Monitoring the Effectiveness of Tunnel Decompression Procedures using Doppler Techniques

D. R. Lamont¹,
¹Health & Safety Executive, Bootle, UK

1.1. Introduction

Is decompression illness (DCI) an inevitable consequence of the return to ambient pressure following exposure to raised atmospheric pressure? It is for a small number of exposures because decompression tables are a compromise between physiological necessity and commercial expediency. The slower the decompression the lower the risk of DCI but the greater the overhead costs are in terms of wages and lost productivity to a contractor. The trend with time has been for ever longer decompression times to be adopted.

Research [1] shows that the tunnelling decompression tables used in the UK from the 1960s till 2001 were around 99.4% effective as only about 0.6% of exposures resulted in DCI. That figure however is an average and does not necessarily give a complete indication of the extent to which DCI impacts on persons working in compressed air.

There is a number of possible measures of DCI incidence and the above figure of 0.6% is normally referred to as the (crude) “bends rate”. Although the risk of DCI increases with both increasing exposure pressure and period, the crude bends rate is completely insensitive to both parameters. The Single Exposure Risk Factor is the preferred measure in the UK as it is directly linked to exposure pressure and period.

Of those entering a compressed air tunnel, some are occasional visitors such as engineers and supervisors whilst others are shift workers such as miners, loco drivers, fitters and electricians. The frequency and duration of exposure and physical nature of work done depends on occupation. Accordingly, another measure of DCI risk is the percentage of an occupational group such as miners and others doing heavy physical work, who experience DCI. A study [2] covering around 120000 exposures over a 25 year period, showed that 18.6% of “shift production workers” i.e. miners and miners labourers experienced DCI and they accounted for 76.4% of the 428 DCI cases identified in the study.

Susceptibility to DCI following exposure to pressure varies with the individual. Both inter and intra-individual susceptibility can be demonstrated. There is inter-individual susceptibility in that only some workers on a shift will experience DCI on a given day. Intra-individual susceptibility is demonstrated in that someone undergoing similar exposures on consecutive days only occasionally suffers DCI after exposure. Some individuals are particularly susceptible or “bends prone” in that they experience repetitive or multiple DCI events on a contract.

One difference between exposure to raised atmospheric pressure and exposure to other physical agents such as noise, vibration etc is that for the latter, there are well defined numerical limits on the dose which an individual can receive. Similar limits do not exist for exposure to pressure.
The term “decompression illness” covers a wide spectrum of diagnosed and self-diagnosed conditions. Whilst there is gradation in severity of symptoms, in tunnelling practice there is no gradation in diagnosis. Sufferers are considered either to be suffering from DCI or not. As suffering from DCI can have economic consequences in terms of being declared unfit for further exposure, an individual worker may only admit to having DCI when the pain becomes unbearable. The diagnosis is therefore highly subjective. This makes accurate analysis of the exposure data more difficult.

Typically in the UK, a short retrospective analysis of exposure data has been undertaken by the Health and Safety Executive (HSE), at the end of a contract but historically, more in-depth analyses have been at intervals of around 20 – 30 years. This is partly to accumulate sufficient data for meaningful analysis. Retrospective analyses provide little immediate benefit to the man at the tunnel face.

A characteristic of compressed air working, certainly in European countries with which the author is familiar, is that decompression is undertaken in accordance with statutory decompression tables whereas in commercial diving, the diving contractor is responsible for selection of the decompression tables. The latter approach gives more scope for flexibility to respond to advances in decompression techniques.

1.2. Causes of DCI
Inert gas bubbles are generally accepted as the primary cause of DCI. Body tissues take up air – oxygen and nitrogen - during compression and the subsequent exposure to pressure. Saturation can occur if the exposure is sufficiently long. During decompression, the blood becomes super-saturated and gas bubbles form. Normally the oxygen in bubbles is metabolised or gassed off in the lungs. Nitrogen – an inert gas - bubbles also form in the bloodstream. Most of these bubbles are removed from the blood during its passage through the lungs. However if they lodge in the fine blood vessels in the tissues they can obstruct the blood vessels leading to local tissue trauma and pain – typically referred to in tunnelling as Type 1 Decompression Sickness. More seriously, bubbles can lodge in the spinal cord or brain leading to paralysis, a manifestation of Type 2 decompression sickness, or death. In addition to the occurrence of acute DCI, chronic DCI, manifested as dysbaric osteonecrosis, is still occasionally found in compressed air tunnel workers.

Over the decades much research has gone into identifying factors which make an individual susceptible to DCI. Although bubbles are the accepted cause of DCI, the mechanism of bubble formation remains unclear. A number of possible contributory factors have been identified over the years. As nitrogen is soluble in fat, obesity is often considered a possible causal factor. This has been questioned in recent years [3].

1.3. Decompression stress
This is the concept that the more severe the exposure in terms of pressure and exposure period the greater the decompression stress in terms of the need for effective decompression. It is a feature of decompression tables that their effectiveness is inversely related to the stress of the exposure.

1.4. HSE response to the problems of DCI
The Health and Safety Executive, the UK government agency responsible for occupational health and safety – has been aware of these issues for many years and has funded extensive research into the problems of work in compressed air. It regulates the practice and has published detailed guidance for the industry. The most recent in-depth retrospective study of UK exposure data [1] was funded by HSE.
For over a decade now HSE has used Doppler monitoring as a research technique in studies of DCI in tunnelling. The equipment is compact and readily portable. Initially ultrasonic monitoring was also used but proved much less appropriate for the relatively arduous conditions on site.

Doppler monitoring has been used by HSE to give a more rapid and an objective indication of the effectiveness of a particular decompression regime for an exposed population. It is less sensitive to small numbers of exposures than direct statistical analysis of exposure data, and allows identification of populations at significant risk of DCI. Doppler monitoring provides a means of quantifying the gas burden in subjects being monitored which also allows for calibration of existing predictive physiological decompression models.

1.5. Doppler monitoring

Doppler monitoring is a physiological monitoring technique whereby sound waves are passed through body tissue. The frequency shift of the reflected echoes is analysed and interpreted to detect bubbles in the circulatory system. It was described in detail by Nishi [4]. Two non-linear grading systems for bubble concentration are commonly used – the Kisman-Masurel method and the Spencer method. Both require considerable skill on the part of the operator in detecting and counting the bubbles passing the detector. Monitoring should be undertaken in accordance with carefully defined protocols to ensure consistency. There are a number of preferred standard locations for placing the Doppler probe including over the pulmonary artery or the subclavian vein. Monitoring is done with the subject at rest or following a defined body movement.

Bubble concentrations are reported as “grades”. The bubble grade can be used as an indicator of decompression stress and may be a more sensitive indicator of inadequate decompression than DCI incidence. Nishi [4] noted that from a sample of almost 3500 (diving) exposures, bubbles were detected following decompression in 56% of them, whilst only 2% gave rise to symptoms of DCI. Bubble grades may also be an indicator of DCI risk however at present the correlation between bubble grades and DCI risk is weak. This is partly due to lack of data and partly to the variability in human response to decompression. Nevertheless high bubble grades are considered to represent a heightened risk of DCI.

An integration technique – the Kisman Integrated Severity Score (KISS) [5] - can be used give an indication of the duration of the peak and severity of bubbling over a longer time period. The peak reading is often used as the reported bubble grade, but the KISS may also be important as indicator of the severity of bubbling.

1.6. What HSE has been doing with Doppler monitoring?

HSE first used physiological monitoring in the 1990s when concern arose at the high incidence of DCI being reported following exposures at around 1 bar g and using the then well-established “Blackpool tables” [6]. Men were monitored following decompression and the results were compared with bubble levels predicted by a mathematical physiological model. The results showed an acceptable level of correlation between measured bubble levels and those predicted. They also confirmed that the incidence of DCI experienced on site was not inconsistent with the bubble grades reported.

On that occasion both Doppler and ultrasonic monitoring was undertaken which allowed an assessment of the suitability of each technique for site use to be made. Both techniques gave similar results in terms of bubble detection and quantification. However the Doppler equipment was found to be more suitable for site use, being much easier to handle because of its compact and portable nature compared to the somewhat bulky and heavy ultrasonic equipment (borrowed from a helpful maternity unit!).
HSE next used Doppler monitoring during hyperbaric trials undertaken prior to the introduction of oxygen decompression in the UK in 2001 [7]. These trials were carried out in an internationally recognised hyperbaric research facility in Aberdeen. Subjects were monitored following an exposure in a hyperbaric chamber during which heavy physical labour was performed. Decompression was done either on air or on oxygen to prove the benefits of oxygen. As a crude comparison, there was one case of DCI following air decompression and no case following oxygen decompression. However analysis of the Doppler grades showed the true effectiveness of the oxygen decompression. Median bubble grades of those breathing oxygen were significantly lower than for those on air. Another result from these trials was an appreciation of the extended time period following decompression, during which bubble grades remained high before declining. This confirmed that men could be at significant risk of DCI for some hours after decompression ended.

Construction of the tunnels for “High Speed 1” the link from London to the Channel Tunnel required the construction of twin railway tunnels under the Thames at Dartford. The contract went to an Anglo-German joint venture who requested approval from HSE to use decompression tables which were a slightly restricted (in terms of excluding the most extreme exposures) version of German tables [8]. As part of the approval procedure, HSE accepted the contractor’s offer to use Doppler techniques to monitor the effectiveness of the decompression regime. Because only a small number of exposure were undertaken and an even smaller number subject to monitoring, the results were of only limited value.

In 2004 HSE commissioned a major research project to study the effectiveness of Doppler techniques as a real time method of monitoring the effectiveness of a decompression regime. The Institute of Occupational Medicine undertook the study in conjunction with leading experts in the field [9]. It reviewed existing published information based on Doppler monitoring in diving and other hyperbaric exposures which was supplemented by analysis of unpublished data using a mathematical model of venous gas volume to give comparisons with Doppler grades. In addition it looked at operational considerations for site use of the technique.

The study’s conclusions included:-

- there was an association between Doppler grade and risk of DCI in several data sets, but the level of risk depended on the data set used,
- DCI only affects a small proportion of the workforce. Those affected might have high Doppler scores and if the association between Doppler grade and risk of DCI could be confirmed, it might enable individuals at increased risk of DCI to be identified,
- ethical issues arise over how to respond to individuals with high Doppler scores but not showing signs of DCI,
- Doppler monitoring might allow fine tuning of decompression tables to be assessed on site. However, accuracy might be compromised due to operating in a less well controlled environment than in laboratory trials.

The study recommended that:-

- more data should be collected and that should be done using standard protocols. A national database to collate the records should be set up,
- Doppler grade IV scores should be interpreted as an indication for considering prophylactic recompression,
- on the basis of current data, it would not be appropriate to set rigid guidelines on what Doppler scores could be considered acceptable in compressed air workers but if the percentage of individuals with Doppler scores of grade III or above exceeded 20%, there was concern in terms of risk of DCI, and the decompression was probably not providing adequate protection for that particular group of individuals in the circumstances.
- further research on individual susceptibility to DCI should be undertaken to determine whether there was an association with bubble grade in those individuals who have higher incidence of DCI.
1.7. Recent experience

In conjunction with HSE(Northern Ireland) (HSENI), Northern Ireland Water and contractor Morgan Est, compressed air tunnel workers from a sewer project in Belfast were monitored using Doppler techniques. A number of shafts were sunk and tunnels of various diameters were built. Ground conditions varied from very soft but highly plastic silt “Belfast sleech” to volcanic dykes. Compressed air was applied at four locations to assist in shaft sinking and on two occasions to facilitate TBM repair.

Figure 1 – Pressure profile for Belfast Sewer contract

Figure 2 – Plot of exposures - Belfast Sewer contract
The contractor requested approval from HSENI to use a variant of the German tables [8] and as part of the negotiations over approval, agreed to undertake a limited amount of Doppler monitoring provided the analysis was funded by others. A report on the monitoring exercise, by Qinetiq [10] and funded by HSE is in preparation. Northern Ireland legislation on work in compressed air is identical in its requirements to that elsewhere in the UK. A pressure profile for the contract showing the extremely intermittent nature of the compressed air work is shown in Figure 1. Figure 2 is a plot of all exposures in terms of exposure pressure against exposure period. Figure 2 also shows that the Doppler monitoring was targeted at the more stressful exposures. A single case of DCI was reported. This followed an exposure at 1.8 bar for 3 hours 37 minutes.

1.8. Monitoring and analysis.

Monitoring by experienced technicians from Qinetiq was carried out to an approved protocol for 21 work shifts over 11 days, split between two visits from November 2008 to February 2009. Exposure pressures ranged from 0.67 to 1.8 bar (g). 65 exposures by 17 individuals were monitored. The mean age of the volunteers was 34, mean height was 1.78m and mean (declared) weight was 86.3kg. Pre-cordial monitoring was done at 30 minute intervals beginning 30 minutes after decompression and continued for up to three hours after decompression ended. Monitoring was undertaken following exposure at pressures of 1.8 bar (g), 1.2 bar (g) and a range of pressures less than 1.0 bar (g). Attendance for monitoring was voluntary and varied markedly between individuals. It was not possible to collect the full amount of data potentially available.

Resting and post-movement Doppler scores were recorded. These covered the full range (0 – 4) of possible grades. Thirty six (55 %) of the 65 monitoring sessions demonstrated a resting grade III or higher. The KISS was used to give additional information on the bubble load over the whole monitoring period.

<table>
<thead>
<tr>
<th>Doppler Grade</th>
<th>Time after decompression (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>I</td>
<td>0</td>
</tr>
<tr>
<td>II</td>
<td>1</td>
</tr>
<tr>
<td>III</td>
<td>1</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>12</td>
</tr>
</tbody>
</table>

Table 1: Doppler Grades (at rest) after exposures of 4 – 6 hours at 1.2 bar (g)

Monitoring of workers after decompression from exposures of 4 to 6 hours duration at a pressure of 1.2 bar (g) revealed the Doppler grades shown in Table 1. The results of a similar exercise after decompression from exposures of 4 to 4.5 hours duration at a pressure of 1.8 bar (g) are shown in Table 2.

<table>
<thead>
<tr>
<th>Doppler Grade</th>
<th>Time after decompression (mins)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>30</td>
</tr>
<tr>
<td>0</td>
<td>14</td>
</tr>
<tr>
<td>I</td>
<td>2</td>
</tr>
<tr>
<td>II</td>
<td>3</td>
</tr>
<tr>
<td>III</td>
<td>7</td>
</tr>
<tr>
<td>IV</td>
<td>0</td>
</tr>
<tr>
<td>N</td>
<td>26</td>
</tr>
</tbody>
</table>

Table 2: Doppler Grades (at rest) after exposures of 4 – 4.5 hours at 1.8 bar (g)
Neither set of exposures resulted in DCI however the greater effectiveness of the decompression regime for 1.2 bar (g) exposures can clearly be seen from the lower Doppler grades tabulated. Based on the recommendations of the IOM report, both the existence of grade IV bubbles and the proportion of grade III or higher would give rise for concern over the effectiveness of the decompression undertaken after exposures of 4 – 4.5 hours at 1.8 bar (g).

Doppler Grades following decompression for exposures of 3.5 to 4 hours at 1.8 bar (g) were also recorded and were noticeably lower than for 4 – 4.5 hour exposures at the same pressure. No grade IV was detected and only 31% of men were at grade III.

At Belfast the research protocol did not allow analysis of results till after the contract was completed. The protocol was partly to maintain objectivity in the monitoring and to prevent ethical issues over prophylactic treatment arising. Had the results been available during the contract period, this would have been an important finding for the regulatory authorities and consideration would have had to be given to limiting exposure at 1.8 bar (g) to 4 hours.

There was one incident of DCI, manifested as ankle pain, which was reported about 13 hours after the end of decompression. Fortunately the individual involved had undergone some monitoring immediately after decompression. That showed a (resting) grade III at 30 minutes, which was a high initial score compared to the others from the shift which were all zero. The individual remained grade III until he left the site after 75 minutes. Doppler monitoring carried out before therapeutic recompression, gave a (resting) grade II. Following recompression on US Navy Treatment Table 6 all symptoms were resolved and Doppler monitoring detected no further bubbles. The man in question had been on his first shift and did not resume work in compressed air.

The outcomes from this project are still being assessed at the time of writing the paper however emerging findings suggest that:

- the full variation in grades from 0 to IV was seen in individuals undergoing the same exposure and decompression.
- acclimatisation to the effects of pressure was not observed however the number of relevant exposures was very limited.
- most tunnellers left around two or two and a half hours after decompression ended and on 15 occasions this was not long enough to see a reduction in bubble grade.
- if Doppler monitoring of compressed air workers is to be employed routinely, some recompense or incentive should be introduced to achieve greater compliance with the monitoring schedule.
- there was insufficient evidence to conclude whether there was an association with bubble grade in those individuals who had a higher incidence of DCI.

1.9. Conclusions

There remains a need for a real time method of monitoring the effectiveness of decompression after exposure in compressed air tunnel works. Doppler monitoring has been shown to be of limited use however considerably more experience in its use and its limitations along with substantially more site data are required to establish its general suitability. The British Tunnelling Society Compressed Air Working Group, of which the author is a member, recently accepted that “Doppler monitoring is one tool in the toolbox of DCI risk assessment, however the number of other tools is unknown and there are no others in the toolbox at present”.

1.10. Acknowledgements

The author wishes to acknowledge the work of those who undertook the research for HSE, referred to in this paper and the contribution of all parties involved in the Belfast contract. The contribution of those who underwent monitoring is particularly appreciated.
1.11. Recommendations

Based on experience to date, a number of recommendations can be made:

- Further research should be undertaken to establish whether Doppler monitoring can be used as a reliable real-time technique for routinely assessing the effectiveness of decompression regimes. With ever higher pressures being used the need for such a technique is increasing.
- Protocols for monitoring and data collection should be established and every opportunity should be taken to acquire high quality data for future analysis.
- If possible guidelines should be agreed for identifying inappropriate decompression schedules and for triggering the identification of individuals for prophylactic recompression therapy.

Without adopting some real time, objective, monitoring procedure as an alternative to relying on DCI incidence, contractors undertaking work in compressed air may be exposing their employees to unnecessary health risk. Consequently they may find it increasingly difficult to defend claims for compensation from employees who have experienced acute DCI or think they have experienced inadequate decompression which some believe could increase the risk of bone necrosis.

1.12. References