysbaric osteonecrosis. (51)

Hempleman, working at the Royal Navy Physiological Laboratory, introduced new decompression tables in 1966 - the Blackpool Tables - which modified the Haldanian concept of the "critical" ratio super-saturation hypothesis by allowing modification of the 2:1 ratio at certain pressures. New decompression tables were calculated on the basis of theoretical conclusions reached as a result of exposing animals and humans to pressures of air under laboratory conditions. This approach questioned Haldane's concept of perfusion as the dominant factor for inert gas uptake and proposed a radical new approach : tissue diffusion as the rate limiting factor. The new tables represented a compromise between practicability and theoretical ideals. These new tables also made the assumption that the body could be viewed as a single tissue model for decompression purposes. (53 & 54) The Blackpool Tables were the Health and Safety Executive approved decompression procedures for decompression from pressures of 1 bar gauge/201kPa absolute or greater (until 17th September 2001 and the introduction of the Addendum on Oxygen Decompression) and were prescribed in the Work in Compressed Air Regulations 1996. They have been successful in reducing (but not removing) the risk of decompression sickness and there have been no fatalities as a consequence of decompression since their introduction.

Using data from the Tyne Pedestrian Tunnel project (1948-1950) Paton and Walder examined the possibility that the incidence of DCS was related to the accuracy with which the decompression was carried out, i.e. the accuracy with which the fall in pressure followed that laid down in the Regulations measured by using barograph records from the decompression locks. (55) Perhaps unsurprisingly analysis showed that the variation of DCS rate with the accuracy of decompression was statistically significant in an inverse relationship. It was noted that negative deviations from the prescribed pressure (i.e. increased rate of decompression over Table) increased the number of cases of DCS whereas positive deviations (i.e. decreased decompression rate over Table) did not, and this was probably due to the fact that when positive deviations occurred the decompression as a whole was lengthened and that this extended procedure afforded some protection. This suggests that the prescribed decompression time defined by the Table was inadequate for at least some pressure/time exposures.

In 1968 McCallum reported concerns from the knowledge and experience gained during the 1939-1945 war that questioned the validity of the Haldanian 2:1 ratio over the whole range of working pressures in diving and civil engineering. Full tissue saturation on air was no longer believed to be complete within 5 hours. It was also suggested that gas bubbles are always formed during decompression, although they may be microscopic in size. (56)

In recent times Kindwall has also criticised current air decompression tables for compressed air workers for their reliance on naval experience and what he regards as a flawed mathematical model based on Haldane's original work. (57) He laments that he does not know of any decompression tables, whether they be diving navy tables or compressed air tables, that become safer as the shifts grow longer and the pressures increase. This of course is partly because such tables are a compromise between being practicable and economically viable as well as physiologically sound. This dissatisfaction has led some tunnel doctors outside the UK to use oxygen decompression that provides a considerably shorter decompression time for a given hyperbaric exposure, with potential benefits, many believe, in terms of reduced incidence of decompression illness and dysbaric osteonecrosis. (3, 58 & 59) Oxygen breathing during decompression has been successfully used by military and commercial divers for more than 30 years so it is perhaps surprising that, despite the apparent medical benefits of oxygen decompression for compressed air work having been accepted by the Health and Safety Executive and others abroad, that oxygen decompression was not introduced sooner into civil engineering compressed air work. Until recently in the UK the reason oxygen decompression was not implemented in practice was due to concerns over fire and other safety issues - the view within HSE being that safety considerations (i.e. the capability of tunnelling contractors and their workforce to safely utilise oxygen decompression in a typical tunnelling environment) are paramount. Taking into account the potential for multiple fatalities caused by unsafe systems of work when utilising oxygen under pressure (and the unfortunate experience of those over the years where incidents have occurred) these concerns are not inappropriate, particularly since the Blackpool Tables in the UK have prevented any deaths or life-threatening episodes of DCS occurring in the last 30 years. (13)

Age: It has been reported anecdotally for over 100 years that increased age appears to result in an increased susceptibility to DCS in caisson workers. (38 & 60) In 1946-47 Paton reviewed age limits with regard to medical fitness standards for compressed air workers whilst formulating the medical and physiological basis of the 1958 Table. He concluded that the evidence was insufficiently strong or conclusive to include any specific age limit as an absolute contra-indication without the presence of other debarring medical conditions. (61) During the construction of the Tyne Tunnel Walder and Paton concluded however that the risk of DCS rises from the age of 40 and increases greatly from the age of 50 years. (41 & 55) It has been accepted for many years that compressed air workers in general terms should not be over 40 years of age. (45, 62 & 63) Thus age limitations have been extensively incorporated into medical fitness standards for compressed air workers, although in general terms appear to be applied more strictly to the shift workers (manual workers) than to non-shift workers (technical or supervisory staff). (43 & 64)

This experience of increased susceptibility to DCS with age in compressed air workers is also reflected in commercial divers (6) and in military pilots. Grey in 1951 found a roughly linear advance of susceptibility to DCS with age in aviators. (65) Investigating a group of compressed air workers with a relatively wide age range, Paton and Walder (1954) demonstrated that, overall, the older the man the sooner he will experience DCS after starting work in compressed air. (55)

However other authors such as Lam 1988 (44) in “Analysis of 793 cases of acute decompression sickness” and Golding (7) (first Dartford Tunnel) have found no association with age and multiple DCS. However this may be as a result of their strict pre-employment medical selection, removing older candidates from the compressed air workforce. Lo and O’Kelly (1987) (43) noted that there was a significant trend for more DCS with advancing years. They observed that the relatively small number of older workers tended to predominate in the technical and supervisory group (i.e. non-shift workers at lower risk of DCS) and that this was therefore a potential confounding factor in studies attempting to correlate age to risk of DCS in compressed air workers. Like others, they had applied an age limit of 40 years for the employment of manual labourers in the compressed air environment at the medical selection stage.

To this day qualitative cautionary advice on age is included in statutory guidance on pre-employment medical examination for compressed air workers in the UK (26 & 45)

Acclimatisation

> ‘A great majority of the cases were among the new hands. In marked contrast with the number of men who were attacked at the end of their first trial was Keith, a sub-foreman… Occasionally the old hands suffered, but the severe cases were new men’.
>
> The building of St. Louis Bridge 1865. From Proceedings, Institute of Civil Engineers, Great Britain, Chapter XXII, Special Subject No. 5 – *The physiological effects of compressed air*.

There is considerable evidence (7 & 55) that regular exposure to pressure causes a reduced susceptibility to DCS which is known as acclimatisation, adaptation or habituation. Haldane was aware of this adaptation phenomenon to pressure as early as 1936 and recommended that compressed air workers be used on half shifts during initial exposures. (66) The phenomenon has been recognised in military and commercial diving practice as well as civil engineering. (67 & 68) Paton and Walder present evidence for compressed air acclimatisation indicating that the incidence of DCS decreases with a half time of 7 ± 4 days during daily exposures. If regular exposure stops, adaptation disappears in about 10 days. Adaptation appears to be specific for each pressure and recurs with each increase in working pressure. (55) This process of adaptation or acclimatisation to pressure has also been reported in diving operations which stress the importance of regular diving or “work-up dives” to reduce the risk of DCS. (69 & 70) In addition, adaptation or acclimatisation must be considered during the experimental testing of new decompression schedules. If the same divers are used too frequently the resulting schedules will be unsafe for unadapted divers.

The exact mechanism of acclimatisation remains unclear. Walder in 1969 suggested that acclimatisation is due to a gradual depletion of gas nuclei. (71) He proposed that different populations of gas nuclei are eliminated at specific working pressures and that adaptation is lost when nuclei re-accumulate. More recently there has been considerable interest in the role of complement in the pathogenesis of DCS. (72) Ward has found that there is a high degree of correlation between the sensitivity of plasma to complement activation by exposure to bubbles in vitro, and the susceptibility of the donor to DCS. This was true both for rabbits and for human volunteers. In the rabbit experiments decompression of the sensitive animals resulted in a loss of some complement fractions and the authors proposed that this could account for the acclimatisation which has been observed in divers and compressed air workers.

As has been shown in data from the Tyne Pedestrian Tunnel project and the first Dartford Tunnel, acclimatisation is of significant practical importance in compressed air work in "new starts" or where the maximum working pressure is significantly increased. (7 & 55) The degree of significance is best demonstrated by the observation that during the Tyne Tunnel project the overall DCS rate was influenced principally by the influx of new compressed air workers. This is important because a high turnover of labour has been almost characteristic of civil engineering compressed air work in the past. (56)

Analysis of the Decompression Sickness Registry Data held in Newcastle which consists of exposure records from 15 compressed air contracts from 1948-1977 using the 1958 Tables and the Blackpool Tables showed that acclimatisation to compressed air work was evident at Dartford 1 and the Tyne Road (1958 Tables) though not at Dungeness B (Blackpool Tables). An abrupt increase in pressure (of 9 lbs/in^2 or 0.6 bar/ 60 kPa) or more compared with the recent average) did result in a higher bends rate. (73) In more recent times acclimatisation appears to be less prominent than in the past in compressed air work and this may be related to greater emphasis in carrying out acclimatisation procedures under UK legislation (27) as well as modifications of the Blackpool Tables resulting in less decompression stress. (74) Commercial diving is generally recognised as having safer decompression schedules for a given exposure (i.e. dive profile) in comparison to tunnellers (3) and using modern commercial air diving tables, acclimatisation does not appear to play a significant role even when the diver has not been diving for some weeks or even months. (75)

It may be a reasonable assumption therefore that acclimatisation may be most marked or obvious when people are exposed to a high degree of decompression stress possibly as a result of an inadequate decompression following a hyperbaric exposure. This could explain why the phenomenon, objectively at least, appears to be more of a problem in modern compressed air work than in commercial diving or hyperbaric therapeutic practice where exposures are shorter and oxygen and mixed gas decompression techniques common place.

Occupation

Paton and Walder in the Tyne Tunnel construction noted that by far the greatest part of the DCS incidence occurred in shift workers rather than in the equally numerous group of men exposed only occasionally and briefly to pressure (technical and supervisory staff). In fact of the shift workers nearly all (95%) suffered DCS sooner or later. There was no observable significant difference between the various categories of shift worker, i.e. miner, manual labour, caulker or others. (55)

Others have also found different incidences of DCS between shift workers and non-shift workers in compressed air work. How during the Rapid Transit Project in Singapore in 1990 found significant differences between different categories of worker – on his particular project the supervisor category (i.e. non-shift workers) had the highest overall incidence of DCS which he considered to be due to the high number of multiple daily exposures (up to 5 per day). (40) He also observed that workers who were doing regular shifts and performing heavier work over a longer period of time but with a single decompression had an incidence of DCS three times the rate of the engineer (non-shift, non-manual) category.

The number and proportion of men in any given project working shifts or non-shifts in compressed air work varies greatly between individual compressed air contracts or projects. Thus during the Tyne Pedestrian Tunnel shift workers and non-shift workers consisted of a similar group of men (177 and 199 respectively). The number of men who had one or more episodes of DCS however varied from 168 shift workers to 16 non-shift workers (i.e. 95% as against 8% respectively). (55) However on the first Dartford Tunnel project in 1957-1959 roughly 1,060 men were shift workers with only 140 non-shift workers. (7) The non-shift workers consisted of a group of men working as engineers, electricians, carpenters, fitters, as well as supervisors who entered and left the tunnel to perform tasks, the duration of which did not coincide with that of the regular 8 hour shifts and who were decompressed according to their exposure to compressed air.

Lam (1988) suggests that the maximum working pressure and duration of exposure are the two most important factors in determining the incidence of DCS in a given working population or occupational group. (44) Nonetheless he cautions that the study of personal susceptibility factors (i.e. age, obesity, experience in compressed air work) must all be taken into account and linked if one is attempting to study risk factors for decompression illness and draw meaningful conclusions between different occupational groups of compressed air workers.

Paton and Walder in the Tyne Pedestrian Tunnel analysed those with DCS to determine if occupation influenced the site affected and found no relationship. (55) In common with other studies of compressed air workers they found a relative preponderance of lower limb bends as opposed to upper limb. This is in contrast to commercial divers and aviators who in general terms have a preponderance for limb pain bends to occur in the upper limbs.

How (1990) found in 76% of the DCS cases amongst compressed air workers that the joints of the lower limb were involved and that of these the knee joint was the commonest joint, although polyarticular presentations were common. (40) Lam (in 793 cases) also found that the lower limbs and again the knees, were the most frequent site of DCS in compressed air workers. (44) His figures were that only the lower limbs were affected in 84.4% of the type 1 cases, only in the upper limbs in 6.9% and both upper and lower limb involvement in 6.9%. This is virtually identical to earlier data from the first Dartford Tunnel project where only the lower limbs were affected in 85% of the 650 type 1 cases, with only upper limb involvement in 7%, and both upper and lower limbs in 8%. (7) Elliott and Kindwall have stated that in caisson workers lower limb symptoms of DCS were 3-4 times as frequent as those in the upper limbs in general terms. These authors appear to have found an increase of 6-7 times in the lower limbs as compared to the upper limbs. (76)

Walder considered the relationship between the posture a man adopts during his hyperbaric exposure and his propensity to get a bend. (77) He contrasted a miner labourer (who pushes skips about) with a man working in a very cramped kneeling position in the shield and another worker who is continuously putting a load on his arms. Despite the varying posture and effort of different compressed air occupations, it was discovered that the bends rate did not differ between the three groups and also that the frequency of the site affected, i.e. whether it was the arm or the leg was no different for the three groups. He also considered the question of exercise and the view that tunnellers are more susceptible to DCS than divers because the former did more rigorous exercise under pressure, however could not make any firm conclusions on the data available.

Obesity

As early as 1868 Mericourt recommended that no obese individual be employed as a sponge fisherman. *(78)*

Dr. A.H. Smith *(79 & 80)* published a monograph on the two caissons established using compressed air for the foundations of the piers for the Brooklyn Bridge, New York during 1871-1872 and provided

> 'figures which appeared to show positively that heavily built men are more frequently and seriously affected than those who are sparsely built'.

'Fulness of habit' was quoted by Snell in 1896 *(38)* as reported by most observers at the time as being a personal idiosyncrasy which appeared to influence the incidence of DCS and due to this association he excluded as far as possible men of very heavy build from compressed air work. He recognised that for any individual it would not follow necessarily that a stout man would always suffer DCS but "it can only be stated that in many cases a liability to illness is increased to a remarkable degree".

Even before Vernon (1907) *(81)* aroused scientific interest in obesity by showing that nitrogen was five times more soluble in oils and fats than in water, there were animal studies which showed fewer pathological lesions in lean than in fat animals after hyperbaric exposure. *(82)* Later studies essentially confirmed these findings. *(83, 84, 85 & 86)*

Another way of expressing this fact is that body fat increases the tissue mass available to absorb more inert gas. Also adipose tissue has a relatively poor blood supply so that dissolved gas is not eliminated so quickly during decompression. Behnke *(77)* is quoted as stating the clearance half-time for adipose tissue is 69 minutes. and that there is only one tissue with a higher nitrogen elimination half-time and that is the fat rich bone marrow.

Thus a man whose body weight comprises 30% fat will have 2000 ml. more nitrogen than a lean man who has only 10% body fat, for every 1 bar/99.7kPa change in pressure with a greater risk of DCS on account of the larger nitrogen content. *(87)* This has led some Physicians to include criteria for obesity/body fat in their medical selection process particularly with regard to 'shift' (manual) workers.

Three animal studies and twelve human studies report an association between DCS and body fat in diving, altitude and caisson work *(88 & 89)* whereas two diving studies found no association. *(90 & 91)* In the two diving studies where no association was found it has been postulated that increased body fat in divers may have a different effect for short dives than for caisson or altitude exposures due to the fact that high body fat in divers may protect against DCS in cold water. *(92)* Based upon a relationship between altitude DCS and weight to height ratios for 49,000 subjects, Grey (1951) *(61)* estimated that a 178 cm. (70") tall man weighing 89 kg (196 lb) was twice as susceptible as a 57.3 kg (126 lb) man of the same height. Gray also considered that there was a relationship between increasing bends incidence and ponderal index (height/weight^3).

Walder *(93)* postulates that bubbles are present throughout decompression and that in those circumstances a degree of saturation of the tissues with gases will be important at all times during decompression and afterwards and that consideration has to be given to tissues where the highest degrees of saturation are likely to occur. This predisposes the obese to a greater risk of DCS on account of the larger nitrogen content. *(87)*

Paton and Walder in 1954 *(55)* demonstrated that weight itself does not seem to be a reliable indicator of the sensitivity of caisson workers to DCS. However it has been recognised for many years that weight does not provide a reliable indication of body fat. (94) It should be noted therefore that whilst skinfold thickness of the triceps and subscapula alone has been correlated with DCS in tunnellers, (95) there has been no proven correlation between the size of an abdominal panniculus and DCS.

The problem appears to one of finding a better index to describe obesity, hence it is disappointing that attempts to correlate symptoms in divers (90) and caisson workers (96) with skinfold thickness and total body fat have proved negative in the past.

To this day no exact or generally agreed criteria yet exists by which men can be eliminated solely on the grounds of fatness but men who are obviously obese on clinical examination are generally excluded from compressed air work. (97) It appears to be generally accepted that if a worker is greater than 20% overweight according to standard height/weight charts, he may be more susceptible to DCS. Nonetheless all would appear to be agreed that weight in itself does not seem to be a reliable indicator of the sensitivity of caisson workers to DCS.

It has been stated that in divers the fattest 25% of the diving population, as judged by skinfold thickness, have a tenfold incidence of DCS. (6) How (40) quotes that those compressed air workers with greater than 24% body fat by skinfold measurement were either certified unfit or given restrictions for work in compressed air. Despite this he found the incidence of DCS among the obese compressed air workers was higher than the other compressed air workers. He related this to long exposures in compressed air work where it is expected that there is near saturation of the fatty tissue by nitrogen resulting in a nitrogen load five times greater during decompression. Thus he was unsurprised when despite only restricted clearance in terms of pressure exposure (duration and maximum working pressure) that it was found the obese compressed air workers still exhibited a higher incidence of DCS.

Individual Susceptibility and Repetitive Decompression Sickness

From the earliest days it has been stated that there are certain pre-disposing factors, such as age and body fatness, which will make some men more susceptible to DCS than others. (38 & 48) Since then a good deal of evidence has been published about these factors which have been reviewed earlier in this document.

It would seem fair to summarise that in compressed air workers the epidemiology of decompression sickness is known thus far to be related in the main to increasing length of exposure, maximum pressure, age, acclimatisation, body fatness and possibly occupation.

Shields *et al* analysed the relationship between the incidence of DCS and various stress indices for the dives involved in commercial offshore diving operations on the UK Continental Shelf during the period 1982-1988. Although DCS was a relatively rare event in this group of divers (1 episode per 1000 dives or less) his study found that 1 in 5 divers suffered from more than one incident of DCS. (98) A similar figure for repetitive DCS was also reported more recently by Luby in his study of DCS over 50,000 commercial air dives carried out in the Northern Arabian Gulf during the period 1993-1995 in a well defined diver population. (99)

Therefore, at least some of the variability of distribution of DCS within occupational groups may result from differences in individual susceptibility and this is clearly illustrated by looking at compressed air workers who are followed over many exposures. Lam and Yau (1989) (89) found that a previous history of DCS was associated with future bouts of illness. Paton and Walder (1954) (55) studied 376 compressed air workers during 40,000 exposures with a mean incidence of DCS of 0.87% during the Tyne Tunnel. 55% had an incidence below the mean, 11% had an incidence equal to the mean, 6% had twice the mean incidence and 10% had five times the mean incidence. The remaining 18% had an incidence twentyeight times the mean but left work after only a few exposures. Paton and Walder also examined (during the Tyne Pedestrian Tunnel contract) whether duration of employment in compressed air in that particular compressed air project depended on apparent susceptibility. They looked at two criteria of apparent susceptibility, i.e. the number of bends in the first 5 days of work, and the number of bends in the first 50 days of work which were termed respectively the 5 day rating and the 50 day rating. They found that of those free from bends in the first 5 days, 65% are still at work 80 days later; whereas among those who had more than one attack of DCS initially only 13% survive to 80 days. Similar contrasts were seen with the 50 day rating. Thus it was clear from this evidence that selection of some sort takes place and that those who experience DCS early in their employment tend to leave early. However they also found that attacks of bends appear to be almost unpredictable and occur at random within a given individual's experience. Their conclusion after a detailed analysis was that as a rule men remained in work until they had 1-3 attacks of bends and then left soon after the last attack. They concluded that to an important extent attacks of DCS were quite random in the compressed air workforce but also that there did appear to be an element of constitutional susceptibility.

Golding *et al* during the Dartford Tunnel project (7) found that a relatively small group of compressed air workers were responsible for quite a large proportion of the DCS cases. They cited, as an example, that if the twelve workers with 5 or more bends were eliminated then the total number of bends for the project would have fallen to 310 and the average DCS incidence over the 6-8 week period of compressed air work would have gone down from 0.98% to 0.77%; if those men with 3 or more episodes of DCS were eliminated (i.e. 4% of the workforce) then the overall DCS incidence for the project would have been halved. They also noted that 20% of the total population of compressed air workers had 1 or more attacks of the bends which meant for an individual worker the risk of an attack of bends at some time during his work in compressed air in that project was quite high (20%); but from the medical aspect the bends percentage, i.e. the number of bends per 100 exposures, was satisfactorily low (1%).

How (40) reported that of 1,737 people who worked in compressed air over a 3 year period, 136 (7.83%) suffered from DCS and that 114 compressed air workers had a single episode (83.8%) while 22 (16.2%) had 2 or more episodes of DCS. The maximum number of episodes of DCS recorded in any single individual was 4. He also observed that a relatively small group of workers with multiple episodes of DCS accounted for a significant percentage of the whole project DCS incidence – 17 workers having 2 episodes of DCS and 4 workers having 3 episodes accounted for 12.5% and 2.9% of the whole project DCS incidence respectively.

Lam (1988) (44) considered that the study of personal susceptibility factors must take into account the amount of individual exposure to compressed air, as well as age, occupation, obesity and experience in compressed air work. He reported that an attack of 1 or more bends during the first 5 compressed air work shifts accounted for 37 workers being unfit to continue compressed air work and that a further 52 workers were deemed unfit for compressed air work on the basis of one or more attacks of bends within a short period of employment. This shows that individual susceptibility and repetitive DCS in relatively modern times remains important since in this particular project 40% of all workers who were declared unfit during the project were deemed so due to what was essentially considered as unacceptable constitutional susceptibility to DCS. This is despite having passed a thorough medical examination, careful use of approved decompression tables, and strict enforcement of medical guidelines complying with the British Code of Practice applicable at that time with regard to age, obesity and general health. Clearly a method of identifying such workers would not only be of significance in reducing human morbidity but also make sound commercial sense to Contractors on the basis of cost and time effectiveness.

Multiple factors would appear to play an important role in determining individual susceptibility to DCS. Gray (1951) *(65)* found individual susceptibility in military aviators best described when age and body type were considered together. Lam and Yau (1989) *(89)* controlled for the effects of multiple variables by logistic regression and found increased individual susceptibility associated with body mass index, previous incidence of DCS and job (engineer or miner).

Data interpretation and hypothesis testing are complicated when multiple variables are present (i.e. acclimatisation, body fat, occupation, maximum working pressure, duration of exposure). The authoritative text by Bennett and Elliott *(22)* states that important variables in DCS are often uncontrolled or unmeasured in diving medicine and the best that can be accomplished with current statistical methods and much of the available data to date is a qualitative indication of factors which may be important under restricted circumstances. They lament the fact that much existing (diving) data is unsuitable for scientific study due to inaccuracy or insufficient clinical information and this would also appear to apply to compressed air work. *(100)*

It is likely however that with smaller numbers of men being used in compressed air work in the future with an increasingly specialised workforce and support specialists (Medical Lock Attendants) that high quality and accurate exposure data will become available. There is now within the United Kingdom a central co-ordinating centre (Compressed Air Working Group/HSE Database) for collection of both medical and exposure data which should provide an important resource for future research on health in compressed air workers. Certainly there would be considerable benefits for Compressed Air Workers, Contract Medical Advisers and Compressed Air Contractors if risk factors (whether individual or exposure related) in the development of DCS could be readily identified.

2.2 COMPRESSED AIR WORK IN THE UK

2.2.1 Occupational Health in Civil Engineering Projects

Occupational health support to construction projects utilising compressed air is provided by the Contract Medical Adviser. The role for the Contract Medical Adviser is defined by law following the Compressed Air Regulations 1996 which replaced the Work in Compressed Air Special Regulations 1958.

The Contract Medical Adviser is responsible for strict control of the medical selection standards, medical fitness of personnel working under pressure, proper record-keeping, systematic health surveillance and ensuring rapid response for the treatment of acute decompression sickness and other medical conditions related to changes in pressure. He is also responsible for the provision of general occupational health advice for those involved in the contract and he will normally be involved in the planning and preparation of a compressed air contract to ensure that the health implications are considered at an early stage. This will specifically involve advice on shift durations and decompression procedures. Such a role has been present to some extent at least on most compressed air projects over the past 50 years despite not being a legislative requirement and certainly well established in the UK over the past 20 years. *(45, 62 & 63)*

Any worker who suffers from DCS (or any other pressured related illness) would normally be reviewed by the Contract Medical Adviser or his deputy before returning to the hyperbaric working environment. In practice this means that all personnel undergo a thorough statutory pre-employment medical examination and are re-examined to determine fitness to work following any DCS. Hyperbaric exposure data is recorded in the form of worker identification, date and time of exposure, working pressure, decompression schedule and any DCS. There is a duty to keep such exposure data and medical records for a minimum period of 40 years.

2.2.2 The Decompression Sickness Central Registry 1964-1984

In 1956 the Medical Research Council (MRC) formed its Decompression Sickness Panel and between 1964 and 1984 ran a Decompression Sickness Central Registry at the University of Newcastle-upon-Tyne. In all the Registry holds in its computer database, some 15,000 identification and medical examination records from nearly 70 compressed air contracts, histories of workmen's exposure to compressed air and, for many, radiographic records. (73) From the late 1960's a joint committee of the MRC Panel and Construction Industry Research and Information Association (CIRIA) examined the medical management of compressed air work, which led in 1973 to CIRIA publishing Report 44, "Medical Code of Practice for Work in Compressed Air". (62) This Code was revised twice; in 1975 (63) and in 1982. (45)

Since 1986 the Compressed Air Working Group (CAWG) of the MRC Decompression Sickness Panel has reviewed current knowledge of medical effects of compressed air work, in order to provide the best possible guidance to industry on healthy working practices.

In June 1989 a year long contract was commissioned by CIRIA with the University of Newcastle-upon-Tyne to carry out the analysis of the Registry data. In January 1990, the Health and Safety Executive through its medical division, undertook the complete funding and management of the research. The final report on the analysis of the data held in the Decompression Sickness Central Registry was submitted to the HSE in April 1991 having been approved by the Project Steering Group and the Compressed Air Working Group. The initial document submitted to the HSE was unpublished. A further report (16) consisted of a compilation of several documents which represented the outcome and results of the DCS Registry data on compressed air.

There were six original questions posed by the Compressed Air Working Group and following the final report on the Further Analysis of the Decompression Sickness Registry Data, the Compressed Air Working Group considered to what extent the results answered those original questions.

The final report also considered recommendations for further study among which was a recommendation for a full case/control study for acute DCS to be undertaken and also for a separate exercise in which there would be a special study of the risk factors for "type II" DCS of which there was 134 events in the whole database.

In the foreword the author of the report, Dr. Evans, acknowledges that even by 1991 the data contained was old (no new contracts having been added since 1980) and that working practices were changing as caisson and tunnelling technology developed to cope with greater depths and higher pressures.

This new and developing situation begged the question how much more useful information could be gained from analysis of the existing data in the Central Registry and also whether, and if so, how an effort could be made to compile similar data about new compressed air contracts.

2.2.3 The HSE Decompression Database 1986 to Present

Around 1994/1995 Mr. Donald Lamont, HM Principal Specialist Inspector, began to receive compressed air workers exposure data in electronic format from civil engineering contractors utilising compressed air on the Jubilee Line Extension project. It was decided that it was important to establish and maintain a United Kingdom National Registry in view of the evolving compressed air work/tunnelling techniques and, in particular, with awareness that internationally at least, oxygen decompression was being used as an alternative to air decompression on the basis of reduced DCS rates and the prospect of a reduction in dysbaric osteonecrosis.

Exposure data from compressed air contracts in the UK was retrospectively and prospectively collated by the HSE for the period 1986 to present. Retrospective collation of data from 1986-1994 was made for those contracts who had worked at pressures greater than 1.0 bar gauge and therefore had required to seek HSE approval. From 1994 onwards all compressed air contracts had exposure data collated. This collection of data was an attempt to continue the National Registry work that had been started by the Newcastle Registry with the aim of monitoring the DCS rate and provide a basis on which any benefits from the introduction of oxygen decompression could be objectively assessed.

This means that the HSE Decompression Database omits “low pressure” compressed air contract data (i.e. those working below 1.0 bar gauge pressure) for the period 1986-1994. Nonetheless it offers, particularly in recent years, an increasingly accurate and reliable reporting of DCS in comparison to the data contained in the Newcastle Registry. Part of this is due to the change in reporting in recent years in which all cases of DCS whether of a minimal nature are referred for assessment and treated. Compressed air work forces are now smaller, increasingly more sophisticated, better trained and more specialised of necessity due to the technical nature of the work they are required to perform in the maintenance/repair of Tunnel Boring Machines. With the introduction of oxygen Medical Locks for on site treatment of compressed air workers, Medical Lock Attendants have also required to become more specialised with better qualification and training and this has resulted in more reliable data and decompression procedures and stricter control of hyperbaric procedures on site generally.

It is now planned that a defined set of medical information will be collated and held centrally on a database by HSE. *(1)* This database will afford the opportunity to pursue new areas of research in compressed air workers which have been hitherto not possible.

2.3 RESEARCH AND OCCUPATIONAL DECOMPRESSION SICKNESS: IMPOSSIBLE VARIABLES?

There are considerable practical difficulties or barriers to the scientific study of DCS both in divers and compressed air workers.

Decompression theory is readily amenable to mathematical modelling. However in practice, the study of performance of a given decompression theory (or indeed decompression table) is complicated by the phenomenon of inter and intra-individual variation with regard to DCS. The former is illustrated by the fact that during the first Dartford Tunnel project there was a 6-8 week period on the Kent side, when 4% of the compressed air workforce suffered 50% of episodes of acute decompression sickness. *(7)* This phenomenon is recognised in the diving world where it has been noted that 20% of the workforce will sustain repetitive DCS episodes despite a relatively low incidence of DCS overall (1:1000 dives). *(98)* Intra-individual variation is recognised both in tunnelling, commercial and military diving practices whereupon a compressed air worker or diver suffers the "bends" from a pressure exposure which he has done many times before without having any problem and with no obvious precipitating factor either within the individual or in terms of the incident exposure. These factors mean that the assessment of a given decompression schedule can be uncertain when assessing safety for an individual compressed air worker or diver undertaking a specific pressure exposure on a particular day. Undoubtedly however the application of decompression theory and technique has effectively improved the safety of the compressed air working and diving populations as a whole and considerably reduced the overall health risks over the past 100 years.

When dealing with individual workers undertaking a particular decompression schedule, the risk of DCS may be affected by the effects of pressure exposure (duration/ maximum pressure), exercise under pressure and during decompression, of physical workload, of temperature variation during work and decompression and also all the personal characteristics described previously from age to obesity that may be related to individual susceptibility. *(22)* Such a wide variation of factors means that it is difficult to plan the perfect decompression schedule in terms of health and safety outcome for all who may utilise the technique, particularly when taking practical (or commercial) considerations into account.

Another serious underlying problem in studying decompression sickness in compressed air workers or divers is the lack of internationally accepted specific or objective criteria to determine the nature or severity of the illness. The authoritative Undersea and Hyperbaric Medical Society Workshop examined the difficulties in defining exactly what is "a bend" in 1991 and unfortunately this major issue remains unresolved with little real progress having been made since despite the considerable efforts of researchers. *(101)* The lack of an accurate definition of the bends means that comparison between different diving or tunnelling contracts is problematical in terms of the health performance of different decompression schedules or procedures when performed at different times or in different locations.

Health outcomes have been used in DCS studies over the years which have included:-

(a) Reported symptoms: These are largely dependent on the individual tunneller recognising that symptoms may represent decompression sickness (training/information) and reporting them (attitude, access to reporting systems) to an appropriate Medical Lock Attendant or Medical Adviser. DCS covers a wide range of potential symptoms and severity, and may range from the vague "niggles" (mild pain in the joints) or skin rashes to serious neurological or life-threatening cardiopulmonary symptoms. In most tunnel/compressed air projects in the United Kingdom until recent times the "niggles" has been regarded as a minor manifestation of decompression and not always reported or treated with therapeutic recompression. Since the late 1990's in the UK due to better induction training and workplace supervision all manifestations of DCS are regarded as being of clinical significance, (particularly when one takes into account the known association with the late complication of dysbaric osteonecrosis) and reporting is now more complete.

(b) Physical signs: In compressed air work in civil engineering projects the quality of the initial (pre-treatment) physical examination of workers with possible acute DCS is determined largely by the medical skills, knowledge and experience of the examining Medical Lock Attendant (historically doctor examination occurs post-treatment to confirm diagnosis and follow-up). In the past in compressed air projects the initial clinical examination (and documentation) has been of a poor technical standard and of little practical help in determining the nature or severity of the acute decompression sickness due to wide variation between individual Medical Lock Attendants.

(c) Therapeutic recompression : Treated in the compressed air worksite medical lock or chamber. DCS can be empirically defined as ‘symptoms and/or physical signs experienced post-exposure which in the opinion of the Medical Lock Attendant required recompression therapy’. In addition to the reporting threshold of the diver and availability of the Medical Lock Attendant, whether therapeutic recompression is performed or not will therefore also depend on the interpretation of the tunneller’s symptoms by the Chamber Operator and/or Contract Medical Adviser (if consulted).

Until recent years many of the Medical Lock Attendants (using air treatments) had received only rudimentary training in the diagnosis and treatment of decompression sickness and would therefore have only a rudimentary understanding or experience of possible clinical signs and symptoms of DCS. Initial patient assessment was often limited as usually the Contract Medical Adviser would not routinely be involved during the acute treatment stage – medical assessment (and diagnosis) by the Contract Medical Adviser usually occurring during or after therapeutic recompression.

Other factors which may influence and affect reporting rates of decompression sickness in the tunnelling workforce include the degree to which a health and safety culture is established within the contract (poor in traditional tunnelling in the United Kingdom but rapidly improving over the past 10 years) as well as attitude and educational barriers within the workforce, including the reality that if DCS is reported then the affected worker may suffer economic threat in the form of lost employment due to temporary or permanent medical restrictions on “fitness to work”.

It is not surprising in view of these potential variables that the CIRIA report *(16)* revealed that the most significant factor influencing the incidence of decompression sickness in the tunnelling compressed air workforce was not maximum working pressure or shift duration but the “name of the contract”, i.e. that two compressed air projects of apparently similar size, working conditions and maximum pressure exposure and shift lengths, could have widely differing incidence rates of DCS. This is difficult to explain in terms of classical decompression theory alone, although the previous paragraphs would appear to be pertinent. In addition the hyperbaric literature seems to be rampant with contradictory scientific findings concerning the nature of DCS. Eckenhoff *et al* report that after 48 hour exposures to pressures as great as 164 kPa (20.5 ft. of seawater gauge pressure or 0.61 bar) in 111 human male volunteer subjects followed by relatively rapid return to atmospheric pressure, there were no signs or symptoms consistent with DCS, although a large incidence of venous gas emboli detection was noted. *(102)* In contra-distinction to these findings it was found during extensive testing of decompression procedures for recreational diving that in eight cases of bends encountered, Doppler signals had no correlation with the clinical diagnosis of DCS. Doppler bubble scores were only slightly higher in the group afflicted with DCS compared to those unaffected and the study concluded that the Doppler technique did not appear to be of diagnostic value for DCS in the absence of other clinical information. *(103)* One view is to accept that this means that Doppler bubble counts are probably useful from a statistical or epidemiological standpoint but may be of little use for predicting individual risk of acute DCS using a particular decompression schedule on a particular day.

Overall the factors outlined above make the study of DCS in the industrial setting an area filled with potential pitfalls for the unwary with a multiplicity of confounding and aetiological factors.

This has led one experienced Contract Medical Adviser to remark “DCS in compressed air tunnelling is a complex, multifactoral disease which must be studied in a holistic way if sensible conclusions are to be reached”. *(104)* Additionally, when the incidence of DCS is relatively low then many exposures (literally thousands) will be necessary to generate enough information on which to base inferences concerning risk factors for DCS. An operational or work setting is the only environment where this data collection is possible but without exact knowledge of working conditions and other relevant (for example, clinical) factors, confident conclusions are often elusive.

3 METHODS OF PROCEDURE

3.1 STUDY DESIGN

A case-control study design was selected for this research because the condition (repetitive DCS) is relatively rare and because a matched design enabling control for some risk factors whilst increasing the power to investigate the industrial or human factors of most interest was considered the best approach.

A simple summary analysis of the HSE Decompression Database was also undertaken to examine the relative contribution of those workers with repetitive DCS to the overall DCS incidence during the study period and to determine if repetitive DCS could be associated with any particular contract characteristics. (Not all contracts contained workers with multiple episodes of DCS.)

3.2 HSE DECOMPRESSION DATABASE 1986-2000

The HSE Decompression Database includes individual exposure records for compressed air workers in the UK from 1986 to present including episodes of DCS which Principal Compressed Air Contractors are legally required to report to HSE during or shortly after compressed air working. Only contracts working above 1.0 bar gauge/201kPa absolute (i.e. those required to seek HSE approval) were included for the period 1986-1994. Thereafter all compressed air contracts in the UK are included. The study period (1986-2000) covers a variety of compressed air projects from “traditional” hand excavation work to TBM inspection and maintenance using air decompression up to a maximum pressure approaching 3.0 bar gauge/ 401 kPa absolute. The Database therefore holds a significantly large number of exposures and reports of DCS.

The Database contains the name of the compressed air worker, date, time and duration of each hyperbaric exposure, maximum working pressure, decompression method, and most importantly, whether or not DCS has been reported. It was recognised by HSE in 1986 that it was important to maintain a United Kingdom National Registry of such information in view of the evolving compressed air work/tunnelling techniques and the relatively high incidence of DCS and dysbaric osteonecrosis in compressed air workers, so the completeness and quality of data is good. (104)

The HSE Decompression Database 1986-2000 was received on CD-ROM from Mr. Donald Lamont, Principal Specialist Inspector, HSE. It was translated into Microsoft and analysed using a Microsoft Access/Excel software package.

3.3 STUDY POPULATION AND SETTING

Compressed air workers in the UK identified from the HSE Decompression Database during the study period 1986-2000.

All pressure exposure data, including reported DCS episodes were derived from the HSE Decompression Database. This information formed the means by which those individuals with repetitive episodes of DCS during a contract were initially identified.

3.4 PRINCIPAL TASKS

(1) Identify all compressed air workers with two or more episodes of DCS (i.e. "bend prone group" or "cases") during a single compressed air contract or project recorded in the HSE Decompression Database during the period 1986-2000. Examine the distribution of those with one or more episodes of DCS in the workforce as a whole.

(2) Quantify incidence of repetitive episodes of DCS, and its contribution to the overall incidence of DCS in the HSE Decompression Database during the study period.

(3) Compare the "bend prone" group of compressed air workers or "cases" with two control groups (i.e. "single bend" control and "zero bend" controls) in terms of age, sex, smoking, alcohol, obesity, previous history of DCS and compliance with acclimatisation procedures.

Compare clinical information recorded in the notes for the three groups including blood pressure, haematology (haemoglobin, packed cell volume, mean cell volume), radiology (chest X-ray), lung function tests (FEV1, peak flow respiratory flow rate, FEV1/FVC ratio) and skin fold thickness.

(4) Consider the implications of any findings in developing an evidence based policy for the assessment of fitness to return to work of compressed air workers after a single episode of DCS.

3.5 CASE-CONTROL SELECTION

All cases and controls were initially selected using the HSE Decompression Database with confirmation following examination of the Contract Medical Adviser's clinical notes. All cases and controls were used once only in the study as described below.

Those compressed air workers who had suffered repetitive DCS (i.e. "cases") were matched with 2 groups of control subjects: individual compressed air workers who had experienced a single episode of DCS and individual compressed air workers who had no episodes of DCS during the same compressed air contract. It was considered important that both cases and controls were selected from the same contract since analysis of the compressed air records held in the Decompression Sickness Central Registry found that *"the variation between the results from the contracts considered in Section 4 suggests that the most important risk factor for acute DCS may be the name of the contract"*. (16) The exact reasons why these contract differences exist are undetermined but presumably relate to the working environment (including pressure exposure, equipment as well as access to Medical Lock Attendants) and to differences in the workforce (including information and training and perceptions of the nature of DCS and the personal consequences of reporting). It was felt therefore that by ensuring that cases and controls came from the same compressed air contracts that possible (multiple) confounding factors could be excluded from the study.

3.5.1 Case selection

"Cases" were defined as those compressed air workers with two or more episodes of DCS during a single compressed air project who have required therapeutic recompression related to occupational pressure exposure and had the diagnosis confirmed by the Contract Medical Adviser during the period 1986-2000. Initial estimates were that there would be approximately 60 cases identified from the HSE Decompression Database.

Where there was disagreement between the HSE report and the Contract Medical Adviser's clinical notes then written diagnosis in the clinical notes and records of therapeutic recompression was considered to indicate an episode of DCS. (Where workers had initially been treated as acute decompression sickness by Medical Lock Attendants but subsequently diagnosed by the Contract Medical Adviser as having a non-pressure related illness, then these were not considered as an episode of acute decompression sickness nor used for “zero bend” or “single bend” controls.)

“Cases” were determined by the first contract during the period 1986-2000 where they had had multiple DCS episodes meeting the above criteria.

3.5.2 Control selection

Two separate groups of control subjects were identified, i.e. those with no DCS episode (Control group 1) and those with a single episode of DCS (Control group 2) having occurred during the contract. All controls were matched to the cases in terms of compressed air contract or project.

Control subjects were initially identified from the HSE Decompression Database. Where there was disagreement between the HSE report and the Contract Medical Advisers clinical notes then written diagnosis in the clinical notes and records of therapeutic recompression was considered to indicate an episode of DCS and the subject (re)allocated into the appropriate category where necessary. Therefore any cases of DCS not reported (or misreported) to HSE for controls were identified from the clinical notes before inclusion in the study.

Control Group 1
This group is called “controls with zero bends”. These are compressed air workers selected from the Database who have no HSE reported episodes of therapeutic recompression for treatment of DCS related to work in compressed air and who have had no recorded diagnosis of DCS in their clinical notes nor therapeutic recompression during the contract.

All “controls with zero bends” will have been exposed to an equivalent maximum working pressure (to within 0.5 bar gauge/ 50 kPa) or greater than cases and an equivalent (within 30%) or greater total number of “significant exposures” during the contract. This is to ensure they will have had similar pressure exposure to the ‘cases’.

Significant exposures are defined:	> 6 hours duration at < 1.5 bar gauge/ 251 kPa absolute pressure
	> 4 hours duration at > 1.5 bar gauge/ 251 kPa absolute pressure

Significant exposures: This definition, although arbitrary, follows a format similar to that adopted by Dr. Evans in the analysis of the Decompression Sickness Central Registry. It is based on the fact that there are few incidents of DCS where shift lengths are less than 6 hours up to 1.5 bar gauge or shift lengths less than 4 hours at pressure greater than 1.5 bar gauge. These sub-divisions attempt to ensure that exposure related factors are taken into account in selecting controls for what is by definition an exposure related disease.

All “controls with zero bends” were matched with occupation during the contract as listed in the HSE Decompression Database or as defined below.

Two ‘controls with zero bends’ were matched with each ‘case’.

Manual shift worker (e.g. labourer, miner)
Non-manual shift worker (e.g. locomotive driver)
Manual non-shift workers (e.g. fitters, electricians, welders)
Non-manual non-shift worker (e.g. inspector, technical or supervisory staff)

> A manual worker is defined by someone undertaking moderate to heavy physical work at the face or construction area as part of their job description. Shift workers are described as those who undertake regular (usually daily) pressure exposures as part of their job description. It is recognised that fitters and electricians often undertake shift-like patterns at times but are not recognised as "shift workers" due to the intermittent pattern of their work.

Some workers had many exposures but few "significant exposures", i.e. short duration pressure exposures, many times. In this situation where possible "controls with zero bends" were selected:-

> Equivalent or longer average shift durations than cases
> A similar calendar period during which pressure exposure occurred (within 6 months) during the contract.
> Total pressure exposure duration (minutes) equivalent to or greater than cases

Ideally "controls with zero bends" will therefore have worked at an equivalent or greater maximum working pressure, with an equivalent or greater total number of significant exposures and will have undertaken a similar work activity. Two controls with zero episodes of DCS were matched to each case wherever possible.

Where there was a group of possible "controls with zero bends" who met the matching criteria defined above then final selection was by random number allocation.

"Controls with zero bends" were initially selected by "no DCS" during the study contract. Latterly they were further selected as having no DCS during the whole of the study period 1986-2000.

***Control Group 2*:**
This group is called "controls with single bend". These were selected from those who have suffered a single episode of DCS requiring therapeutic recompression during the contract identified from the HSE Database and/or clinical notes. Where there was disagreement between the HSE Database and the clinical records then an episode of DCS was determined by the process described under 'Case selection'. They were matched to the cases in terms of contract or project, maximum working pressure (to within 0.5 bar/50kPa or greater as a minimum).

The matching of "controls with single bend" to "cases" followed the same format as listed for "controls with zero bends" for all matching criteria.

Ideally "controls with single bends" have therefore worked at an equivalent or greater maximum working pressure, with an equivalent or greater total number of significant exposures and will have undertaken a similar work activity. In projects where the number of subjects available as "single bend controls" is limited relative to cases then matching was carried out using the above criteria in order as far as possible. One tunneller with a single episode of DCS was matched with each case.

Where there was a group of possible "controls with single bends" who met the matching criteria defined above then final selection was by random number allocation.

3.6 DATA COLLECTION

All cases and controls were given a unique identifier and a case number. All relevant exposure and clinical data was coded and entered onto a written and then computerised spreadsheet using Microsoft Excel which facilitated easy tabulation of the results.

Quality control of all computerised data entries was made by a 10% random check compared to the written spreadsheets by an independent party prior to analysis.

3.6.1 Clinical Information

Contract Medical Advisers (CMAs) are approved by the HSE in the UK and follow a standardised approach to the pre-employment medical examination for compressed air workers in terms of format, style and criteria of medical fitness to work. The numbers of CMAs during the study period were relatively small – only some 5-6 individual doctors. Crucially CMAs have a legal obligation to retain the clinical records for a period of 40 years.

Clinical data was collated for cases and controls from contemporaneous clinical records of the pre-employment/initial compressed air medical examination held by the Contract Medical Adviser. Confidentiality was maintained by only the author having access to clinical records and all compressed air worker data being anonymised before entry on to the database. No formal ethical approval was considered necessary at the time this study was initiated. (Although no particular Ethical concerns were anticipated at the onset of the study, it is accepted by the author that formal Ethical approval would now be required under current professional guidelines introduced whilst the study has been underway).

Contemporaneous clinical data on age, sex, smoking habit, alcohol consumption, height, weight, skinfold thickness, previous DCS, previous compressed air work, blood pressure and haematology results (haemoglobin, white cell count, mean cell volume and haematocrit) were recorded from the initial or pre-employment compressed air medical examination records. Chest x-rays were recorded as “normal” or “abnormal” as determined by the Contract Medical Adviser or Radiology Report following chest x-ray as part of the initial compressed air work medical examination. Lung function tests from vitalograph print outs or clinical examination notes (FEV1, peak flow respiratory flow rate, FEV1/FVC ratio) were collated from the clinical records. It was difficult to standardise ECG findings and since significant abnormalities are likely to be have resulted in a person being medically unfit for compressed air work then electrocardiogram records were not examined. All clinical data were recorded on an individual written spreadsheet, anonymised, and then entered on to a Microsoft Excel computer spreadsheet.

3.6.2 Pressure Exposure

All cases and controls were identified from the HSE Decompression Database and the following information collected for each individual compressed air worker from each contract:-

Name of compressed air worker
Name of contract
Duration
Date of first exposure
Date of last exposure
Number of final exposure (i.e. 10 for 10th exposure)
Total exposure duration (mins.)

Maximum pressure
Average shift length
Average pressure
Number of significant exposures < 1.5 bar gauge/ 249 kPa absolute
Number of significant exposures ≥ 1.5 bar gauge/ 249 kPa absolute
Total "significant" exposures

This information was collated on individual written spreadsheets for cases and both control groups then computerised using Microsoft Excel.

3.6.3 DCS Incidents : Exposure Data

It has been recognised since the earliest days of compressed air work (and diving) that the exposure characteristics would be the main determinant of the risk of DCS for an individual worker. It is appropriate therefore in a study of DCS in compressed air workers to record some basic information concerning the pressure exposures preceding incidents where DCS has occurred.

Information was recorded for each incident of DCS in 'cases' and single bend controls in order to determine whether known provocative factors within the compressed air procedures or system of work had occurred and could therefore be considered as a contributory factor (or causal factor) to the episode of DCS.

A 20% sample of "controls with zero bends" were also examined in terms of provocative factors within the compressed air procedures from dates on which no DCS had occurred. An exposure selected at random from the zero controlled bend was examined as described below. Although it was not the primary aim of this paper to consider the role of exposure factors in the causation of repetitive episodes of DCS clearly the pressure exposure characteristics preceding episodes of DCS could be an important confounding factor for this study.

The following pressure data was recorded in each episode of DCS for the cases and control groups from the HSE Decompression Database. This included data on exposure, number, maximum pressure and duration of the DCS incident exposure (or selected exposure for zero bend controls).

- Days since last previous pressure exposure
- Number of consecutive daily exposures before the incident exposure
- Compliance with contemporary recommended exposure limits
- (< 1 bar pressure, no more than 10 hours pressure exposure in a 12 hour period,
- 1 bar pressure 8 hours maximum exposure including decompression in a 12 hour
- period).
- The number of repetitive exposures within 24 hours of the incident exposure.
- Change between the incident exposure working pressure and the man exposure pressure during the previous 7 days or 7 exposures.
- The maximum working pressure over the previous 7 days.
- The minimum working pressure over the previous 7 days.

This data determines whether an individual with repetitive DCS has been exposed to a regime of hyperbaric exposure which could be regarded as either provocative or possibly contributory to the recorded episode of DCS. There is advantage in recognising such factors since such a group of workers could reasonably be considered to be a sub group of 'cases' and "controls with single bends".

3.7 POWER CALCULATION

Power calculations for 1:1 matched case controls are based either on the expected differences between the pairs or on the number of discordant pairs depending on the nature of the risk factor. If instead there are c controls per case the number of matched sets required is the number of pairs multiplied by (1+c)/2c (Machin D, Campbell M, Fayers P, Pinol A. Sample size tables for clinical studies. 2nd Ed. Blackwell Science, Oxford. 1997. p74). If the conservative step of considering only the unbent subjects as the controls in our power calculations is taken then our 60 matched sets are equivalent to 80 matched pairs. If the individuals with only one bend are counted with the controls, i.e. 3 controls per case, then 60 matched sets would have the same power as 90 matched pairs.

With 80 matched pairs (or 60 matched sets) a mean difference in age of 5 years between cases and controls can be detected using a paired t-test with at least 80% power provided the standard deviation of this difference is less than 15.8 years. With 80 matched pairs a mean difference in BMI of 2 kg./m^2 can be detected using a paired t-test with at least 80% power provided the standard deviation of this difference does not exceed 6.3 kg./m^2. Conditional logistic regression will be used to analyse the matched sets and it is expected that there will be some power loss when adjusting for confounders. However conservative assumptions have been made in these calculations and we believe that the real standard deviations for the differences would be lower than those suggested and hence there would be sufficient power available to adjust for confounders with 60 matched sets.

3.8 ANALYSIS OF DATA

A simple summary analysis of the HSE Decompression Database 1986-2000 was undertaken using a Microsoft Access and Microsoft Excel software package.

Statistical analysis of data for cases and controls was undertaken using the appropriate statistical package - SPSS (Statistical Package for the Social Sciences) and STATA (StatCorp 1999. Stata Statistical Software Release 6.0 College Station, TX: Stata Corporation).

Conditional logistic regression which is required when looking at several risk factors in matched case control data was performed. Multi-variate analysis was used to assess the relationship of each potential personal risk factor, both independently and in association with other risk factors, for cases and controls.

The compressed air worker clinical data (i.e. “human factor” or personal characteristics) was analysed in three steps or stages with all workers strictly matched by contract, pressure exposure and occupation.

Step 1: 1 × case **-v-** 1 × single bend control **-v-** 2 × zero bend controls

Step 2: 1 × case **-v-** 1 × single bend control and 1 × case **-v-** 2 × “pure” zero bend controls*****

*****where any compressed air worker who had ever had an episode of DCS was excluded.

This step was considered appropriate because it would be possible to have a “zero bend control” who was known to have been bent on other compressed air contracts either before or during the study period.

Step 3: 1 × “bend”***** **-v-** 1 × “pure” zero bend control.

*****where the “bend” is either a “case” or “single bend control”.

Step 3 was undertaken because of the relatively small numbers involved. If the personal characteristics associated with susceptibility to DCS can be considered as a continuum, by combining both “cases” and “single bend controls” and matching these to a “pure zero bend control” then any significant differences in personal characteristics between the two groups may be more readily identified. Effectively this gives the study a greater statistical power.

4. RESULTS AND ANALYSIS

4.1 SUMMARY DATA: HSE DECOMPRESSION DATABASE 1986-2000

The HSE Decompression Database was examined for the study period 1986-2000 inclusive. All compressed air workers were identified who:

- A: had had two or more episodes of DCS reported during a single compressed air contract (ie "cases")
- B: had had suffered one episode of DCS reported during a single compressed air contract (ie "single bends")
- C: had not had DCS reported during a single compressed air contract (ie "zero bends")

Table 1 provides a summary of all data. It shows the distribution by contract, of DCS among the HSE Decompression Database workforce for the study period.

Table 1

Summary Data - HSE Decompression Database 1986-2000

Name of Contract	No. of CAW	Year	CAW with number of bends					Total no of DCS	No of cases	% DCS att to cases	No. of DCS att to cases
			0	**1**	**2**	**3**	**4**				
Lowestoft	34	1986	26	5	1	2	0	13	3	61.5	8
Rochdale	46	1987	46	0	0			0	0	0	0
N Woolwich	84	1987	63	13	3	4	1	35	8	63	22
LWRM	88	1988	62	16	10	0	0	36	10	55.5	20
Royal Docks Donelon	87	1989	68	12	6	1	0	27	7	55.5	15
Ramsden Dock	233	1991	198	28	6	1	0	43	7	35	15
Ennerdale	63	1992	55	6	2	0	0	10	2	40	4
Southport	93	1993	87	6	0			6	0	0	0
Cromer	91	1993	66	15	6	4	0	39	10	61.5	24
JLE 107	78	1994	78	0	0			0	0	0	0
JLE 110	101	1995	83	11	5	1	1	28	7	61	17
Fylde	74	1995	65	8	1	0		10	1	20	2
JLE 105	336	1995	292	32	9	3	0	59	12	46	27
Swanage	70	1996	61	4	4	1		15	5	73	11
Weston	98	1996	93	5	0			5	0	0	0
Swansea 5	156	1996	136	13	6	1	0	28	7	53.5	15
Bacton	53	1997	50	3	0			3	0	0	0
Hastings	53	1998	49	4	0			4	0	0	0
DLR	78	1998	78	0	0			0	0	0	0
Swansea 6	152	1998	152	0	0			0	0	0	0
Hull	56	1999	50	5	1	0	0	7	1	28	2
GYPP	36	1900	33	3	0			3	0	0	0
TOTALS	**2160**		**1891**	**189**	**60**	**18**	**2**	**371**	**80**		**182**

Table 1 demonstrates that those men with episodes of repetitive DCS accounted for 49% of all DCS episodes during the period 1985-2000 for compressed air work in the UK.

Thus approximately 4% of the workforce (i.e. 80 men from a total compressed air workforce of 2160) accounted for half the episodes of reported Decompression Sickness requiring therapeutic recompression during the study period.

This confirms that a relatively small group of workers apparently susceptible to (repetitive) DCS, are a significant source of morbidity from compressed air work in the UK. The finding of 4% of the workforce suffering 50% of the bends was also that reported by Golding *et al* during construction of the Dartford Tunnel in 1960.

4.1.1 Contract Data

A further analysis of the HSE decompression database examining individual compressed air contracts was made. During the study period, 13 compressed air contracts had “cases” and 9 contracts had no “cases”. Since this is a case control study of repetitive DCS therefore only those contracts containing “cases” were studied further. However a simple comparison between the “study” contracts and the “non study” contracts in terms of pressure and other characteristics is provided in Tables 2-5 inclusive.

Tables 2 and 3 show contract characteristics for maximum and average working pressures as well as total number of exposures and a qualitative description of the work. Most hand excavation projects involve “constant “ pressure exposure for the duration of the contract albeit with pressure fluctuations with the majority of the workforce manual workers. Most TBM interventions involve “ periodic or intermittent” pressure exposures during the term of the contract with a high proportion of welders and other skilled workers. Some contracts may involve both e.g. hand excavation (HE) work in compressed air breaking out from a tunnel shaft or constructing cross passages on a TBM project.

Table 2

“Study” Contracts: Contract characteristics

Name Of Contract	Start	End	Max press bar (g)	Av press bar (g)	No of men	Total no of exp	Mean exp/man	Contract desc
Lowestoft	18/02/86	18/06/86	2	1.68	34	1026	30	HE
N Woolwich	10/09/87	27/01/89	1.93	1.45	84	7468	89	HE
LWRM	04/10/88	15/01/89	2.14	2.05	88	3051	35	HE
Royal Docks Donelon	23/02/89	15/01/90	1.6	1.3	87	3327	38	HE
Ramsden Dock	16/01/91	22/05/91	2.3	0.96	233	9045	39	HE
Ennerdale	27/04/92	19/04/93	1.8	1.4	63	2805	45	HE
Cromer	10/12/93	10/09/94	2.34	1.42	91	6403	79	TBM/HE
JLE 110	26/01/95	17/11/95	2.5	1.93	101	2458	24	HE
Fylde	01/05/95	17/11/95	2.4	1.9	74	1121	15	TBM
JLE 105	28/09/95	11/11/96	1.15	0.8	336	19623	59	HE
Swanage	21/02/96	22/11/96	1.86	1.12	70	5309	76	TBM/HE
Swansea 5	13/09/96	24/01/97	1.82	1.12	156	8157	52	TBM/HE
Hull	26/03/99	26/11/99	1.9	1.21	56	424	8	TBM
Mean			1.98	1.41	113	5401	48	

Table 3

“Non-Study” Contracts: Contract characteristics

Name Of Contract	Start	End	Max press bar (g)	Av press bar (g)	No of men	Total no of exp	Mean exp/man	Contract desc
Rochdale	05/05/87	19/06/87	0.9	0.89	46	710	15	HE
Southport	21/01/93	17/12/93	1.21	0.88	93	10581	114	TBM
JLE 107	30/11/94	04/03/96	2	0.82	78	568	7	TBM/HE
Weston	11/07/96	14/08/97	0.95	0.88	98	7144	73	HE
Bacton	24/11/97	06/08/98	1.52	0.96	53	2910	55	HE
Hastings	11/01/98	28/07/99	2.1	1.25	53	1291	24	TBM
DLR	18/02/98	20/08/98	1.3	0.82	78	1813	23	HE
Swansea 6	20/06/98	23/07/98	1.1	0.74	152	14970	98	TBM
GYPP	18/01/00	03/02/00	2.1	1.59	36	150	4	TBM
Mean			1.46	0.98	76	4460	58	

Tables 2 and 3 show that the “study” contracts i.e. those associated with repetitive DCS or “Cases” were at higher pressure, both in terms of the maximum pressure achieved during the contract and in terms of the average pressure which better reflects typical working pressure. The study contracts often had an average pressure greater than 1.0 bar gauge/199kPa absolute with a greater number of compressed air workers being exposed.

4.1.2 Study Contracts: Exposure Data and DCS Rates

Further analysis of contract exposure data and DCS rates was made. The results are summarised in Tables 4 & 5 which show the pressure characteristics in detail. These include the total contract pressure duration, average shift duration, average exposure time per man and number of “significant exposures” and DCS data.

Table 4

Study Contracts – Exposure Data and DCS Rates

Name Of Contract	Total press duration (mins)	Avg shift duration (mins)	Avg dur of exp/man (mins)	Sig exp <1.5 bar (g)	Sig Exp >1.5 bar (g)	Total no of DCS	% bend rate	% sig exp
Lowestoft	261149	255	7681	8	527	13	1.27%	52%
N Woolwich	2227699	298	26520	2297	1940	35	0.47%	57%
LWRM	531277	174	6037	0	814	36	1.18%	27%
Royal Docks Donelon	834626	251	9593	1201	54	27	0.81%	38%
Ramsden Dock	2567008	284	11017	4	1647	43	0.48%	18%
Ennerdale	595332	212	9450	804	208	10	0.36%	36%
Cromer	1962820	307	24232	2086	1277	39	0.67%	53%
JLE 110	374726	152	3710	20	2127	28	1.14%	87%
Fylde	285934	255	3864	29	217	10	0.98%	22%
JLE 105	8898102	453	26482	1516	0	59	0.30%	8%
Swanage	1484787	280	21211	2291	55	15	0.28%	57%
Swansea 5	1951786	239	12511	2979	50	28	0.34%	1%
Hull	87070	205	1555	97	0	7	1.89%	23%
Mean	1697101	259	12605	1025	686	27	0.50%	37%

Table 5
Non-Study Contracts – Exposure Data and DCS Rates

Name Of Contract	Total press duration (mins)	Avg shift duration (mins)	Avg dur of exp/man (mins)	Sig exp <1.5 bar(g)	Sig Exp >1.5 bar(g)	Total no of DCS	% bend rate	% sig exp
Rochdale	122400	172	2661	2	0	0	0.00%	0%
Southport	2836132	268	30496	1853	0	6	0.06%	18%
JLE 107	76971	136	987	84	0	0	0.00%	15%
Weston	1425448	200	14545	2298	0	5	0.07%	32%
Bacton	708083	243	13360	744	124	3	0.10%	30%
Hastings	167927	130	3168	24	59	4	0.31%	6%
DLR	452320	249	5799	754	0	0	0.00%	42%
Swansea 6	71908	5	473	82	0	0	0.00%	1%
GYPP	15119	101	420	0	8	3	2.67%	5%
Mean	652923	167	7989	649	21	2	0.05%	16%

Tables 4 and 5 show that “study” contracts have on average a greater number of “significant exposures” and a significantly higher bends rate.

Interestingly perusal of Tables 2 and 4 shows that those study contracts with the fewest exposures have the highest Bends rate (i.e. Lowestoft, LWRM, JLE 110 and Hull). Although there are exceptions, in general, this data shows that the percentage Bend rate diminishes as the contracts lengthen. This could represent either an acclimatisation or 'healthy worker' effect within the compressed air workforce.

It is perhaps not surprising that the contracts most likely to produce “cases” or men with repetitive DCS are the longer and/or more prolonged working at higher pressures with many “significant exposures”. This is to be expected for what is a pressure related disease. Tables 4 and 5 indicate the mean duration of pressure exposure for “study contracts” to be more than double that of “non-study contracts” (1,697,101 minutes and 652,923 minutes pressure exposure respectively).

This analysis does not, however, shed light on why some men suffer obvious health effects from pressure exposure that does not appear to adversely affect the majority of the workforce.

Overall percentage DCS rate for 1986–2000 for all compressed air contracts was 0.34% (i.e. episodes of DCS per 100 exposures). The comparable bends rate for the Dartford Crossing in 1957 was 0.98% *(7)*.

4.2 HUMAN FACTORS IN DECOMPRESSION SICKNESS IN COMPRESSED AIR WORKERS

4.2.1 Introduction

Of the thirteen study contracts four were omitted from the study. The contracts and reasons for omission are listed below:

Lowestoft:	No clinical data
North Woolwich:	Clinical data not accessible
Royal Docks Donelon:	No clinical data
Fylde:	Incomplete pressure data

On perusal of the clinical notes for individual compressed air workers a number of additional episodes of DCS meeting the study criterion but unreported to HSE were found for cases, single bend controls and zero bend controls. This resulted in one additional case for each of the following contracts: JLE 105, Swanage and JLE 110. Conversely the odd HSE reported DCS episode was not confirmed by the clinical notes. Occasionally this necessitated changing category (approximately 12 occasions). Seven men's individual clinical notes were missing : six zero bend controls (reallocated) and one case (omitted). A further case was lost due to the same man occurring as a case on two separate contracts. A total of 62 cases were used in the study.

Following perusal of the clinical data, cases and controls were allocated as per the study protocol. It was not possible to always match each case with a corresponding single bend control and two zero bend controls. This resulted in "Extra" or "unmatched" cases and single bend controls. Where "extra" case or single bend controls occurred these were matched with a single zero bend control and included in analysis later in the study. Fifty-two fully matched sets were used.

The final distribution of cases and both control groups by contract is given in Table 6 below.

Table 6

Study Contracts – Final Distribution of Cases and Controls

	Fully matched			**Extras**		
Name of Contract	**Cases**	**Single**	**Zero control**	**Cases**	**Single**	**Zero control**
Cromer	7	7	14	3	2	5
Ennerdale	2	2	4	0	2	2
Hull	1	1	2	0	0	0
JLE105	11	11	22	2	2	4
JLE110	6	6	12	0	2	2
LWRM	10	10	17	0	0	0
Ramsden Dock	7	7	14	0	9	9
Swanage	3	3	6	3	1	4
Swansea 5	5	5	10	2	1	3
Total	**52**	**52**	**101**	**10**	**19**	**29**

All personal data was collated from the clinical notes of the pre-employment or initial compressed air medical examination conducted by the Appointed Doctor or Contract Medical Adviser.

Two zero bend controls were found to have suffered an episode of DCS before or during the study period outwith the study contract and were therefore excluded as "pure zero bend controls" in later analysis.

Four men appeared twice in the study contracts on separate occasions:-

- One as a "case" on two separate contracts (only the first entry was included)
- One as a "case" and "single bend control" (counted as a case once only)
- One as a "zero bend control" on two contracts (only the first entry was included)
- One as a "zero bend control" (minimal pressure exposure) and single bend control (included as a single bend control)

Initially the data are described using appropriate summary statistics. Then comparisons between the groups are made using a variety of methods. The most robust of these methods is conditional logistic regression because it makes use of the matched structure of the data. Some unmatched descriptions are included to identify potential relationships and differences, however they must be considered as preliminary analyses which do not address the research questions directly.

For many of the analyses attention is focused on the 52 fully matched sets containing a subject with multiple bends, one with a single bend and at least one no bend control.

4.2.2 Continuous variables

Table 7

Description of the 52 fully matched sets for characteristics which are normally distributed

Characteristic	Group	Count	Mean	SD
Height (metres)	Multiple	52	1.76	0.06
	Single	52	1.76	0.07
	Control	101	1.75	0.07
Weight (kilograms)	Multiple	49	79.98	10.17
	Single	52	79.24	11.49
	Control	98	78.33	9.52
Body mass index (kg/m^2)	Multiple	49	25.84	3.19
	Single	52	25.58	3.13
	Control	98	25.61	2.85
Ponderal index (cm/kg$^{1/3}$)	Multiple	49	40.97	1.78
	Single	52	41.10	1.81
	Control	98	40.99	1.69
% Bodyfat	Multiple	20	15.73	3.61
	Single	23	15.00	5.33
	Control	40	16.92	4.34
Haemoglobin (g/dl)	Multiple	21	15.22	0.90
	Single	22	15.18	0.89
	Control	40	15.45	0.95
Mean cell volume (fl)	Multiple	14	90.84	4.39
	Single	19	89.40	4.25
	Control	27	90.47	3.56
Mean corpuscular haemoglobin (pg)	Multiple	14	30.74	1.78
	Single	19	30.40	1.50
	Control	27	30.67	0.95
Packed cell volume	Multiple	21	0.45	0.03
	Single	22	0.45	0.03
	Control	40	0.46	0.03
Diastolic BP (mm/Hg)	Multiple	52	73.19	10.35
	Single	52	72.38	12.09
	Control	100	75.00	12.27
FEV 1 actual (litres)	Multiple	52	4.31	0.59
	Single	52	4.38	0.72
	Control	100	4.17	0.69
FEV1 predicted (litres)	Multiple	52	4.18	0.35
	Single	52	4.19	0.40
	Control	101	4.05	0.43
FEV1 % of predicted	Multiple	52	103.16	12.14

Characteristic	Group	Count	Mean	SD
	Single	52	104.81	15.65
	Control	100	103.17	13.46
FEV1 standardised residual	Multiple	52	0.25	0.97
	Single	52	0.38	1.26
	Control	100	0.25	1.04
FER actual	Multiple	52	82.92	6.20
	Single	52	82.38	7.27
	Control	100	81.43	6.52
FER % of predicted	Multiple	52	101.50	7.88
	Single	52	100.85	8.82
	Control	100	100.30	7.78
FER standardised residual	Multiple	52	0.17	0.89
	Single	52	0.10	1.00
	Control	100	0.03	0.89
FVC actual (litres)	Multiple	52	5.21	0.73
	Single	52	5.31	0.72
	Control	101	5.15	0.84
FVC predicted (litres)	Multiple	52	4.99	0.41
	Single	52	5.00	0.48
	Control	101	4.85	0.49
FVC % of predicted	Multiple	52	104.46	11.36
	Single	52	106.66	13.17
	Control	101	106.17	13.34
FVC standardised residual	Multiple	52	0.37	0.92
	Single	52	0.51	1.05
	Control	101	0.49	1.05
PEFR predicted	Multiple	52	9.63	0.51
	Single	52	9.63	0.58
	Control	87	9.35	0.61

		Count	Median	25 %ile	75 %ile
Final number of exposures	Multiple	52	63.00	19.00	136.00
	Single	52	66.50	39.50	133.75
	Control	101	81.00	51.75	131.75
TRICEPS skinfold (mm)	Multiple	20	8.20	5.90	10.18
	Single	23	7.60	6.10	11.00
	Control	41	8.00	6.20	9.53
BICEPS skinfold (mm)	Multiple	20	4.15	3.68	5.18
	Single	23	3.90	3.00	6.00
	Control	41	4.40	3.58	5.60
SUBSCAPULAR skinfold (mm)	Multiple	20	10.20	8.93	13.73
	Single	23	10.30	8.70	16.00
	Control	41	12.10	10.10	15.50
L SACROIIAC skinfold (mm)	Multiple	20	8.40	6.98	12.33
	Single	23	8.60	5.70	12.60
	Control	41	9.00	6.38	14.00
R SACROILIAC skinfold (mm)	Multiple	20	8.20	6.70	11.63
	Single	20	7.00	5.30	11.55
	Control	37	9.60	7.33	13.80
CALF skinfold (mm)	Multiple	20	7.75	6.73	9.33
	Single	20	7.20	5.28	11.73
	Control	37	7.00	5.83	9.80
TOTAL SKIN FOLD	Multiple	20	31.10	27.63	41.50
	Single	23	33.50	23.50	44.00
	Control	41	33.80	27.23	44.80

		Count	Median	25 %ile	75 %ile
Age years at initial medical exam	Multiple	52	29.50	26.25	33.75
	Single	52	29.00	24.00	36.00
	Control	101	31.00	27.00	40.25
Alcohol (units/week)	Multiple	51	16.00	8.00	25.00
	Single	52	12.00	6.00	23.25
	Control	99	14.00	6.00	34.00
White blood cell count ($\times 10^9$/l)	Multiple	14	8.00	6.70	9.30
	Single	19	6.90	5.90	9.00
	Control	27	7.70	6.40	9.20
Systolic BP (mm/Hg)	Multiple	52	125.00	120.00	130.00
	Single	52	122.00	116.25	139.50
	Control	100	130.00	120.00	140.00
FER % of predicted	Multiple	52	81.90	81.14	82.49
	Single	52	81.99	80.73	82.89
	Control	101	81.63	79.97	82.35
PEFR actual (litre per minute)	Multiple	42	643.50	558.00	678.00
	Single	43	627.00	550.00	709.00
	Control	83	600.00	510.00	672.00
PEFR actual (litre per second)	Multiple	42	10.73	9.30	11.30
	Single	43	10.45	9.17	11.82
	Control	77	10.00	8.51	11.20
PEFR % of predicted	Multiple	42	109.44	98.43	117.38
	Single	43	109.46	98.17	118.27
	Control	77	107.54	95.86	117.63
PEFR standardised residual	Multiple	52	1.93	0.31	3.22
	Single	52	2.06	0.43	3.36
	Control	87	2.17	0.54	3.16

This simple analysis suggests that there are no significant differences between the three groups for the clinical information collated.

Not all data sets were complete because the clinical notes did not always contain all the information required. However where deficiencies did occur they were usually consistent within contracts and therefore evenly distributed between cases and both control groups.

4.2.3 Categorical Characteristics

Description of categorical characteristics for the 52 fully matched sets are shown in Tables 8-11 inclusive shown.

Data analysis determined the frequencies of the three groups with categorical characteristics in relation to previous compressed air exposure, previous DCS from compressed air work, occupation, and smoking. Occupation was balanced between the three groups by the matching. Comparisons were not made using chi-squared tests because these comparisons would not take into account the matching structure of the data. Inspection of the frequencies and percentages with previous types of exposures and smoking behaviour suggested no obvious differences between the multiple bend cases, single bend and no bend controls.

Table 8 shows the distribution of those who had previous pressure exposure from compressed air work amongst the cases and both control groups. Approximately 30% of men in all groups had previous experience of compressed air work.

Table 8
Previous Compressed Air Work

			Multiple, single and zero control			
			Multiple	**Single**	**Zero control**	**Total**
Previous CAW?	Yes	Count	19	16	31	66
		% within group	37.3%	30.8%	30.7%	32.4%
	No	Count	32	36	70	138
		% within group	62.7%	69.2%	69.3%	67.6%
	Total	Count	51	52	101	204
		% within group	100.0%	100.0%	100.0%	100.0%

Tables 9 and 10 show the distribution of DCS arising from previous compressed air work below and above 1.0 bar (gauge) working pressure for cases and both control groups.

Table 9
Previous DCS < 1.0 bar (gauge)

			Multiple, single and zero control			
			Multiple	**Single**	**Zero control**	**Total**
Previous DCI < 1.0 bar	Yes	Count	2	1		3
		% within group	11.1%	6.7%		4.8%
	No	Count	16	14	30	60
		% within group	88.9%	93.3%	100.0	95.2%
	Total	Count	18	15	30	63
		% within group	100.0%	100.0%	100.0%	100.0%

Table 10
Previous Decompression Sickness > 1.0 bar (gauge)

			Multiple, single and zero control			
			Multiple	**Single**	**Zero Control**	**Total**
Previous DCI > 1.0 bar	Yes	Count	4	2	2	8
		% within group	36.4%	16.%	6.9%	15.4%
	No	Count	7	10	27	44
		% within group	63.6%	83.3%	93.1%	84.6%
	Total	Count	11	12	29	52
		% within group	100.0%	100.0%	100.0%	100.0%

The zero bend controls appear to have over-representation from those who have previously worked in compressed air without suffering a bend when compared to multiple and single bend controls. This trend may be demonstrating a “healthy worker” or survivor effect but the numbers are very small.

4.2.4 Occupation

Cases were distributed by occupation as listed in Table 11. Single bend and zero bend controls were matched as per the study protocol.

From the perusal of various notes and records during this study it was obvious that the occupational “label” attached to a compressed air worker often changed between documents. For example, the title of “miner”, “labourer”, “locomotive driver” or even “pit boss” often occurred to the same man during the same contract.

In retrospect there were probably only three meaningful occupational classifications. These are:-

Shift, manual workers: This group consists of miner, labourer, locomotive driver, TBM driver and pit boss.

Non-shift, manual/skilled: This group consisted of welder, electrician or fitter. Sometimes these men worked shifts and sometimes they were non-shift.

Non-shift, non-manual: This group consisted of manager, engineer and supervisor.

On one contract, Ramsden Dock, all compressed air workers were described as “other manual/ skilled”. (These men were mainly undertaking manual work and were mostly recruited from a local diving company.)

Table 11

Distribution by Occupation in 52 cases

Occupation	Cases	% Within Cases
Miner	27	51.9
Labourer	7	13.5
Welder	1	1.9
Other Manual/Skilled	3	5.8
Engineer	1	1.9
Electrician	2	3.8
Loco Driver	4	7.7
TBM Driver	1	1.9
Fitter	5	9.6
Supervisor	1	1.9
Total	**52**	**100.0**

4.2.5 Smoking

A similar proportion of the cases, single bend and zero bend controls were current smokers (32/62.7%, 29/55.8% and 57/57.0% respectively) or non smokers.

4.2.6 DCS Incident Exposure Data

Each exposure preceding an episode of DCS was examined for some characteristics recognised as being provocative for DCS for cases and single bend controls. A 20% random sample from the zero bend control group was also examined from dates on which no DCS episodes had been reported.

Table 12 summarises the mean data for each group for:

> incident exposure pressure; incident exposure duration; days since previous exposure; number of consecutive daily exposures before the incident exposure; multiple exposures; compliance with maximum exposure limits (see page 31); change between incident exposure pressure and the mean exposure pressure from the previous 7 days/ 7 exposures; maximum pressure in previous 7 days; minimum pressure previous 7 days.

Table 12

DCS Incident Exposure Data

		DCS Incident Exp Data				Avg all cases	Single bends	Random sample of zero bends
		Bend 1	Bend 2	Bend 3	Bend 4			
Count		**52**	**52**	**8**	**1**	**113**	**52**	**20**
Exposure Pressure	Avg	22.1	23.2	24.4	29.7	24.9	23.5	20.7
Exposure Duration	Avg	373	367	380	242	340.5	374	251
Days Since Previous Exposure	Avg	1.7	1.3	1	2	1.5	1.3	1.4
No of Daily Consecutive Exposures	Avg	1.1	1.7	1.7	0	1.1	1.5	2.9
No of Repetitive Exposures in < 24 hrs	Avg	4.5	0.3	0.1	0	1.2	0.7	0.3
Max Exposure Limit compliance	Yes	88%	93%	50%	100%	82.8%	90%	63%
	No	12%	7%	50%	0%	17.3%	10%	37%
Change in Working Pressure 7 days/7 exp	Avg	2.5	1.4	3.8	0.29	2.0	1.7	2.18
Max Working Pressure over previous 7 days (psi)	Avg	22.5	23.5	24.6	29.7	25.1	23.6	21.7
Min Working Pressure over previous 7 days (psi)	Avg	17.2	20	19	29	21.3	18.9	16.8

The exposure duration is significantly shorter in the random sample of zero bends, otherwise there are no obvious differences in exposure characteristics which would be expected to precipitate bends. Since the cases and controls were matched for average shift duration and number of “significant exposures” overall this finding may be a result (or artefact) from the relatively small sample of zero bend exposures. The zero bend group also had lower compliance with maximum exposure limits. This result is also difficult to explain since, if anything, the converse would be expected.

Comparison of data in matched sets – comparison of all complete sets (not sets 44, 48 or 50) : Friedman’s Test

The next comparison attempted was a matched comparison of the multiple bend cases, the single bend controls and the no bend controls. Only the matched sets with complete matching and 4 subjects per set could be included. Analysis for 49 sets was made – 3 sets had to be dropped because each was missing one control. The analysis used was Friedman's test, which is a matched set extension of the non-parametric Wilcoxon test for matched pairs.

There is no easy way to make the test recognise that the controls should be treated as one group and the division of the two zero bend controls is artificial. This test in its current form ranks the measurements for a variable across a single matched set 1, 2, 3 and 4. It then investigates the distribution of the ranks for each group and compares them to see if they are sufficiently similar. If not then there must be a significant difference between the groups after taking account of the matching structure. A $p < 0.05$ value could therefore have been obtained because of a difference between the two zero bend control groups. This is clearly a major limitation of this type of statistical analysis. Because of the limitation to only complete groups and the fact that the controls cannot be recognised as one group of individuals this analysis was not as effective nor informative as was initially anticipated and therefore discounted from the final results.

Overall the results from Friedman's test were similar to that found in other (more appropriate) statistical analysis of the data. The clearest difference identified using Friedman's test was the much higher number of final exposures in the zero bend control groups in comparison to the multiple and single bend cases. This is shown in Table 13 below.

Table 13
Median values for the 4 groups and *p*-values for Friedman's tests: Final Exposures

Significant	Overall	Multiple bends	Single bends	No bend: Control 1	No bend: Control 2	Friedmans *p*
Final exp	72.00	63.00	66.00	73.00	89.00	<0.001

4.2.7 Analyses to compare the characteristics within the matched structure

Conditional logistic regression was used to compare the multiple bend cases with firstly the single bend controls and secondly the no bend controls. This was done only for the 52 matched sets where the three groups were completely matched.

Then conditional logistic regression was used to compare the multiple and single bends together with the no bend controls. Matched sets were included provided that there was at least one individual who had one or more episodes of bends on the relevant contract and at least one individual who had not had a bend on that contract or during the study period. Each set had at least one bend (either multiple or single) and at least one "no bend" control. There were 81 sets analysed. Some of these sets had a multiple bend, a single bend and two "no bend" controls (49). Some had a multiple bend, a single bend and one zero bend control (3). The remainder have a multiple bend (10) or single bend (19) and one or two zero bend controls. The 81 matched sets therefore comprised 49 + 3 + 10 + 19. The statistical package (STATA) compared the study characteristic (e.g. weight) of the cases or bends (however many there were) to the characteristic of the zero bend controls (however many there were).

Finally, a comparison was made between 130 pairs consisting of "any bend" and a matched single "zero bend control".

Initially only one characteristic was considered at a time. The results of these four comparisons are displayed in Table 14 (Odds ratios and *p*-values for conditional logistic regression comparisons) below. *p*-values are shown for all comparisons. No Bonferroni correction has been used despite the large number of tests. However if the Bonferroni correction were used, it would be expected that none of the results in Table 14 would achieve statistical significance taking into consideration that over 80 statistical tests were used. Odds ratios are displayed where the *p*-value was < 0.2. The reason for this was to look for consistency between the comparisons.

Table 14

Odds ratios and *p*-values for conditional logistic regression comparisons

	Multiple vs single bends		**Multiple vs no bend controls**		**Any bend vs controls**		**Any bend vs a single control**	
Sets	52		52		81		130 pairs	
	Odds ratio	***p***	**Odds ratio**	***p***	**Odds ratio**	***p***	**Odds ratio**	***p***
Previous CAW		0.53		0.29		0.46		0.50
Final number of Exposures	0.99*	0.001	0.98*	0.001	0.98*	<0.001	0.98*	<0.001
Height (metres)		0.85		0.40		0.25		0.20
Weight (kilograms)		0.76		0.33		0.81		0.89
BMI (kg/m^2)		0.70		0.51		0.62		0.62
PI (cm/kg$^{1/3}$)		0.73		0.76		0.42		0.45
Triceps skinfold (mm)		0.84		0.94		0.89		0.96
Biceps skinfold (mm)		0.83		0.47		0.55		0.69
Subscap skinfold (mm)		0.87	0.85	0.099	0.91	0.12	0.93	0.17
L Sacroil skinfold (mm)		0.54		0.67		0.39		0.53
R Sacroil skinfold (mm)		0.80		0.31	0.93	0.15		0.24
Calf skinfold(mm)		0.44		0.86		0.94		0.88
Total skinfold (mm)		0.69		0.37		0.31		0.42
% Bodyfat		0.23	0.91	0.19	0.89*	0.026	0.91	0.067
Age (years)		0.89	0.95*	0.027	0.96*	0.026	0.97*	0.041
Smoking		0.40		0.57		0.23		0.24
Alcohol (units/week)	1.02	0.18		0.57	0.99	0.15		0.22
Haemoglobin (g/dl)		0.94		0.21		0.26		0.47
MCV(fl)		0.43		0.55		0.81		0.99
MCH (pg)		0.28		0.63		0.76		0.88
PCV		0.81		0.40		0.30		0.45
WBC (x10^9/l)	1.37	0.20		0.51		0.60		0.85
Systolic BP (mm Hg)		0.45	0.98	0.11	0.98	0.078	0.99	0.11
Diastolic BP (mm Hg)		0.65		0.32	0.98	0.15	0.98	0.16
Lung function Measures	**Odds ratio**	***p***	**Odds ratio**	***p***	**Odds ratio**	***p***	**Odds ratio**	***p***
FEC1 actual		0.59		0.26	1.31	0.12	1.32	0.11
FEV1 predicted		0.95	2.37	0.066	1.96*	0.041	1.89*	0.05
FEV1 % of predicted		0.52		0.99		0.57		0.51
FEV1 stand. Residual		0.57		0.99		0.58		0.51
FER actual		0.68	1.04	0.17		0.64		0.55
FER predicted		0.89	1.36*	0.027	1.24*	0.026	1.21*	0.041
FER % of predicted		0.68		0.33		0.97		0.86
FER stand. Residual		0.69		0.35		0.99		0.88
FVC actual		0.49		0.74	1.23	0.18	1.22	0.19
FVC predicted		0.92	1.93	0.10	1.69	0.061	1.67	0.065
FVC % of predicted		0.33		0.41		0.70		0.71
FVC stand. Residual		0.43		0.45		0.70		0.70
PEFR l/min		0.55	1.004*	0.050	1.002	0.079	1.001	0.073
PEFR l/sec		0.55	1.29	0.055	1.12	0.13	1.11	0.12
PEFR predicted		0.95	2.43*	0.016	1.81*	0.013	1.75*	0.018
PEFR % of predicted		0.52		0.22		0.33		0.30
PEFR stand. Residual		0.49	1.19	0.19	1.10	0.14		0.12

It is clear from the table of results that there are very few significant *p*-values for the comparisons made in these matched analyses. There does not appear to be any one characteristic which differs significantly between multiple bend cases and single bend controls apart from the difference in the number of exposures. These comparisons had the smallest number of subjects since there were 52 pairs. However any large underlying real differences between multiple bend cases and single bend controls would have appeared with *p*-values approaching 0.05 even if the power for these comparisons was not sufficient for statistical significance. This suggests that it would be extremely difficult to identify individuals from those who had suffered a bend for the first time on a contract who were in danger of subsequent bends on the same contract.

For age and % body fat the odds ratios are less than one which suggests that older and fatter people are less likely to be cases. This is counter to the previous literature and clinical intuition. The fact that zero bend controls are older and have reduced DCS despite a greater number of pressure exposures suggests a possible “healthy worker effect”. It may be that an as yet undetermined human factor overwhelms the effects of age and body fat.

The interpretation of the lung function results is also not straightforward. At first sight there appear to be some significant differences in lung function results between cases and controls. Most of the differences are with predicted lung function, in particular predicted FEV1, predicted FER, predicted FVC (not significant) and PEFR. There is no obvious clinical reason why predicted lung function would have an influence on health or susceptibility to bends. Differences in the predicted lung function values between the multiple bend and no bend controls and also between any bend cases and no bend control groups must be due to differences in the factors which make up the predicted lung function values. Predicted lung function results are calculated using height and age so any variation between the groups in these values must be as a result of differences in height or age. Perusal of Tables 7 and 14 shows no apparent difference in height between the groups although there was in age (cases being younger). Thus the apparent difference between the groups in predicted lung function results can be attributed to the comparatively younger age of cases compared to control groups. This is supported by the fact that there is no difference in the percentage of predicted values or Standardised Residual Value (both of which adjust for age) achieved for FEV1, FER or FVC between cases and controls.

Some actual lung function values also appear to be statistically significant (PEFR) or close. There is a suggestion that larger PEFR increases the risk of being a case relative to controls. The odds ratios for this characteristic are not large. For every 1 l/minute increase in PEFR the chance of being a case increases by 0.4%. Therefore for a 10 l/minute increase in PEFR the chance of being a case increases by 4%. This is statistically significant when comparing the multiple bend cases to the controls but it is probably not clinically important. Since a large PEFR is usually considered to be a positive indicator of lung health this result is also clinically counter intuitive. This effect is probably unrelated to smoking habit since there was no difference between the groups of smokers and non-smokers. Once again differences in actual PEFR results between the groups could be explained by the cases being comparatively younger than the controls and therefore having larger PEFR. This is supported by the fact that the percentage of predicted values and the Standardised Residual Value (both of which adjust for age) for PEFR show no significant difference between case and control groups. Thus the apparent differences between cases and control groups for predicted and real lung function results can be considered to be spurious due to the influence of age differences between groups. Overall there is nothing to suggest that there is a real difference in lung function results (between cases and controls) once the difference in age has been taken into account.

Further conditional logistic regressions were completed to evaluate the candidate variables against each other. Only those which were identified as significant when included in the models on their own were considered in combination.

Age, final number of exposures, % body fat and measured PEFR were put in to conditional logistic regression models for multiple bend vs. no bend control with 52 matched sets and for any bend vs no bend control with 81 matched sets. Manual backwards selection methods were used to discard non-significant variables until only significant variables remained. The only remaining variable in the model for multiple bends vs controls was the final number of exposures. The odds ratio for this term suggested that for every additional exposure the odds of being a multiple bend case reduced by 2.3 % (95% confidence interval: 0.9 %, 3.7 %). The same variable was the only one remaining in the model comparing any bend with no bend controls in the 81 matched sets. The odds ratio suggested that for every additional exposure the odds of being in the bend group reduced by 1.6 % (0.7 %, 3.4 %).

These odds ratios for final exposure are not very far from 1, the odds ratio indicating no differences. The odds ratios with age are further from 1, but these results may well be due to the differences in the number of final exposures. The relationships found are counter intuitive and very unlikely to be real. As stated earlier these effects are likely to be an artefact of the matching between the cases and the controls to ensure that the controls had at least the same exposure as the case to which they were matched. (Although cases would have medical restriction from pressure exposure immediately following a bend, typically during the study period this would only be 24 hours. This ‘sickness absence’ would not therefore significantly reduce the final number of exposures of cases over the control groups over the duration of the contract.) This meant that the controls generally had a higher number of exposures than the relevant cases. In retrospect it may have been better to ensure that controls had exposures that were simply within a fixed percentage of those of the case to which they were matched rather than allowing controls with much greater exposure to be included.

However the sparseness of significant associations between case status and characteristics and the lack of findings in the intuitive direction suggest that there is no evidence from this study that characteristics can be used to identify those individuals at risk of suffering a bend. In particular the complete lack of differences between the characteristics of multiple bend and single bend subjects suggests that identifying individuals at risk of repeated bends will continue to be extremely difficult when using the features examined in the current clinical examinations for compressed air work in the UK.

4.2.8 Study Power

Using the formula from Machin *et al* 52 matched sets of 3 is equivalent to 69 pairs (as 60 sets was equivalent to 80 pairs – see page 31).

69 pairs (52 sets) will have 73% power to detect a difference in means of 5 years, assuming a standard deviation of differences of 15.8 years, using a paired t-test with a 0.050 two-sided significance level. To retain 80% power with 52 sets the difference that could be detected increases to 5.4 years. 69 pairs (52 sets) will have 73% power to detect a difference in means of 2 kg/m^2, assuming a standard deviation of differences of 6.3 kg/m^2, using a paired t-test with a 0.050 two-sided significance level. To retain 80% power with 69 pairs (52 sets) the difference that could be detected increases to 2.2 kg/m^2.

Analysis was also performed for 130 pairs as well as the matched sets above. This power calculation is more powerful but was not given priority over those for the matched sets because the study was designed around matched sets.

A sample size of 130 will have 80% power to detect a difference in means of 3.9 years, assuming a standard deviation of differences of 15.8 years, using a paired t-test with a 0.050 two-sided significance level. A sample size of 130 will have 80% power to detect a difference in means of 1.6 kg/m^2, assuming a standard deviation of differences of 6.3 kg/m^2, using a paired t-test with a 0.050 two-sided significance level.

Therefore it is likely that the study has sufficient power available to adjust for confounders with 52 matched sets. Overall the Results were consistent across all sets of data analysis and it is unlikely a significant difference between cases and controls would have been missed in the study had one existed.

5 DISCUSSION

5.1 MAIN FINDINGS

Thirteen of 22 contracts, representing all compressed air workers in the HSE Decompression Database during the study period, produced workers with multiple episodes of DCS (DCS) requiring therapeutic recompression. This group of men represented only 4% of the total workforce studied (80/2,160) yet suffered half of all DCS episodes that were caused by compressed air work. This was despite the overall bends rate or incidence being relatively low (0.34% or approximately 3 bends per 1,000 exposures) during this period. Interestingly this finding (i.e. 4% of the workforce suffering 50% of all bends) is identical to that reported by Golding et al *(7)* during construction of the Kent side of the first Dartford Crossing which commenced in April 1957. At that time 1,021 compressed air workers using the approved air decompression schedule (from the Work in Compressed Air Special Regulations 1958 or 'The 1958 Table') suffered an average bends rate of 0.98%. The compressed air work was conducted over a 68 week period at pressures up to 28 p.s.i.g. {approximately 2.0 bar gauge/301kPa absolute} with over 71,000 exposures most of which were 8 hours or more. These facts and the overall distribution of DCS shown in the 1986-2000 HSE Decompression Database compressed air workforce strongly supports the hypothesis that individual susceptibility to DCS exists and that it is a potent influence on the overall bends rate. This experience also foretells that even if improved decompression techniques or procedures are introduced (such as oxygen or mixed gas decompression) into compressed air work that substantially reduce the overall bends rate that some individuals will still continue to suffer more than their share of the bends (and of course any associated morbidity).

The contract characteristics in this study that were associated with multiple episodes of DCS in some workers were as one would expect of a pressure related illness, i.e. the size of the compressed air workforce and the level of decompression stress (higher working pressures, longer shifts and/or more "significant exposures").

Unfortunately no individual characteristics or human factors were identified in this study that could be associated with those workers apparently most susceptible to episodes of DCS requiring therapeutic recompression. In particular, there were no differences for the "classical" risk factors (age and obesity) or any other clinical parameter assessed by the initial or pre-employment compressed air medical examination between those with multiple, single or zero bends when strictly matched by contract, occupation and pressure exposure. It is likely from the design of this study and the various statistical analyses utilised that had clinically significant differences existed between the cases and the two control groups then they would have been detected. Sadly, therefore another conclusion of this study repeats that of Golding and his colleagues in 1960. "*An obvious possibility for lessening the incidence of the disease (DCS) is the elimination of susceptible subjects. Unfortunately at present there exists no means of identifying such men, save by seeing whether they get bends.*"

The finding that some zero bend controls did more pressure exposures overall and were older and fatter probably indicates a "survivor" or "healthy worker" effect. Thus some men are "bend proof" or resistant to overt symptoms or signs of DCS and continue to work in compressed air with apparent immunity from health effects. Conversely, it has been recognised, and generally accepted in the UK for some time, that workers tend to leave the industry shortly after their first to third episode of treated DCS. *(63).*

In view of the negative study findings it is difficult to formulate a credible evidence based policy for the assessment of fitness to return to work of compressed air workers following a single episode of DCS requiring therapeutic recompression. An empirical blanket ban on return to compressed air work following a single bend without further means of identifying susceptible subjects could be unnecessarily restrictive to the individual compressed air worker and probably lead to a serious reduction in the reporting of suspected DCS symptoms. Nevertheless it has to be considered that the best predictor of future bends is a history of DCS and if present this is therefore a most important risk factor, about which both the employer and individual compressed air worker should be carefully counselled.

The study findings could make it seem very important to initiate further, probably more complex or invasive, clinical research to try to identify what individual characteristics or human factors are associated with susceptibility to DCS in compressed air workers. However, there is an argument against such studies on ethical grounds because of infringement of productivity or individual comfort or because of the possible iatrogenic consequences of invasive procedures (e.g. investigation for patent foramen ovale or generating anxiety in subjects from test results) or cost.

Before such studies could be justifiably recommended or initiated, it is necessary to consider carefully the magnitude and nature of the health effects, both short and long-term, caused by or associated with repetitive episodes of DCS. Thus if severe, long-term health effects from repetitive DCS such as functional neurological impairment (including cognitive dysfunction) or dysbaric osteonecrosis occurred that were shown to adversely affect quality of life, employment or longevity, then identifying the human factors related to individual susceptibility to DCS would be a priority consideration. Indeed, if severe health effects were demonstrated the place of compressed air work in civil engineering could rightly come into question since this would be essential if the health of the compressed air worker were to be preserved. In such circumstances an evidence based policy for fitness to return to work in compressed air workers following a single bend would also appear to be very important.

Conversely, should the health effects from repetitive DCS be determined as acute or short-term only and limited to minor symptoms such as “pain only” or “the niggles” with no additional or cumulative delayed morbidity demonstrated, then the situation for the compressed air worker would not be so serious. This scenario would weaken the case for potentially complicated and costly further investigations into human factors associated with or causing individual susceptibility to DCS (particularly so since oxygen decompression is now mandatory in the UK above 1.0 bar (gauge) pressure for compressed air work and this is expected to substantially reduce the overall incidence of DCS and therefore the number of workers suffering multiple bends).

Based on the current literature, there are sufficient concerns about delayed or long-term health effects in divers and compressed air workers from DCS to justify further research in this field. A study could be designed to determine the short-term and long-term health effects in those compressed air workers who had suffered multiple episodes of DCS. This would facilitate a more complete assessment of the health effects that multiple DCS episodes produce in the minority of the compressed air workforce affected. Although such a study would not be easy to organise or conduct, the results would help formulate a strategy to manage the problem of repetitive DCS correctly without either dismissing it or initiating inappropriate further investigations or preventative measures. Furthermore, such a study would be likely to produce at least some findings that were relevant to the general compressed air and diving workforces and add to the knowledge base of the illness of DCS.

5.2 PROBLEMS ENCOUNTERED

The pressure exposure data as originally reported to HSE was of mixed quality in terms of presentation and format though generally accurate and complete. Considerable delay (several months) therefore occurred while the data was processed by the HSE and entered on to a computer database. In general the most time consuming data processing was required from those compressed air contracts in the earlier years of the study period but the training, experience and qualifications of the Lock Attendants (or person compiling the compressed air records) was clearly an important factor too.

One study contract, Fylde, had incomplete pressure and clinical data and was therefore omitted from further analysis.

Additional significant delays occurred processing the pressure and manlist data contained in the HSE Decompression Database as received from the Health and Safety Executive into a final format that was suitable for analysis.

Further difficulties and delays occurred in sourcing and retrieving the clinical notes for individual contracts from the different Contract Medical Advisers. For two study contracts, Lowestoft (3 cases) and Royal Docks Donelon (7 cases) no clinical records or notes were available and these were omitted from further analysis. Although clinical data was available for ten study contracts, for one of them (North Woolwich with 8 cases) the clinical notes were not accessible within a timescale that permitted further inclusion in the study.

On one contract (LWRM) review of the clinical notes resulted in the following changes in category:-

3 zero bend controls → became “cases”
3 cases → became zero bend controls
1 single bend control → became zero bend control
1 zero bend control → became single bend control

In general however the clinical notes/records corresponded well with the DCS reports contained in the HSE Decompression Database.

5.3 LIMITATIONS OF THE STUDY

The definition of DCS in this study is of necessity an empirical or pragmatic one due to the current lack of an accepted, objective diagnostic method or test. Reporting bias could therefore confound this study in a number of ways at either the level of the contract or individual compressed air worker as detailed below.

Individual factors in the compressed air worker that could influence the reporting of symptoms of DCS but which are not linked to the severity of the illness itself could confound this study. Thus a man with a low pain threshold or certain psychological factors could result in reporting bias, i.e. one man’s “niggle” is another man’s bend. It is not possible in a retrospective study to control for this and little is reported in the literature that indicates what effect, if any, this might have on the study results.

Within a particular compressed air contract, the quality and amount of information and training provided to the workforce and the established “reporting culture” will influence the compressed air worker recognising and reporting possible DCS symptoms. The availability, competence and willingness of the Medical Lock Attendants to treat, record or report DCS will also influence reporting rates. These organisational factors were not examined but were mitigated as far as possible in this study by both cases and controls being selected from the same contract and matched by occupation. This matching would also help reduce bias from factors in the working environment or individual pressure exposures that may have predisposed an individual to DCS.

A further limitation in this study was the relatively small number of cases and controls. This was unavoidable because the HSE Decompression Database represents all the data that was available to be included in the study. This was mitigated to some extent by the design of the study and the various types of statistical analyses that were undertaken.

Although this study determines the distribution of repetitive DCS in the HSE Decompression Database during the study period, it does not define other than in a very simplistic and empirical way, the clinical severity of the health effects. Nor could it take into account any delayed or long-term sequelae from the bends which are likely to be important in terms of overall morbidity.

Finally, the HSE Decompression Database does not include ‘low pressure’ compressed air contracts for the period 1986-1994 and so may be considered unrepresentative of all compressed air work during the study period. However, ‘low pressure’ contracts i.e. below 1.0 bar gauge/ 201 kPa absolute produce few cases of DCS and would be unlikely to produce any cases of repetitive DCS. (73) Whilst the omission of some low pressure compressed air contracts may have a (minor) influence on the overall proportion of DCS attributable to cases during the study period it will not affect the findings regarding human factors and individual susceptibility to DCS.

6. CONCLUSIONS

(1) A small proportion (4%) of the compressed air workforce in the HSE Decompression Database during the period 1986-2000 suffered half the episodes of DCS requiring therapeutic recompression. This is an identical proportion to that reported by Golding *et al* over 40 years ago when the bends rate was considerably higher. These findings, and other reports in the literature, strongly suggest that individual susceptibility to DCS exists and that it is operationally significant.

(2) Some compressed air contracts produce more men with multiple bends than others. Those contracts having a larger compressed air workforce, higher working pressures and longer exposures {greater than 6 hours at pressures below 1.5 bar gauge/ 251 kPa absolute or greater than 4 hours at pressures over 1.5 bar gauge/ 251 kPa absolute} were more likely to produce multiple bends in some workers. The longer the duration of the compressed air project, the greater the opportunity for repetitive DCS in some workers to occur. This was reflected in the mean duration of compressed air exposure on Contracts producing repetitive DCS being 1,697,101 minutes, which was more than twice the mean duration of exposure for the non-study Contracts at 652,923 minutes.

(3) No significant clinical differences were found between those with multiple bends (cases), single bends or zero bends when analysing various clinical or human factors assessed during the initial or pre-employment compressed air medical examination.

This finding which was consistent using a variety of appropriate statistical tests examining categorical and non-categorical personal characteristics in a relatively large study population is unlikely to be due to chance.

This study therefore suggests that 'bend prone' workers do exist but that the current pre-employment compressed air medical history and examination will not reveal them.

If true this is an important negative finding and is counter to many of the risk factors quoted in the literature associated with compressed air workers. Such reports are often historical or anecdotal however and there has been no similar case control study in compressed air workers yet published to permit direct comparison of these findings.

(4) It is not possible, on the basis of the study results alone, to formulate a credible evidence based policy for the assessment of fitness to return to work of compressed air workers following a single episode of DCS requiring therapeutic recompression. There is some evidence however to suggest that a survivor or “healthy worker effect” is operating in the compressed air workforce with regard to susceptibility to DCS – presumably related to factors other than those examined in this study. This could be the subject of further research.

(5) Additional information is required to help determine a strategy for further appropriate investigation or preventative measures in relation to repetitive DCS in compressed air work. Firstly it will be necessary to describe and quantify the short-term and long-term health effects associated with, or caused by, repetitive DCS. This will enable repetitive DCS to be placed in perspective with regard to the morbidity resulting to the compressed air workforce. Only then can appropriate further research studies and preventative measures be considered and implemented where necessary without fear

of either dismissing or over-reacting to the problem. Such research (i.e. on the short and long-term morbidity from repetitive DCS) would also be likely to produce results that were of more general importance.

(6) If individual or human factors causing, or associated with, susceptibility to DCS could be identified, then a significant reduction in episodes of DCS resulting from compressed air work could occur. Until such factors are identified and appropriate preventative measures implemented, it is probable that a few workers will continue to suffer a significant proportion of the overall bends. This is likely to apply even if the bends rate is substantially decreased by, for example, the routine application of oxygen decompression in the UK.

7. RECOMMENDATIONS

This study has not identified individual characteristics or human factors predisposing to repetitive DCS in compressed air workers. Furthermore, the findings indicate that it is not possible to differentiate, on the basis of the current initial or pre-employment compressed air medical examination, between those who will suffer bends and those who will not.

The fact that, despite different working conditions and bends incidence, the proportion of compressed air workers suffering from repetitive DCS is the same from 40 years ago strongly supports that individual susceptibility exists.

Therefore, it is recommended that two distinctly separate approaches should be taken to reduce repetitive DCS occurring in the compressed air workforce.

(a) Suppress the overall bend rate further. This is likely to happen due to the introduction of oxygen and mixed gas decompression into compressed air work.

(b) Consider further how to identify individual factors associated with or causing DCS. This study suggests that different methodology or clinical examination will be required.

Based on the findings of this study and on information from the literature, the following are suggested:-

(1) Further research to determine the nature and magnitude of short and long-term health effects arising from repetitive DCS in compressed air workers should be initiated.

(2) An appropriate evidence based strategy to prevent and control repetitive DCS in compressed air workers should be developed based on the results of the above investigation(s).

(3) The HSE Decompression Database recording episodes of DCS and pressure exposure data from all compressed air contracts is a valuable research tool and should be maintained.

(4) Serious consideration should be given to establishing a similar central register in the UK recording suspected delayed or chronic health effects in former (or current) compressed air workers. This should specifically include dysbaric osteonecrosis and, possibly suspected neurological or cognitive impairment or where concerns exist, about late health effects from or associated with episodes of acute decompression sickness.

APPENDIX A UNITS OF PRESSURE

A knowledge of the physical laws and principles related to pressure is essential before one can understand most of the medical problems encountered in compressed air work.

Atmospheric (or barometric) pressure is the pressure exerted by the mass of atmosphere above us. This pressure decreases as one moves upward through the atmosphere and increases as one descends down into a mine or into the sea. However because water is much heavier than air, the pressure changes experienced by a diver are much greater than those encountered by miners or pilots.

Pressure is measured in a variety of units from one of two reference points. It can be expressed with respect to a vacuum (i.e. zero pressure) and this is referred to as absolute pressure. The second method measures pressure above the local or ambient pressure and these are called ‘gauge pressures’ since it would be what an observer would read off a pressure monitor within the given environment.

Thus at sea level the absolute pressure is 1 atmosphere (commonly referred to as one atmosphere absolute, or 1 ATA) and the gauge pressure is 0. With compression to one bar over atmospheric pressure in a tunnel lock the **absolute pressure** would therefore be 2.0 bar and the **gauge pressure** would be 1.0 bar i.e. 2 bar absolute equals 1 bar gauge.

The diving and compressed air industries and associated disciplines are multidisclipinary in nature involving facets of engineering, science and medicine. This is reflected in a wide variety of units to denote pressure. These include absolute and gauge atmospheres, metres of sea water, feet of sea water, pounds per square inch, bars and several other units. Table 1 contains conversions for the more commonly used units.

Table 1
Pressure Conversion Factors
(Commonly used approximations shown in brackets)

1 ATMOSPHERE	=	10.07 (10) metres sea water
	=	33.05 (33) feet sea water
	=	33.93 (34) feet fresh water
	=	1.033 kg/cm^2
	=	14.696 (14.7) lbs/in^2 or pounds square inch (psi)
	=	1.013 bars
	=	101 kilopascals, kPa
	=	760 millimetres mercury, mm Hg
	=	760 Torr

The situation is further complicated in that the diving industry will typically use pressure in atmospheres absolute whilst tunnelling and civil engineering projects tend to use bar in gauge pressure. For consistency of approach in this paper, all units of pressure will initially be given in the author’s preferred unit followed by conversion to the unit of bar gauge pressure and kilopascals absolute using the conversion factors listed in Table 1. This is because the bar is the unit of pressure most widely used in compressed air and civil engineering applications in the UK and the HSE decompression tables are listed in bar gauge. Kilopascals (absolute) is included as the preferred pressure unit of the International Scientific community.

The unit of bar gauge pressure equates to 100 kPa. For simplicity and consistency, where absolute pressure is quoted it is assumed that atmospheric pressure is 101 kilopascals (this may very depending on altitude).

REFERENCES

(1) Health and Safety Executive. Oxygen Decompression Seminar; 1999 Mar 05; London.

(2) Flook V. Decompression risk factors in compressed air tunnelling: Options for health risk reduction. HSE Contract Research Report 201/1998. HMSO; 1998.

(3) Kindwall EP. Compressed air tunnelling and caisson work decompression procedures: development, problems and solutions. Journal of Undersea and Hyperbaric Medicine 1997;24(4):337-45.

(4) Hempleman HV. History of Decompression Procedures. In: Bennett PB, Elliott DH, editors. The Physiology and Medicine of Diving. 4th ed. London: Saunders; 1993. p. 342-75.

(5) Historical and Physiological concepts of decompression. In: Edmonds C, Lowry C, Pennefather J, editors. Diving and Subaquatic Medicine. 3rd ed. Oxford: Butterworth-Heinemann; 1992. p. 140-58.

(6) Edmonds C, Lowry C, Pennefather J, editors. Diving and Subaquatic Medicine. 3rd ed. Sydney: Butterwork and Heinemann; 1992. p. 159-78.

(7) Golding FC, Griffiths P, Hempleman HV, Patton WDM, Walder DN. DCS during construction of the Dartford Tunnel. British Journal of Industrial Medicine 1960; 17:167-80.

(8) Walder DN. Bone Necrosis. In: Jardine FM, McCallum RI, editors. Engineering and Health in Compressed Air Work. 1st ed. London: E and FN Spon; 1994. p. 16-28.

(9) Elliott DH. Raised Barometric Pressure. In: Adams PH, Baxter PJ, Lee WR, Raffle PAB, editors. Hunters Diseases of Occupations. 8th ed. London: Edward Arnold; 1994.

(10) King J. Discussion Session: Challenges for the future. In: Jardine FM, McCallum RI, editors. Engineering and Health in Compressed Air Work. 1st ed. London: E and FN Spon; 1994. p.52.

(11) King JD, Contract Medical Adviser [personal communication]. Meeting of Compressed Air Working Group. Institute of Civil Engineers; 1999 Nov.

(12) Ridley T, Hyperbaric and Safety Consultant [personal communication]. Meeting of Compressed Air Working Group. Institute of Civil Engineers; 1999 Nov.

(13) Paton WDM, Walder DN. Compressed air illness – an investigation during the construction of the Tyne Pedestrian Tunnel 1948-1950. Special Report No. 281. London: Medical Research Council; 1954.

(14) Jardine FM, editor. Results of the Analysis of compressed air records in the Decompression Sickness Central Registry. Project Report 6. London: CIRIA; 1996.

(15) Francis TJR, Smith DJ, editors. Describing Decompression Illness. Proceedings of 42nd Workshop of Undersea and Hyperbaric Medical Society 79 (Deco); 1991 May 15; Bethesda, Maryland. Bethesda (MD): UHMS; 1991.

(16) Evans A. Section 2: Final Report April 1991. In: Results of the Analysis of compressed air records in the Decompression Sickness Central Registry, Project Report 6. London: CIRIA; 1992. p. 32-4.

(17) Lamont D. [personal communication]. CTRL Health Research Group Meeting. CTRL House. London; 2002 Apr 09.

(18) Encyclopaedia Britannica. Micropaedia. Volume 10. 15th ed. London: Encyclopaedia Britannica; 2002. Smeaton, John; p. 889.

(19) Kindwall EP. A Short History of Decompression Sickness. In: Bove AC, Davis JC, editors. Diving Medicine. Philadelphia: WB Saunders; 1990. p. 1-11.

(20) Moir EW. Tunnelling by Compressed air. Journal of the Royal Society of Arts 1895-96;44:567-83.

(21) Bull de la Soc. Industr. d'Angers et du Depart de Maine-et-Loire. Rapport sur les puits à air comprimé de M. Triger. Mémoir sur un appareil à air comprime pour le percement des puits de mine, et autres travaux sous les eaux et dans/les sables submergés. 1845.

(22) Bennett PB, Elliott DH. The Physiology and Medicine of Diving. 4th ed. London: Saunders; 1993.

(23) Elliott DH. Nature of Decompression Illness. In: Jardine FM, McCallum RI, Spon FN, editors. Engineering and Health in Compressed Air Work. 1st ed. London: E and FN Spon; 1994.

(24) Bert P. La pression barométrique. Paris: Masson; 1878.

(25) Travers MW. The Experimental Study of Gases. New York: MacMillan Company; 1901.

(26) Health and Safety Executive. A guide to the Work in Compressed Air Regulations 1996. London: HMSO; 1996.

(27) Health and Safety Executive. A Guide to the Work in Compressed Air Regulations 1996 Guidance on Regulations (Guidance on Oxygen Decompression and the use of breathing mixtures other than compressed natural air in the working chamber). London: HMSO; 2001.

(28) Smith A. St Louis Med & Surg J. 1870(3). Quoted in: Hill L. Caisson sickness and the physiology of work in compressed air. London: Edward Hill; 1912. p. 105.

(29) Fryer DI. Sub-atmospheric DCS in man. Slough, UK: Technivision Services; 1969.

(30) Triger M. Lettre à M. Arago. Comptes rendus de l'Academie de Sciences 1845;20:445-9.

(31) Blavier M. Rapport sur le procédé suivi, a Douchy, pour traverser des nappes dêau considerables. Ann des Mines 1846;9(4^{e} ser):349-64.

(32) Pol B, Watelle TJJ. Mémoir sur les effets de la compression de l'air appliquée au creusement de puits à houille. Ann. D'Hygiene Publique et de Médecine Légale (Paris) 1854;1:241-79.

(33) Elliott DH, Kindwall EP. Manifestations of the Decompression Disorders. In: Bennett PB, Elliott DJ, editors. The Physiology and Medicine of Diving. 3rd ed. London: Ballière Tindall; 1982. p. 461-72.

(34) Smith DJ *et al*. Concordance: A problem with the current classification of Diving Disorders. Undersea Biomed. Res. 1992;19(Suppl):40.

(35) Gorman DF *et al*. Neurological Sequelae of Decompression Sickness: A Clinical Report. In: Bachrach AJ, Bove AA, Greenbaum LJ, editors. Underwater and Hyperbaric Physiology. 9th ed. Bethesda (MD): Undersea & Hyperbaric Medical Society; 1987. p. 993-8.

(36) McCallum RI. A Study of the Mortality of Professional Divers: A Preliminary Report. In: Elliott DH, Halsey MJ, Hope A, Lund T, Wiig H, editors. Long Term Health Effects in Diving. Bergen, Norway: Norwegian Underwater Technology of Bergen; 1994.

(37) Balldin UI and Lundgren CE. The effect of immersion on inert gas elimination. Acta Physiological (scanned) 1969;330(Suppl):83.

(38) Snell EH. Compressed Air Illness or so called Caisson Disease. London: HK Lewis; 1896. p. 1-61.

(39) Jaminet A. Physical effects of compressed air and of the causes of pathological symptoms produced in man by increased atmospheric pressure employed for the sinking of piers in the construction of the Illinois and St Louis bridge over the Mississippi River at St Louis Missouri. St Louis (MO): 1871. Quoted in: Snell EH. Compressed Air Illness or so called Caisson Disease. London: HK Lewis; 1896. p. 35.

(40) How J, Vijayan A, Wong TM. DCS in the Singapore Mass Rapid Transit Project. Singapore Med. J. 1990;31:529-38.

(41) McCallum RI, editor. Decompression of Compressed Air Workers in Civil Engineering. Proceedings of an International Working Party; 1965 Oct; Oxford. London: Oriel Press; 1967.

(42) Lam TH, Tse E, Yau KP. Pre-employment medical examinations in a compressed air tunnelling project in Hong Kong. Undersea Biomedical Research 1985 June;12(2):205-13.

(43) Lo WK, O'Kelly FJ. Health experience of compressed air workers during construction of the Mass Transit Railway in Hong Kong. J. Soc. Occup. Med. 1987;37:48-51.

(44) Lam TH, Yau KP. Manifestations and treatment of 793 cases of DCS in a compressed air tunnelling project in Hong Kong. Undersea Biomedical Research 1988;15(5):377-88.

(45) Construction Industry Research and Information Association. Medical Code of Practice for Work in Compressed Air. 3rd ed. CIRIA 1982; 4.

(46) Von Schrötter H. Der Sauersstoff in der Prophylaxe und Therapie der Luftdruck – Erkrankungen. Berlin: Hirschwald; 1906. p. 8.

(47) Institution of Civil Engineers. Jacobs on the Hudson River Tunnels. Minutes of Proceedings of The Institution of Civil Engineers Sep 1910; London: The Institution; 1910; 181:207-8.

(48) Hill L. Caisson sickness and the physiology of work in compressed air. London: Edward Arnold; 1912. p. 255.

(49) Boycott AE, Catto AY, Damant GCC, Haldane JS. Admiralty Committee on Deep Water Diving. Parliamentary paper CN 1549. London: HMSO; 1907.

(50) Behnke AR. The application of measurements of nitrogen elimination to the problem of decompressing divers. US Naval Medical Bulletin 1937; 35:219-40.

(51) Walder DM. Effectiveness of the British Decompression Table. In: Decompression of Compressed Air Workers and Civil Engineering. London: Oriel Press; 1967. p.65.

(52) Factories Inspectorate. The Work in Compressed Air Special Regulations 1958. London: HMSO; 1957.

(53) Hempleman HV. Investigation into the diving tables. Report 3. RN Personnel Research Committee, UPS 131. London: Medical Research Council; 1952.

(54) Hempleman HV. British Decompression Theory. In: Bennett PB, Elliott DH, editors. The Physiology and Medicine of Diving and Compressed Air Work. 1st ed. London: Baillière Tindall Cassell; 1969. p. 291-318.

(55) Paton WDM, Walder DN. Compressed Air Illness – An investigation during the Construction of the Tyne Tunnel 1948-50. Spec Report Ser. No. 281. London: HMSO; 1954.

(56) McCallum RI. Decompression Sickness: A Review. British Journal of Industrial Medicine 1968;25(4).

(57) Kindwall EP. Optimum Schedules for Caisson Decompression. In: Jardine FM, McCallum RI, editors. Engineering and Health in Compressed Air Work. Proceedings of the International Conference; 1992 Sep; Oxford. London: E and FN Spon; 1994.

(58) Ribeiro IJ. Oxygen decompression for tunnel workers in Brazil – The Sao Paulo Subway construction experience. In: Jardine FM, McCallum RI, editors. Engineering and Health in Compressed Air Work. 1st ed. London: E and FN Spon; 1994.

(59) Behnke AR, Jones Jr JP. Preliminary BART Tunnel Results. In Beckman EL and Elliott DH, editors. Dysbarism-Related Osteonecrosis. Washington (DC): US Dept. of Health, Education and Welfare; 1974.

(60) Catsaras (1890). Quoted in: Grey JS. Constitutional factors affecting susceptibility to DCS. In: Fulton J, editor. Decompression Sickness. London and Philadelphia: Saunders; 1951.

(61) Paton WDM. Physiological Basis of Decompression Tables in Civil Engineering. In: McCallum RI, editor. Decompression of Compressed Air Workers in Civil Engineering. Proceedings of an

International Working Party; 1965 Oct; Oxford. London: Oriel Press; 1967.

(62) Construction Industry Research and Information Association. Medical Code of Practice for Work in Compressed Air. 1st ed. CIRIA 1973 Feb.

(63) Construction Industry Research and Information Association. Medical Code of Practice for Work in Compressed Air. 2nd ed. CIRIA 1975 Dec.

(64) Kindwall EP. Medical aspects of commercial diving and compressed air work. In: Zenz C, editor. Occupational Medicine: Principles and practical applications. Chicago: Year book medical; 1975. p. 361-421.

(65) Gray JS. Constitutional factors affecting susceptibility to DCS. In: Fulton JF, editor. Decompression Sickness. Philadelphia: WB Saunders; 1951. p. 182-91.

(66) Rubenstein CJ. Quoted in: Role of decompression conditioning in the incidence of DCS in deep diving. US Navy experimental diving unit report Bethesda (MD): United States Navy; 1968.

(67) Walder DN. Adaptation to DCS in caisson work. Proceedings of the Third International Biometerology Congress; 1968; Oxford. London; 1968 p. 350-9.

(68) Walder DN. The prevention of DCS. In: Bennett PB, Elliott DH, editors. Physiology and Medicine of Diving and Compressed air work. 2nd ed. London: Bailliére Tindall; 1975. p. 456-70.

(69) Hempleman HV. Decompression procedures for deep, open sea operations. In: Lambertsen CJ, editor. Proc. Third symp. Underwater Physiology. Baltimore: Williams and Wilkins; 1967.

(70) Elliott DH. Some factors in the evaluation of oxyhelium decompression schedules. Aerospace Med. 1969;40:129-32.

(71) Walder DN. Prevention of DCS in compressed air workers. In: Bennett PB, Elliott DH, editors. The Physiology and Medicine of Diving and Compressed Air Work. 1st ed. London: Bailliére Tindall and Cassell; 1969. p. 437-50.

(72) Fraser WD, McCulloch D, Stanga D, Ward CA, Yee D. Complement activation involvement in DCS of rabbits. Undersea Biomed Res 1990;17:51-66.

(73) Jardine FM, editor. Results of the analysis of compressed air records in the Decompression Sickness Central Registry. In: Construction Industry Research and Information Association. Project Number 6. London: CIRIA; 1992.

(74) Lamont Donald, Specialist Inspector for Tunnelling Operations HSE [personal communication]. HSE Decompression Database 1986-2000.

(75) McKiver NKI, Medical Director of Hyperbaric Services 1976-2000 [unpublished personal communication]. North Sea Medical Centre. 2000 Nov.

(76) Elliott DH, Kindwall EP. Manifestations of the Decompression Disorders. In: Bennett PB, Elliott DH, editors. Physiology and Medicine of Diving. 3rd ed. London: WB Saunders; 1982. p. 461-72.

(77) Walder DN. Aetiological Factors in Decompression Sickness. In: McCallum RI, editor. Decompression of Compressed Air Workers in Civil Engineering. Proceedings of an International Working Party; 1965 Oct; Oxford. London: Oriel Press; 1967.

(78) Hills BA. Decompression Sickness, Volume 1: The Biophysical Basis of Prevention and Treatment. New York (NY): John Wiley & Sons; 1977. p. 42.

(79) Smith AH. The Effects of High Atmospheric Pressure including the Caisson Disease. Prize Essay Alumn. Ass. Coll. Physic. Surg. N.Y. Brooklyn (NY): Eagle Book & Job Printing Dept; 1873. p. 43.

(80) Smith AH. The Physiological pathological and therapeutic effects of compressed air. Detroit (MI): 1886.

(81) Vernon HM. The Solubility of air in fats and its relation to caisson disease. Lancet 1907;(ii):691-3.

(82) Heller R, Mager W, Von Schrötter H. Luftdruck-erkrankungen mit Besonderer Berücksichtigung der Sogenannten Caissonkrankheit. Vienna, Austria: Wien Holder; 1900. p.1230.

(83) Boycott AE, Damant GCC. Caisson Disease: influence of fatness. J. Hyg. London 1908;8:445-6.

(84) Gersh I. Gas bubbles in bone and associated structure, lung and spleen of guinea pigs decompressed rapidly from high pressure atmospheres. J. Cell. Comp. Physiol. 1945;26:101-17.

(85) Gowdey CW, Philip RB. Experimental analysis of the relation between body fat and susceptibility to DCS. Aerospace Med. 1964;35:351-6.

(86) Gowdey CW, Philip RB. Etiology and treatment of experimental DCS with special reference to body lipids. Milit Med. 1965;130:648-52.

(87) How J, Vijayan A, Wong TM. Medical Aspects of Compressed Tunnelling – The Singapore Experience. In Jardine FM, McCallum RI, editors. Engineering and Health in Compressed Air Work. 1st ed. London: E and FN Spon; 1994.

(88) Dembert ML. Individual factors affecting DCS. In: Vann RD, editor. The Physiological Basis of Decompression: Proc 38th UHMS Workshop., UHMS Pub. 75 (Phys); 1989 Jan 1; Bethesda, Maryland. Bethesda (MD): Undersea and Hyperbaric Medical Society; 1989.

(89) Lam TH, Yau, KP. Analysis of some individual risk factors for DCS in Hong Kong. Undersea Biomedical Res. 1989;16(4)283-92.

(90) Wise D. Constitutional Factors in Decompression Sickess. Panama City (FL): Navy Experimental Diving Unit (US); 1963. Report No. 2-63.

(91) Curley MD, Robin GJ, Thalmann ED. Percent Body Fat and human DCS. Undersea Biomed. Res. 1989;16(Suppl)Abstract 33.

(92) Thalmann ED, Vann RD. Decompression Physiology and Practice. In: Bennett PB., Elliott DH, editors. Physiology and Medicine of Diving. 4th ed. London: Saunders; 1993. p. 376-432

(93) Walder DN. Aetiological Factors in Decompresson Sickness. In: McCallum RI, editor. Decompression of Compressed Air Workers in Civil Engineering. Proceedings of an International Working Party; 1965 Oct; Oxford. London: Oriel Press; 1967

(94) Fletcher RF. The measurement of total body fat with skinfold calipers. Clin. Sci. 1962;22:333-46.

(95) MRC. DCS and aseptic necrosis of bone: Investigations carried out during and after the construction of the Tyne Road Tunnel. Decompression Sickness Panel Report. Br. J. Ind. Med. 1971;28:1-21.

(96) Walder DN. Some problems of working in an hyperbaric environment. Ann R. Coll. Surg. 1966;38:288-307.

(97) Kindwall EP. Compressed Air Work. In: Bennett BP, Elliott DH, editors. The Physiology and Medicine of Diving. 4th ed. London: Saunders; 1993.

(98) Duff PM, Giles R, Shields TG, Wilcock SE, editors. DCS from commercial offshore air diving operations on the UK Continental Shelf during 1982 to 1988. Aberdeen: Robert Gordon Institute of Technology; 1993. Contract No.: TA/93/22/249. Sponsored by the Department of Energy.

(99) Luby J. A study of DCS after commercial air diving in the Northern Arabian Gulf: 1993-1995. Occup. Med. 1999;49(5)279-83.

(100) Evans, T. [personal communication]. Compressed Air Working Group 2000 May.

(101) Lamphier EH, Nashimoto I, editors. What is Bends? UHMS Pub. 80. Proceedings of the 43rd UHMS Workshop. 1991 Jan 06; Bethesda, Maryland. Bethesda (MD): Undersea and Hyperbaric Medical Society; 1991.

(102) Carrod G, Eckehnoff RG, Olstad CS. Human dose – response relationship for decompression and endogenous bubble formation. Journal of Applied Psychology 1990 Sep;69(3)914-8.

(103) Bayne CG, Flynn ET, Hunt WS, Johanson DC, Weathersby PK. Doppler bubble detection and DCS: a prospective clinical trial. Undersea Biomedical Research 1985 Sep;12(3):327-32.

(104) King J, Contract Medical Adviser [personal communication]. London Hyperbaric Services; 2001 Sep.

ACKNOWLEDGEMENTS

The Directors of the North Sea Medical Centre without whose support this research would not have been possible.

Mr Donald Lamont, Principal Specialist Inspector (Health and Safety Executive) kindly granted permission to use the HSE Decompression Database 1986-2000 and provided invaluable assistance with analysis.

The members of the Compressed Air Working Group and the Contract Medical Advisers who provided feedback and access to the clinical data.

Dr Stephen Watt (Senior Lecturer, Environmental & Occupational Medicine) and Dr. Gordon Prescott (Medical Statistician, Department of Public Health) both University of Aberdeen, provided academic support and assistance.

Dr Tom Pace (Consultant Occupational Physician) and Dr Nick McIver (Former head of Hyperbaric Services) both of the North Sea Medical Centre, provided professional support and guidance throughout.

Miss Sheena Kennedy, Mr Tony Kirby, Mrs Julie Yaxley and administrative staff of the North Sea Medical Centre, for their unstinting practical assistance and support.

Dr Jonathan Broome and Dr Ian Calder for advice and guidance on the final format and presentation of this report.

A grant for financial support to this Research Project from the Health and Safety Executive was gratefully received.

Printed and published by the Health and Safety Executive
C1.10 11/03

HSE
BOOKS

MAIL ORDER
HSE priced and free
publications are
available from:
HSE Books
PO Box 1999
Sudbury
Suffolk CO10 2WA
Tel: 01787 881165
Fax: 01787 313995
Website: www.hsebooks.co.uk

RETAIL
HSE priced publications
are available from booksellers

HEALTH AND SAFETY INFORMATION
HSE Infoline
Tel: 08701 545500
Fax: 02920 859260
e-mail: hseinformationservices@natbrit.com
or write to:
HSE Information Services
Caerphilly Business Park
Caerphilly CF83 3GG

HSE website: www.hse.gov.uk

RR 171

£15.00

ISBN 0-7176-2771-3

9 780717 627714