Case reports

Shunt-mediated decompression sickness in a compressed air worker with an atrial septal defect

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Abstract

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We report a compressed air worker who had diffuse cutaneous decompression sickness with pain in his left shoulder and visual disturbance characteristic of migraine aura after only his third hyperbaric exposure. The maximum pressure was 253 kPa gauge with oxygen decompression using the Swanscombe Oxygen Decompression Table. He was found to have a very large right-to-left shunt across a 9 mm atrial septal defect. He had transcatheter closure of the defect but had some residual shunting with release of a Valsalva manoeuvre. Thirty-two other tunnel workers undertook the same pressure profile and activities in the same working conditions during the maintenance of a tunnel boring machine for a total of 233 similar exposures and were unaffected. As far as we are aware this is the first report of shunt-mediated decompression sickness in a hyperbaric tunnel worker in the United Kingdom and the second case reported worldwide. These cases suggest that shunt-mediated decompression sickness should be considered to be an occupational risk in modern compressed air working. A right-to-left shunt in a compressed air worker should be managed in accordance with established clinical guidance for divers.

Introduction

In recent decades, manual excavation of tunnels has been replaced by tunnel boring machines (TBM), which mechanically excavate soil and insert pre-cast concrete lining segments. The excavating tools at the front of the TBM require periodic inspection and maintenance. Sometimes compressed air pressurisation using a system of locks is required to allow safe access to the cutter-head.

Compressed air workers are at risk of decompression sickness (DCS), which is caused by corporeal gas nucleation when the workers return to normal atmospheric pressure. It is well recognised that compressed air work carries an increased risk of DCS compared to commercial diving.[1,2] A case-control study of United Kingdom (UK) compressed air workers on the Health and Safety Executive Decompression UK Database 1986–2000 found that 4% of the workforce, who had repeated episodes of DCS, suffered 50% of the episodes of DCS requiring therapeutic recompression.[3] It concluded that there are "*bend prone*" compressed air workers, but that the history and clinical examination (and tests) undertaken at the routine pre-employment compressed air medical examination did not identify individual risk factors.

In divers, a right-to-left shunt (whether atrial or pulmonary) is a recognised risk factor for some forms of DCS after relatively unprovocative hyperbaric exposures, because a shunt allows venous bubbles to bypass the pulmonary filter and to embolise systemic tissues where they are amplified if the tissue is supersaturated with dissolved gas.[4]

In tunnellers, DCS does not usually present with the clinical characteristics of shunt-mediated DCS recognised in divers. This has caused some clinicians to question whether a right-to-left shunt is a risk factor for DCS in compressed air workers.[5]

We describe what we believe is the first report of shunt-mediated DCS in a UK compressed air worker. The worker consented to and fully co-operated with the publication of his case history and related images in this case report. There is a previous report of a tunnel worker who had an

Table 1
Swanscombe oxygen decompression schedule for exposures at 253 kPa (2.5 bar) gauge

Working pressure (bar)	Exposure period (hours.mins)	Time to first stop (mins)	Time (mins) at stop pressures (gauge)							Total decompression time (hours.mins)
			O_2 1.0 bar	Air 1.0 bar	O_2 1.0 bar	→	O_2 0.5 bar	Air 0.5 bar	O_2 0.5 bar	
2.5	2.30	5	25	5	18	→	7	5	14	1.19

episode of DCS, including neurological DCS with onset ten minutes after surfacing, after a pressure exposure that was thought to be unprovocative. He was also found to have an atrial septal defect.[6]

Case report

A 32-year-old tunneller had DCS after only his third hyperbaric exposure. He had no problems after his first and second exposures, three and two days earlier. Those exposures were at 253 kPa (2.5 bar) gauge and total durations of three hours 50 minutes and three hours 53 minutes including the time for oxygen decompressions. In compressed air work pressures are expressed in gauge pressure, which is the pressure relative to atmospheric pressure.

He completed his third compressed air shift doing manual work in the TBM cutterhead for two hours 30 minutes at 253 kPa gauge without problems. He then underwent uneventful oxygen decompression for one hour 19 minutes using the Swanscombe Table whilst seated in the TBM lock. That involved periodic 100% oxygen breathing through a full-face mask with air breaks during staged decompression from 101.3 kPa (1 bar) gauge following the table protocol (Table 1).

Three other workers were exposed to the same pressure and work environment that shift without issues.

After a one hour 'bend watch' on-site, he drove home. He noticed itchiness of posterior right arm and back which spread to his right flank approximately two hours after completing shift decompression. He reported a florid skin rash affecting his back, chest and abdomen to the site hyperbaric emergency line almost three hours after decompression. He thought it was chemical irritation. He was otherwise asymptomatic. The advice of the medical lock attendant was to monitor his rash and send pictures to assist clinical assessment (Figure 1). The rash was also over the posterior aspect of the left shoulder (Figure 2).

Approximately four hours after decompression, he developed mild left shoulder pain / ache which worsened to prevent sleep and full movement of the shoulder. The rash had progressed over his body.

After discussion of the rash with the contract medical adviser at four hours 45 minutes post decompression, the worker was advised to urgently attend the site for treatment of suspected DCS. When he arrived on site six hours 50 minutes post-decompression his main symptom was severe left shoulder pain. The skin rash had extended to cover his right flank and both upper thighs (Figure 3).

Decompression sickness was diagnosed and treatment commenced in the site medical chamber using US Navy Treatment Table 6.

There was no improvement of pain or rash on initial recompression or after the 1st oxygen cycle at 284 kPa. The shoulder pain and the rash significantly improved after the 2nd oxygen cycle with further improvements of pain and itch after the 3rd oxygen cycle and complete resolution after one extension at 284 kPa (4th cycle). He was asymptomatic with only residual mild skin discolouration at the end of treatment.

At post-treatment assessment he reported that about four hours after his shift decompression he had experienced transient disturbance of his peripheral vision with 'black and white lines' lasting 15 minutes associated with mild nausea.

The contract medical adviser confirmed the diagnosis of DCS with skin, neurological (visual disturbance consistent with migraine aura) and musculoskeletal manifestations. Long bone MRI screening for dysbaric osteonecrosis was negative.

Cutaneous and neurological DCS is reported infrequently in tunnellers.[2] Those manifestations are commonly associated with a right-to-left shunt in divers.[4] Therefore, because the worker wished to continue hyperbaric tunnelling, he had a transthoracic echocardiogram with bubble contrast which showed a very large atrial right-to-left shunt at rest with increased shunting with each normal inspiration.

Subsequently a 10 mm Amplatzer septal occluder was implanted in a 9 mm diameter atrial septal defect. Repeat bubble contrast echocardiograms at four months and 11 months post-procedure demonstrated no residual right-to-left shunt during normal respiration but a significant residual shunt with release of a Valsalva manoeuvre. It is hoped that endothelium overgrowth on the device will further reduce

Figure 1
Skin rash approximately three hours after oxygen decompression

Figure 2
Skin rash over left shoulder approximately three hours after oxygen decompression

Figure 3
Skin rash approximately six hours 50 minutes after oxygen decompression

the size of this residual shunt to be confirmed by repeat bubble contrast echocardiography. Meanwhile he continues normobaric tunnel work

Discussion

We report a tunnel worker who had DCS after only his third hyperbaric exposure. He was found to have an atrial septal defect with a very large right-to-left shunt during normal breathing.

Three other workers who had the same exposure on the same shift were unaffected. Overall, 32 other workers completed 233 similar exposures at 253–324 kPa (2.5–3.2 bar) gauge using the Swanscombe Table during the project without suffering DCS. Although the total number of hyperbaric exposures is small, it is notable that the only episode of DCS was in a tunnel worker with an atrial septal defect who suffered DCS after only his third pressure exposure. In addition, our experience during 20 years in other tunnelling projects with this decompression procedure at this working pressure indicates a low risk of DCS.

Over the last two decades, work and decompression procedures have changed in hyperbaric tunnelling. Working pressures have increased significantly with correspondingly reduced working times in the air range and use of oxygen decompression. These 'modern' working practices contrast with historical UK compressed air exposures from 1984–2002, which typically used working pressures less than 182 kPa (1.8 bar) gauge and relatively prolonged but single daily exposures using air decompression techniques.[2]

The Swanscombe Table is thought to be industry 'best practice' for modern compressed air work for decompression safety / DCS rate. It is based on a modified German oxygen table introduced in 1990.[7] From 1990 'new' German oxygen tables were developed due to concerns about high DCS rates in tunnelling in Germany and were validated based on Canadian models by the Department of Underwater Medicine at the Cologne Institute on behalf of the German Federal Government. These 'German oxygen tables' became mandatory for all oxygen decompressions by law in Germany from 1990 onwards and were widely used throughout Europe. Subsequently the new tables were found to greatly reduce the incidence of DCS in compressed air workers, but DCS was not completely abolished especially in the higher pressure air range (close to or greater than 304 kPa (3 bar) gauge pressure at the maximum working time exposure limits.

The Swanscombe Table has had the benefit of close monitoring of its decompression safety performance under field conditions since 2002, with reduction of exposure times for problematic exposure/pressure bands based on 'real-life' bend rate analysis but also using quality assured field Doppler monitoring on multiple UK compressed air work projects, which is rare in tunnelling.

Current experience suggests the Swanscombe Table has improved decompression safety, because it has a relatively low rate of workers developing DCS when compared to other decompression tables used in compressed air tunnelling although numbers of exposures (and thus DCS cases) are relatively small.

Field Doppler studies were last performed in 2020 by QinetiQ on 10 tunnel workers exposed to 330 kPa (3.2 bar) gauge air who decompressed using the Swanscombe compressed air/oxygen tunnelling decompression table. The report is unpublished, but we are able to report that subclavian and precordial Doppler measurements with fist clench and knee bend gave maximum Kisman-Masurel Doppler scores of zero in six workers, scores of one in two workers and scores of two in two workers.[8] These limited data suggest that the Swanscombe Table can be considered to be 'low risk', for DCS even in 330 kPa (3.2 bar) gauge exposures but also show that small numbers of venous bubbles are liberated in some individuals after decompression using this Table. This occurs after many decompressions but generally small numbers of bubbles do not pass through the pulmonary capillaries. When there is a right-to-left shunt, venous bubbles can circumvent the pulmonary filter to reach the systemic circulation and embolise supersaturated tissues where the bubbles are amplified to cause shunt-mediated DCS.[4]

All commercially used decompression schedules in compressed air work have a risk of a person developing DCS, thus it is not really possible to say that any schedule or Table is 'safe'. However, we consider that the Swanscombe Table can reasonably be considered to have been developed to have a relatively low or reduced risk of a worker developing DCS when compared to other decompression tables used in compressed air tunnelling.

The case reported here suggests that for workers with a large right-to-left shunt even modern compressed air tunnel work can have a risk of DCS. These observations are supported by the earlier report of an episode of shunt mediated DCS in a tunnel worker with an atrial septal defect and history of recurrent DCS over several years although the decompression profiles for those pressure exposures prior to 1990 were probably less conservative than the Swanscombe Table.

This case therefore has significance for the hyperbaric tunnelling industry. The DCS rates in modern hyperbaric tunnelling operations have improved over the past 20–30 years with oxygen decompression and improved work techniques, but the rates of DCS remain higher than for current commercial diving table performance particularly at the end of the compressed air range (greater than 304 kPa [3.0 bar] gauge).

Our patient first noticed skin symptoms approximately two hours after decompression with transient visual disturbance reported four hours after decompression when the rash was progressing. The occurrence of cutaneous DCS and symptoms similar to migraine aura are common presentations of shunt-mediated DCS in divers.[4, 9–11] When migraine aura-like symptoms occur at the time of other manifestations of DCS in a diver, when some tissues are supersaturated, it suggests that paradoxical gas embolism is occurring and likely to be responsible for the DCS manifestations.[10] Skin rash and visual disturbance are rare DCS manifestations in compressed air workers. There was only one skin bend and 13 episodes of Type 2 DCS in 428 episodes of DCS in compressed air workers during 1984–2002 in Britain in a report by the Health and Safety Executive.[2]

Joint pain is not usually associated with a right-to-left shunt in divers except when cutaneous DCS is accompanied by shoulder pain, and the rash extends over the affected shoulder.[4,9] The pain in the shoulder experienced by this tunnel worker was when there was overlying cutaneous DCS and the onset of the pain coincided with visual aura, suggesting paradoxical gas embolism at that time. Therefore the shoulder pain may have been shunt mediated.

His shoulder pain was slow to resolve during hyperbaric oxygen therapy which, based on our own unpublished observations (> 100 cases treated over 30 years), is also unusual for DCS in compressed air workers. Others agree that joint pains symptoms of DCS in compressed air workers usually resolve immediately on therapeutic recompression or during the first oxygen cycle of USN Table 6 (Dr John King personal communication).

Migraine aura-like symptoms occur fairly frequently after bubble contrast echocardiography when there is a large right-to-left shunt.[4,10] It does not require tissues to be supersaturated with dissolved gas to amplify bubbles. Therefore, it can be the result of bubble emboli *per se*. In this case, the migraine-like symptoms occurred about four hours after decompression. By then, neurological tissues would no longer be supersaturated. Therefore, more serious neurological manifestations were unlikely to occur.

We are aware of only one other case report of shunt-mediated DCS in a compressed air worker or tunneller globally.[6] The 44-year-old tunnel worker presented in October 2002 after an exposure of 42 minutes at 274 kPa (2.7 bar) gauge, and reported symptoms consistent with shunt-mediated DCS. He had "*paraesthesia, burning, and pain in the right leg 10 minutes after the end of the decompression phase. In the next hour, all of these sensitisations worsened and were followed by ataxia*". The author reported the worker had suffered from several "*unexplained*" episodes of DCS requiring hyperbaric oxygen treatment over the previous 15 years (from 1988–2002), but no detailed exposure or clinical histories were given .The report stated the tunnel worker was affected after standard pressure profiles that had not caused symptoms of decompression illness in his colleagues and that transoesophageal echocardiography following the episode in 2002 revealed an atrial septal defect in this otherwise healthy man. Cranial magnetic resonance imaging showed ischaemic brain lesions.

Guidance on screening and managing right-to-left shunts in divers with patent foramen ovale (the commonest cause of interatrial shunt) has been produced as recommendations in the South Pacific Underwater Medicine Society / United Kingdom Sport Diving Medical Committee (SPUMS / UKDMC) consensus published in 2015.[12] We believe it is appropriate to use the same guidelines for compressed air workers.

Conclusions

This case and the case report from 2004 suggest that shunt-mediated DCS should be considered to be an occupational health risk in compressed air workers.

The possibility of a right-to-left shunt should be considered in compressed air workers presenting with types of DCS commonly seen in divers with a shunt (cutaneous, cerebral, spinal or inner ear) and/or migraine aura-like symptoms after decompression. When appropriate, transthoracic bubble contrast echocardiography should be performed before further occupational pressure exposure. We are not suggesting that all compressed air workers be screened for right-to-left shunts but rather that workers be medically managed and treated as recommended for divers in the SPUMS / UKDMC consensus document.

We suggest the pre-exposure medical questionnaire for compressed air workers should enquire about conditions associated with an increased prevalence of interatrial shunt (e.g., personal history of migraine with aura or cryptogenic stroke, family history of PFO, atrial septal defect or congenital heart disease in a first degree relative). Bubble contrast echocardiography should be considered in those whose history suggests an increased risk of a right-to-left shunt before they undertake hyperbaric work.

We also believe that the increased risk of serious DCS means that any person with a medium or large right-to-left shunt should not undertake compressed air work unless they have had successful closure of the shunt.

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