Diving and Hyperbaric Medicine

The Journal of the South Pacific Underwater Medicine Society and the European Underwater and Baromedical Society©

SPUMS

Volume 54 No. 2 June 2024

EUBS

Regional management of diving fatalities

HBO for femoral avascular necrosis

HBO for central retinal artery occlusion

Dipstick urinalysis in diving medicals

Effect of hypercapnia on decompression sickness

Cardiac investigations before hyperbaric oxygen

Shunt mediated DCS in a compressed air worker

HBO for post-surgical haematoma and oedema

Drinking and driving vs nitrogen and diving

E-ISSN 2209-1491

ABN 29 299 823 713

CONTENTS

Diving and Hyperbaric Medicine Volume 54 No. 2 June 2024

Diving and Hyperbaric Medicine is indexed on MEDLINE, Web of Science® and Embase/Scopus
Articles from 2017 are deposited in PubMed Central®

PURPOSES OF THE SOCIETIES

To promote and facilitate the study of all aspects of underwater and hyperbaric medicine
To provide information on underwater and hyperbaric medicine
To publish a journal and to convene members of each Society annually at a scientific conference

---

DIVING AND HYPERBARIC MEDICINE

https://www.dhmjournal.com/

Diving and Hyperbaric Medicine **is published online jointly by the South Pacific Underwater Medicine Society and the European Underwater and Baromedical Society**
E-ISSN 2209-1491; ABN 29 299 823 713

The Editor's offering

Welcome to the second iteration of DHM for 2024. There is much to interest those whose primary focus is diving medicine or hyperbaric medicine in this issue.

Elizabeth Elliott and colleagues describe the development of polices and procedures for management of a diving fatality in Tasmania, Australia. Management of diving fatalities is often suboptimal from the perspective of optimising the chances of accurately determining the cause. Although processes will vary in different jurisdictions, this article provides many examples of the sorts of considerations that are important in formulating regional policy.

John Currie and colleagues from Perth Australia, report a series of avascular femoral bone necrosis cases treated with hyperbaric oxygen (HBO). Although not a controlled trial, the use of HBO seemed to modify the natural history of this notoriously difficult to treat and disabling problem, as also reported by others. This is one of the accepted indications for HBO that is not supported by randomised trials because of the significant difficulty in running such studies in this sporadic condition. Hopefully its inclusion in clinical registries will at least allow collection of high volumes of non-randomised data over the coming years.

William Emmerton and colleagues, once again from Perth, surveyed hyperbaric units providing acute services in Australia and New Zealand to establish practices in relation to treating retinal artery occlusions with HBO, and to evaluate the extent to which these practices conformed to Undersea and Hyperbaric Medical Society (UHMS) recommendations. There was much variability in protocols, and little conformity with UHMS norms. The authors advocate for a simplified approach starting with a high dose of HBO.

Arne Melessen and colleagues from the Netherlands continue a thematic line of work in which they evaluate the utility of investigations that have long been considered integral to fitness for diving evaluations. This time they provide an evidence-based argument for not using urine dipstick analysis on asymptomatic diver or submariner candidates who lack any relevant history. This sort of work from this group and others has seen a welcome reorientation and rationalization of aspects of occupational diver medicals over many years now.

Lucille Daubresse and colleagues from the military group in Toulon, France have reviewed the evidence for a role for hypercapnia in both the causation and prevention of decompression sickness (DCS). I found this article interesting because it explored an obscure literature, some of which I was unaware of. The potential role of hypercapnia seems nuanced and dependent on the type of decompression (to altitude vs from diving) and the timing of the hypercapnic exposure (before, during, or after the decompression). Although some of the literature pertains to animal models, the findings are thought-provoking, and identify potential areas for further investigation.

Connor Brenna and colleagues from the Toronto group have reviewed the evidence for use of cardiac investigations before HBO. They explain how HBO may induce stress in the cardiovascular system but conclude that patients with low-risk features for heart failure do not require routine investigations. They provide a guideline for identifying those patients who are high risk and who therefore might benefit from investigation of cardiac function prior to HBO.

Andrew Colvin and colleagues describe the first reported UK case of shunt-mediated DCS (primarily cutaneous DCS) in a compressed air tunnel worker. The patient was found to have a large atrial septal defect. Although the occurrence of shunt-mediated DCS is well established among divers, it is much less 'front-of-mind' among compressed air workers. The authors recommend that clinical guidance on related matters (such as testing for a right-to-left shunt) for divers should also be applied to compressed air workers.

Dilşad Dereli and colleagues from Turkey describe the case of a 17-month-old male with Noonan's syndrome and thrombocytopenia who had haematoma formation and threatened tissue necrosis after circumcision and orchidopexy. Hyperbaric oxygen was provided as an adjunct to other interventions and the child made an excellent recovery. The authors are appropriately cautious when discussing the extent to which this can be confidently attributed to HBO. Nevertheless, they identify HBO as a potentially useful intervention in similar sporadic events.

Finally, in one of our occasional 'World as it is' articles, Gerard Laden and Bruce Mathew from Hull, UK, pick up on a recent publication in which nitrogen narcosis was shown to increase risk-s taking behaviours. They challenge us with the observation that (for example) drinking and driving is regulated within strict limits for exactly that reason, yet no clear limits exist for nitrogen narcosis.

Congratulations to the UHMS on their recent successful meeting in New Orleans. Unfortunately, I was unable to attend due to a clash with a long-organised diving expedition to Fiji (see cover photo).

Simon Mitchell
Editor, Diving and Hyperbaric Medicine Journal

Cover photo: Rob Williams in Cathedral Cave in the remote Lau group of islands, Fiji.

Original articles

Formulating policies and procedures for managing diving related deaths: a whole of state engagement from frontline and hospital services in Tasmania

Elizabeth J Elliott[1], Karl Price[1], Bernard Peters[2]

[1] *Diving and Hyperbaric Medicine Unit, Royal Hobart Hospital, Hobart, Tasmania, Australia*
[2] *Tasmania Police Marine and Rescue Services, Tasmania, Australia*

Corresponding author: *Dr Elizabeth Elliott, Royal Hobart Hospital, Liverpool St, Hobart, Tasmania 7000, Australia*
ORCiD: *0009-0005-3679-621X*
elizabeth.elliott@ths.tas.gov.au

Keywords
Autopsy findings; Diving deaths; Diving incidents; Diving medicine; Forensic pathology

Abstract
(Elliott EJ, Price K, Peters B. Formulating policies and procedures for managing diving related deaths: a whole of state engagement from frontline and hospital services in Tasmania. Diving and Hyperbaric Medicine. 2024 30 June;54(2):86–91. doi: 10.28920/dhm54.2.86-91. PMID: 38870949.)

Introduction: Tasmania is a small island state off the southern edge of Australia where a comparatively high proportion of the 558,000 population partake in recreational or occupational diving. While diving is a relatively safe sport and occupation, Tasmania has a significantly higher diving death rate per head of population than other States in Australia (four times the national diving mortality rate).

Methods: Three compressed gas diving deaths occurred in seven months between 2021–2022 prompting a review of the statewide approach for the immediate response of personnel to diving-related deaths. The review engaged first responders including the Police Marine and Rescue Service, hospital-based departments including the Department of Hyperbaric and Diving Medicine, and the mortuary and coroner's office.

Results: An aide-mémoire for all craft groups, digitalised checklists for first responders (irrespective of diving knowledge), and a single-paged algorithm to highlight inter-agency communication pathways in the event of a diving death were designed to enhance current practices and collaboration.

Conclusions: If used, these aids for managing diving related deaths should ensure that time-critical information is appropriately captured and stored to optimise information provided for the coronial investigation.

Introduction

Tasmania is an island state situated off the southern edge of Australia, the land size being similar to Ireland or Switzerland. The Tasmanian population was approximately 558,000 in 2021,[1] with potentially 18,500 recreational divers (approximately 3.7% of the population) based on recreational fishing licences[2,3] (with the consideration that some people may hold dual licences, some will hold none, and some licence holders will only be snorkellers rather than compressed gas divers), and an imprecise number of occupational divers.[4] Tasmania has a burgeoning aquaculture industry (farmed seafood) and wild harvest industry. Wild seafood harvest licenses allow for an estimate of commercial diver numbers extrapolated from issued licenses. The diver numbers from the aquaculture industry would necessitate direct contact with the numerous businesses to determine exact numbers. From a commercial perspective, what is known is from the commercial licences managed by the Water and Marine Resources, Fisheries Compliance and Licencing Branch, with 119 active abalone and 53 commercial (including periwinkles, sea urchins, and Undaria) dive licences (J.S. personal communication, August 29, 2023). Occupational diving in Tasmania also includes police, military, scientific, and offshore oil and gas industry divers. There is no centralised database to document either active recreational or occupational divers.

Commercial fishing, aquaculture, and associated processing industries contributed $1.15 billion total gross value to the Tasmanian economy in 2017/18.[5] Diving is a popular sport for Tasmanians, however, accuracy around population data for divers is difficult to achieve due to imprecise surveys, lack of a centralised occupational divers register, and an unregulated recreational divers' register.

According to published information from a combination of reports including the Australasian Diving Safety Foundation, Divers Alert Network Asia-Pacific, and 'Project Stickybeak', from 1995 to 2015 Australia had a total of 222 compressed

gas diving-related deaths, an average of 11 per annum.[6–8] Over these 20 years Tasmania recorded 17 compressed air diving deaths, more than three times the national mortality rate (1.67 versus 0.53 deaths per million population).[2,6–8] The majority of compressed gas diving-related deaths occurred in a 100 km radius of Hobart.[2] Between September 2021 and March 2022, four diving related deaths (three compressed air, one snorkeller) occurred in Tasmanian waters, stimulating a review of the statewide approach for the immediate response of personnel to diving-related deaths, from first responders through to the mortuary.

The Department of Diving and Hyperbaric Medicine (DDHM) at the Royal Hobart Hospital initiated a review of the current chains of communication, external services and internal departments involved, and looked to improve the collection and storage of information and equipment from the sites involved with the diving death. The DDHM's input was often requested by the Tasmania Police Marine and Rescue Service (MRS). Initial retrieval considerations are frequently discussed with the DDHM physicians and forensic analysis of the diving equipment is provided by the DDHM technicians. It was of concern to the DDHM physicians and technicians that critical information for the post-mortem analysis of the victim and their equipment could be lost due to the lack of a centralised, documented process. The DDHM therefore engaged with the office of the Statewide Forensic Medical Services to discuss the merit of implementing a documented process for internal (at the Royal Hobart Hospital) and external agencies. There was also an analysis of how processes across the other hospitals and health centres in Tasmania would be co-ordinated in the event of a deceased diver to support preservation of information for the coronial investigation. The MRS were instrumental in their engagement with the other frontline services, and the coroner's associate, with clarifying the aims of the project.

The main aims for constructing multidisciplinary policies and procedures in approaching a diving victim were to:

- Engage collaboratively with frontline agencies who are the first responders to diving fatalities, the coroner's office via the coroner's associate, and respective departments and personnel within the Tasmanian Health Services who may be involved in a diver's death, with the ultimate aim of providing concise and comprehensive facts for the coroner;
- Construct a reference document (e.g., an aide-mémoire [*Appendix 1]) to support frontline agencies, the coroner's office, and the respective hospitals and departments in approaching this relatively rare event;
- Provide reproducible methods for documentation of information (e.g., digitalised inventory of diving dress and equipment [*Appendix 2] in addition to body worn camera footage) from the scene of the diving incident to the securing and storage of diving equipment for post-mortem analysis;
- Capture time sensitive information, such as ensuring timely access to a post-mortem computed tomography scan, or erect chest X-ray;
- Troubleshoot potential issues with victims being retrieved from remote regions, particularly with respect to time for retrieval to the Royal Hobart Hospital, mode of transport, and weather logistics; and
- Formalise points of communication between external agencies and the hospitals in a single-paged algorithm [*Appendix 3].

We aimed to create statewide protocols for compressed gas diving only, excluding snorkelling and free diving, as the pathophysiology implicated in deaths for these activities may be different. These attendance protocols would also be designed to be instituted for serious diving incidents where death is a possibility to ensure valuable evidence is not lost. It is not the intention of this paper to present or analyse the cause of death of the victims or scrutinise the events surrounding the diving death, rather to focus on elements to enhance the response and communication across agencies and organisations involved in the initial retrieval of the victim, access to, and provision of, time-critical assessment of the victim, recording and retrieval of their equipment, and, ultimately, resolution of the coronial investigation.

Methods

The MRS and DDHM collaborate closely in the event of compressed gas diving deaths, with application of their combined knowledge to assist analysis of diving events and equipment and determine contributing factors to the death. As there were an exceptional number of dive victims over the 2021/22 Summer, an introspective assessment of current hospital-based systems was triggered, as well as procurement of frontline service engagement to develop replicable documents for implementation across the State. This project was conducted through in-person meetings, telephone contact, and email with invested craft groups and their representatives.

In the event of a serious diving-related event, the police statewide radio dispatch services is usually the first point of contact for collation of information on behalf of the Tasmanian Police and Ambulance Tasmania. They, in turn, notify the appropriate services such as the coroner's associate, local uniform members, MRS, and Tasmanian Police Forensic Services, and the Office of the State Forensic Pathologist (based in Hobart). Previously, a non-officiated line of communication ensued from the MRS to the DDHM at the Royal Hobart Hospital, which had been historically implemented through word of mouth. This process stemmed from a time when the MRS engaged with the DDHM to assist

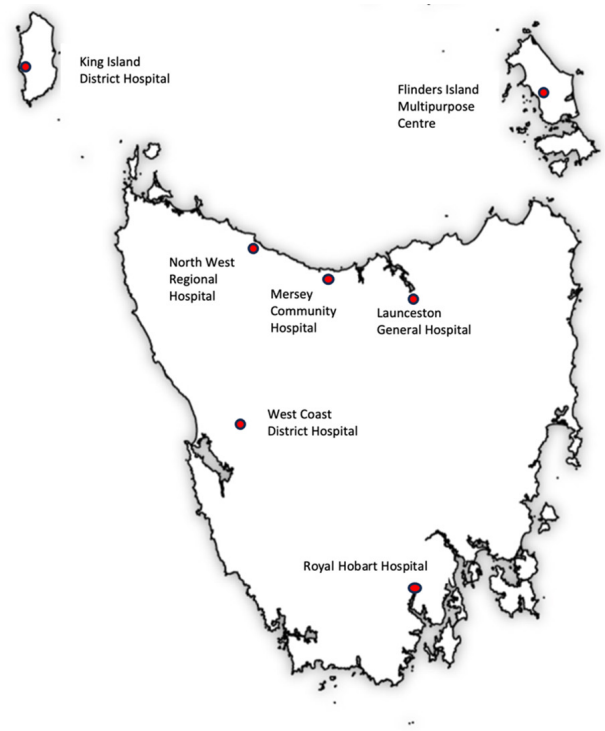
Footnote: * Appendix 1–3 are available on DHM Journal's website: https://www.dhmjournal.com/index.php/journals?id=335

with the post-mortem assessment of the diving gear. With changes in roles and responsibilities within the groups, there was a risk that corporate memory could be lost. In addition, due to the limited number of MRS personnel and the fact that they are based in Hobart, there was a risk for omission of critical information due to inexperienced attending police officers for incidents outside southern Tasmania. There was also a potential risk for delay in timely imaging of the victim to assess whether cerebral arterial gas embolism (CAGE) could be a contributing factor in the death. Therefore, radiology services were also included in the algorithm. From a conversation between the MRS and the DDHM in early 2022, it became evident that expanding the discussion to include the other agencies and departments was essential to ensure inclusive and comprehensive practice in facilitating the best possible outcome for these emotive, stressful, and uncommon incidents.

Tasmania has 12 public hospitals and community centres that service the population in the local region. There were six sectors in the state that were identified for inclusion in the project. The Royal Hobart Hospital in the south, Launceston General Hospital in the north, North West Regional Hospital and Mersey Community Hospital in the north west, West Coast District Hospital in the west of the state, King Island District Hospital and Health Centre, and Flinders Island Multipurpose Centre service the six sectors (Figure 1). In the event of a diving-related death where the victim cannot be retrieved to the Royal Hobart Hospital (preference) alternative plans for each sector were required.

Figure 1

Tasmanian state hospitals and medical facilities involved in the statewide diving related deaths algorithm. Image of the map of Tasmania with hospital locations provided as red spots



Results

Tasmania has a close-knit diving community due to its small population, size and niche recreational and commercial interests and investments in the marine environment. The technicians' in the DDHM work in close association with the MRS and Coroner's Office in assisting with post-mortem analysis and assessment of diving equipment. This combination provided a unique opportunity to engage with ancillary services in revising current practices while addressing the timely management of diving deaths. The impetus was due to the recognition of a lack of a formal process for intrahospital, interhospital and external-agency collaboration in response to a diving-related death. By formalising lines of communication across and within organisations (plus including the possibility of victims not being able to be brought to the Royal Hobart Hospital in a timely manner) this collaboration is projected to improve precision by identifying various contributors to the death, as well as enhancing on-site acquisition of diving equipment.

FRONTLINE AGENCIES

The Tasmanian MRS group engaged the external agency representatives to determine the roles and responsibilities of each craft group. The first responders (State Communications and Operations – representing the radio dispatch services, forensic police services, Ambulance Tasmania, retrieval services) and the coroner's associate were able to illustrate their roles and responsibilities and describe how these integrated with an event, such as a diving death. These discussions were documented and published as an 'aide-mémoire' (*Appendix 1), formulating a coherent line of communication between craft groups. The importance of accurately recording the 'in-situ' status of equipment was recognised. In order to facilitate accurate recording of the equipment a checklist of essential items for first responders attending the scene of a diving death, including basic instructions and explanations, was also created. Three checklists, namely: self-contained underwater breathing apparatus (scuba), surfaced supplied breathing apparatus (SSBA) (including hookah), and mixed gas rebreather (scuba mix) were constructed in such a way that the initial attending police officer, irrespective of their knowledge or experience with the different elements of compressed gas diving, would be able to complete (*Appendix 2). These checklists have been incorporated into Tasmanian police templates as a living document that can be accessed electronically by any personnel attending a diving death scene. Tasmania police procedures were also amended to request attendance at the scene by a police dive squad supervisor where possible, however, specialist verbal advice could be offered at minimum.

HOSPITALS

The Royal Hobart Hospital is the largest referral centre in Tasmania and is where State-wide Forensic Medical Services are based. For three of the six sectors (South, North, and North West) there are dedicated Executive Directors of Medical Services who provide coordination and administrative support to hospital-based medical services for their region. In the rare event that the victim could not be brought to the Royal Hobart Hospital, the Executive Directors of Medical Services for North and North West were engaged by the DDHM to assist with formulation of site-specific considerations for receipt of the diving victim. This was particularly relevant regarding obtaining time-critical post-mortem imaging should the body be housed in their mortuary until transfer to the Royal Hobart Hospital was possible. The radiology departments and external radiology providers were therefore also involved in the collaboration. The West Coast District Hospital based in Queenstown (West), King Island District Hospital and Health Centre (King Island), and Flinders Island Multipurpose Centre (Flinders Island) have a unique structure in that the hospital or centre is primarily serviced by the local general practitioner(s) with provision of medical services coordinated through Ochre Health Group. In this instance, the Tasmanian co-ordinator for Ochre was identified to be the point of contact, allowing for communication across the sites should initial, time-critical post-mortem imaging need to take place in these locations.

RADIOLOGY SERVICES

Radiological services for all six health services (North West Regional Hospital includes the Mersey Hospital campus) differ with the Royal Hobart Hospital and Launceston General Hospital both having all hour's access to in-house radiology, including computed tomography (CT) scans. The North West facilities can access urgent radiology support afterhours (2300 to 0700) through a private radiology group, which comes with a private fee for CT scans. The West, King Island, and Flinders Island facilities have access to X-rays only. Where private services are required, the coroner's associate, on behalf of the coroner's office, provides the authority to request access to these resources (see *Appendix 3).

In order to determine if decompression illness (DCI), particularly cerebral arterial gas embolism (CAGE), is implicated in the diving death, a timely post-mortem CT of the victim's head, chest and abdomen is required within eight hours to detect gas, particularly in the cerebral arteries and heart chambers.[9] The optimal timing of a post-mortem CT is within three hours. This is because of nitrogen off-gassing in the victim during the post-mortem period which can contribute to artefactual gas at autopsy.[9] Beyond eight hours, there is considerably less value in a post-mortem CT due to the presence of gas from putrefaction.[9] Where CT services are not accessible, as for the services supported by Ochre Health Group, erect chest X-ray (CXR) should suffice in assisting with visualising gas in the thorax within the time restriction.[9] Post-mortem CTs and CXRs are also difficult to interpret with a history of cardiopulmonary resuscitation (CPR), particularly with advanced CPR involving intubation and positive airway pressure support.[9]

Discussion

DIVING AS A DISCIPLINE

There are currently five disciplines of diving (snorkelling, free diving, scuba, surface supply breathing apparatus, mixed gas scuba diving), which are primarily divided according to what gas used for breathing (compressed air vs other gas mixtures), and how it is accessed (self-contained vs surface-supplied). Snorkellers swim on the surface with the aid of a mask, snorkel and fins and do not use compressed gas. Free diving is when divers breathe air at the surface and breath-hold dive. This cohort of divers were excluded from this current diving deaths assessment due to the absence of compressed gas causes of death. Scuba diving is when divers breathe air from cylinders mounted on their back. Surface supply breathing apparatus is when divers have an umbilicus attached to their air source, supplying air from the atmosphere via a compressor or from large gas cylinders on the surface. Surface supply is used interchangeably with the term 'hookah' breathing apparatus. Technical diving using scuba equipment and mixed gases (oxygen with a specific mix of nitrogen and/or helium) is becoming more popular. Mixed gases can also be utilised via surface supplied breathing apparatus. Technical diving can also include the use of rebreather circuits, which allow the breathing gas to be 'scrubbed' of carbon dioxide and re-breathed in order to extend diver submersion time and has the added bonus of producing very few exhaled gas bubbles.

There are many organisations and groups within Tasmania that support and train the diving industry, both commercially and recreationally. Tasmania is home to one of only two diver training schools globally that provides construction and saturation diving instruction that complies with Australian Diver Accreditation Scheme (ADAS) level 1 to 4 certification. There are some 12 recreational dive clubs in Tasmania, including a university-based organisation. The Institute for Marine and Antarctic Science is a centre of excellence with education and research with the University of Tasmania and supports many scientific divers. Tasmania and its associated islands provide 26% of the Australian production for the commercial wild fish and aquaculture industry with only 0.9% of the land mass.[3,10]

RISKS WITH DIVING

Diving is a safe pastime and occupation. However, there are known inherent risks with compressed gas diving. Regarding diving in Tasmanian waters, there are regional anomalies

that add risks, such as the colder water temperature, remote locations, and technical difficulty of diving. There is an increased risk of immersion pulmonary oedema, for example, due to the colder temperatures.[11,12] The colder water can induce hypothermia, impacting on a person's ability to self-rescue. Diving in colder temperatures (generally < 14°C) necessitates wearing thicker insulation with the need to increase weights and the resultant greater exertion required by the wearer. It can also increase the risk of DCI through augmented 'on-gassing'.[13] A recent study found that there is a negative effect on thicker wetsuits (> 7 mm) on smaller chest circumferences with respiratory function (change of FVC up to 15%).[14] The colder water (~11°C) in winter, however, still entices divers as it provides the best conditions with visual clarity underwater, with the better, well known Tasmanian dive sites down to 40 m depth.[15]

A recent study[2] conducted an assessment of factors contributing to Tasmanian diver deaths between 1995–2015 based on previously published methodology.[16] Of the 17 Tasmanian recreational compressed gas diving deaths, five were SSBA and 12 were scuba divers, with no occupational diver deaths in this period.[2] While drowning was the main cause of death, CAGE was the next most common (four or five of 17 deaths).[2]

CAGE AND POST-MORTEM CT SCAN

Cerebral arterial gas embolism secondary to pulmonary barotrauma is a known disabling condition and cause of death in compressed gas diving. It is implicated in approximately 15% of Australian diving deaths[6] and was overrepresented in up to 5/17 (29%) of Tasmanian diving deaths.[2]

Nitrogen accumulates in body tissues and intravascular space with depth of diving over time. The nitrogen can then precipitate out of solution due to decreased ambient pressure with ascent. The ascent can be to the water's surface, and may then be exacerbated by altitude (e.g., during retrieval). This contributes to post-mortem decompression of the tissues, which, combined with decomposition, can result in artefactual gas over time, hence the urgency for post-mortem CT or erect CXR and considerations for the method of retrieval of the victim.[9] An X-ray is the only imaging available in the remote Tasmanian locations of Queenstown, King Island, and Flinders Island.

TRANSPORT

Nitrogen off-gassing places theoretical restrictions on modes of transport over 300 m altitude, i.e., with road travel via mortuary ambulance, fixed-wing or rotary-wing retrieval.[17] The primary consideration, however, is time to imaging and not so much the effect of altitude on the tissues with respect to 'off gassing' and post-mortem decomposition. The retrieval services, DDHM physician and forensic pathologist should discuss considerations for retrieval of the body, and the coroner's associate confirms the decision for the method of transport, i.e., land versus air. The preference is for the victim to be brought to the Royal Hobart Hospital, where the Office of the State Forensic Pathologist is based. This is where the majority of post-mortems for diving deaths have taken place in the past. Rarely, does urgent initial processing of the deceased body need to take place outside of the Royal Hobart Hospital. The prioritisation of a deceased retrieval was agreed by all parties to be triaged lower than a live retrieval. This could influence where the victim would initially be assessed, dependent on location, weather conditions, and access to appropriate transport means. Therefore, all six medical services needed to be engaged in the process for assessing a diving death.

CARBOXYHAEMOGLOBIN

Other potential influences on a diver's death could include disabling doses of drugs, ethanol, and carbon monoxide (CO). The latter has been implicated in compressed gas diving deaths, particularly with SSBA as it is a colourless, odourless, tasteless, non-irritative gas that can enter the diver's breathing gas supply, and which competes with oxygen binding to haemoglobin, forming carboxyhaemoglobin (COHb). The depuration rates for COHb, drugs, and to some extent, ethanol are such that the concentrations remain stable in the victim after death and allows for delayed sampling which can be undertaken by the forensic pathologist at post-mortem.[18–20]

LIMITATIONS

This project was successful in that Tasmania is a small state regarding population size and land mass. The processes undertaken to enact the state-wide engagement may not be appropriate in larger states but could be applicable to individual regions in Australia.

Conclusions

Diving is a relatively safe sport, although diving deaths are over-represented in Tasmania. This could be due to the greater number of divers per head of population and the more challenging marine conditions. Between September 2021 and March 2022 there were three compressed gas diving deaths in Tasmania that stimulated a review of the statewide response from frontline to hospital-based personnel. Each craft group plays a pivotal role in providing timely post-mortem assessment and collection of information from:

- the diving site (i.e., photo documentation of the site, body-worn camera footage, equipment set-up, corroborating witness statements);
- the deceased body (i.e., depending on location post-mortem CT/erect CXR, autopsy); and
- collation of information (i.e., body-worn camera footage, witness statements, post-mortem diving equipment analysis, expert analysis of all information).

We would encourage other states to consider the benefits of establishing interagency collaboration. The statewide engagement in diving-related deaths fostered sharing of knowledge, camaraderie, and appreciation for each craft group's value in supporting the Tasmanian community.

References

1 Australian Bureau of Statistics [Internet]. Snapshot of Tasmania. High level summary data for Tasmania in 2021. 2022. [cited 2023 Jan 15]. Available from: https://www.abs.gov.au/articles/snapshot-tas-2021.

2 Ascencio-Lane JC, Smart D, Lippmann J. A 20-year analysis of compressed gas diving-related deaths in Tasmania, Australia. Diving Hyperb Med. 2019;49:21–9. doi: 10.28920/dhm49.1.21-29. PMID: 30856664. PMCID: PMC6526051.

3 University of Tasmania, Institute for Marine and Antarctica Science. Fisheries and aquaculture; 2021. [cited 2023 July 19]. Available from: https://www.imas.utas.edu.au/research/fisheries-and-aquaculture.

4 Tasmanian Seafood Industry Council. Seafood industry workforce profile [Internet]. 2017. [cited 2022 Aug 15]. Available from: https://www.skills.tas.gov.au/__data/assets/pdf_file/0010/174934/Seafood_Industry_Workforce_Profile_-_May_2017.PDF.

5 Fisheries Research and Development Corporation, Institute for Marine and Antarctic Studies, and BDO EconSearch. Tasmanian fisheries and aquaculture industry 2017/18: economic contributions summary; 2019. [cited 2023 Jul 19]. Available from: https://www.imas.utas.edu.au/__data/assets/pdf_file/0007/1308067/Economic-Contributions_TAS-Summary_NOV2019.pdf.

6 Lippmann J. Snorkelling and breath-hold diving fatalities in Australia, 2001 to 2013. Demographics, characteristics and chain of events. Diving Hyperb Med. 2019;49:192–203. doi: 10.28920/dhm49.3.192-203. PMID: 31523794. PMCID: PMC6884103.

7 Lippmann J, Stevenson C, McD Taylor DM. Scuba diving fatalities in Australia, 2001 to 2013: diver demographics and characteristics. Diving Hyperb Med. 2020;50:105–14. doi: 10.28920/dhm50.2.105-114. PMID: 32557411. PMCID: PMC7481108.

8 Lippmann J. Fatalities involving divers using surface-supplied breathing apparatus in Australia, 1965 to 2019. Diving Hyperb Med. 2021;51:53–62. doi: 10.28920/dhm51.1.2-9. PMID: 33761535. PMCID: PMCID: PMC8084708.

9 The Royal College of Pathologists of Australia. Autopsy and the investigation of scuba diving fatalities. [Approved: 2003 July, Reviewed: 2009 August and 2013 August]. 2013. [cited: 2022 Aug 15]. Available from: https://www.rcpa.edu.au/getattachment/eb46cf47-cf52-4845-91a1-e799ab4cb969/Autopsy-and-the-Investigation-of-Scuba-Diving-Fata.aspx.

10 Australian Bureau of Statistics [Internet]. 1384.6 – Statistics – Tasmania, 2008. [cited 2023 Jul 19]. Available from: https://www.abs.gov.au/ausstats/abs@.nsf/0/D1C2967E40D51C1DCA2573C5000D9EC3?opendocument.

11 Edmonds C. The evolution of scuba divers pulmonary edema. Undersea Hyperb Med. 2016;43:83–91. PMID: 27265985.

12 Hageman SM, Chakraborty RK, Murphy-Lavoie HM. Immersion pulmonary edema. StatPearls [Internet]. Treasure Island (FL): StatPearls Publishing; 2024 Jan. PMID: 29763028.

13 Toner C, Ball R. The effect of temperature on decompression and decompression sickness risk: a critical review. Naval Medical Research Institute; 2004. [cited 2023 Jul 28]. Available from: https://apps.dtic.mil/sti/pdfs/ADA445847.pdf.

14 Stevens G, Smart D, Cox M. The influence of wet suit thickness (7 mm and over) on lung function in scuba divers. Thesis submission for SPUMS Diploma.

15 The Tasmanian Travel Booking Site; Tasmania [Internet]. Scuba Diving; c2023. [cited 2023 Aug 4]. Available from: https://tasmania.com/adventure-sports-activities/scuba-diving/.

16 Lippmann J, Stevenson C, Taylor DM, Williams J, Mohebbi M. Chain of events analysis for a scuba diving fatality. Diving Hyperb Med. 2017;47:144–54. doi: 10.28920/dhm47.3.144-154. PMID: 28868594. PMCID: PMC6159623.

17 Smart D. Health risk management in the Tasmanian abalone diving industry. Diving Hyperb Med. 2010;40: 83–7. PMID: 23111899. [cited 2023 Jul 28]. Available from: https://dhmjournal.com/images/IndividArticles/40June/Smart_dhm.40.2.83-87.pdf.

18 Holmgren P, Druid H, Holmgren A, Ahlner J. Stability of drugs in stored postmortem femoral blood and vitreous humor. J Forensic Sci. 2004;49:820–5. PMID: 15317202.

19 Kunsman GW, Presses CL, Rodriguez P. Carbon monoxide stability in stored postmortem blood samples. J Anal Toxicol. 2000;24:572–8. doi: 10.1093/jat/24.7.572. PMID: 11043662.

20 Sutlovic D, Versic-Bratincevic M, Definis-Gojanovic M. Blood alcohol stability in postmortem blood samples. Am J Forensic Med Pathol. 2014;35:55–8. doi: 10.1097/PAF.0000000000000077. PMID: 24457583.

Acknowledgements

The authors would like to thank Senior Constable Scott Williams, Dr Chris Lawrence, and Dr John Lippmann. The authors would also like to acknowledge and thank the support from the Tasmanian frontline agency representatives, and representatives from the Royal Hobart Hospital, Launceston General Hospital, North West Regional Hospital, Mersey Hospital, and Ochre Medical Group.

Conflicts of interest and funding: nil

Submitted: 6 November 2023
Accepted after revision: 16 February 2024

The use of hyperbaric oxygen for avascular necrosis of the femoral head and femoral condyle: a single centre's experience over 30 years

John RB Currie[1], Ian C Gawthrope[1], Neil D Banham[1]

[1] *Department of Hyperbaric Medicine, Fiona Stanley Hospital, Perth, Australia*

Corresponding author: *Dr John Currie, Department of Hyperbaric Medicine, Fiona Stanley Hospital, 102-118 Murdoch Drive, Murdoch WA 6150, Australia*
ORCiD: *0009-0009-0086-4953*
john.currie51@yahoo.co.uk

Keywords
Bone healing; Bone necrosis; Dysbaric osteonecrosis; Hyperbaric research; Inflammation; Orthopaedics; Treatment

Abstract
(Currie JRB, Gawthrope IC, Banham ND. The use of hyperbaric oxygen for avascular necrosis of the femoral head and femoral condyle: a single centre's experience over 30 years. Diving and Hyperbaric Medicine. 2024 30 June;54(2):92–96. doi: 10.28920/dhm54.2.92-96. PMID: 38870950.)
Introduction: Avascular necrosis (AVN) is a rare progressive degenerative disease leading to bone and joint destruction. Patients often require surgical intervention. Femoral AVN is the most common anatomical location. Hyperbaric oxygen treatment (HBOT) has been shown to be effective in AVN. We present data collected from one centre over a 30-year period and compare the results with other published data.
Methods: A retrospective chart review of all patients receiving HBOT for AVN at Fremantle and Fiona Stanley Hospitals since 1989 was performed. The primary outcome was radiological appearance using the Steinberg score, with secondary outcomes being subjective improvement, the need for joint replacement surgery and rates of complications.
Results: Twenty-one joints in 14 patients (14 femoral heads and seven femoral condyles) were treated with HBOT since 1989. Two patients were excluded. Within the femoral head group, nine of the 14 joints (64%) had stable or improved magnetic resonance imaging (MRI) scans post treatment and at six months (minimum); 10 joints (71%) had good outcomes subjectively, three joints required surgical intervention, and three patients developed mild aural barotrauma. Within the femoral condyle group, all five joints had stable or improved post-treatment MRI scans (four had visible improvement in oedema and/or chondral stability), four joints reported good outcomes subjectively, none of the patients required surgical intervention (follow-up > six months).
Conclusions: This single centre retrospective study observed prevention of disease progression in femoral AVN with the use of HBOT, comparable to other published studies. This adds to the body of evidence that HBOT may have a significant role in the treatment of femoral AVN.

Introduction

Avascular necrosis (AVN) is a progressive degenerative disease affecting an estimated 300,000–600,000 people worldwide each year.[1,2] It is relatively rare yet its negative impact on joint function and quality of life is significant. The femoral head is by far the most common anatomical location and makes up 75% of all cases of AVN, while AVN of the femoral condyle, otherwise known as spontaneous osteonecrosis of the knee (SONK) makes up only 2.5%.[3] AVN develops secondary to compromised intraosseous blood supply causing necrosis and apoptosis of the bone, followed by structural instability and collapse.[4–6]

The causes of AVN generally fall into three categories: traumatic, idiopathic and secondary.[7] Risk factors for secondary AVN include prolonged steroid use (most common), diabetes mellitus, alcoholism, musculoskeletal decompression sickness and sickle cell disease.[8] The grading of AVN varies but one well established scale is the Steinberg classification which grades AVN from one to six (I–VI) based on radiological appearance and clinical symptoms (Table 1).[9,10]

The natural history of AVN has been well described in the literature and evidence suggests that without intervention it will progress in the majority of patients.[11] However, the rate of AVN progression can be hard to predict and can vary depending upon the aetiology of underlying risk factors and patient demographics. The progressive nature of the disease leads to radiological evidence of progression which can generally be observed within six to twelve months. One study followed-up patients with early (Stage I & II) AVN of the hip over a 12-month period and found statistically significant magnetic resonance imaging (MRI) progression with lesion width progressing from 22.4 mm to 26.4 mm.[12] Another found that 80–85% of symptomatic patients will go on to have subchondral collapse within two years.[13,14]

Table 1
Steinberg grading system; MRI – magnetic resonance imaging

Grade	Description
0	Normal radiographs, bone scan and MRI
1	Normal radiograph Abnormal bone scan and/or MRI
2	Abnormal radiograph with cystic and sclerotic changes
3	Subchondral collapse producing crescent sign
4	Flattening of the femoral head
5	Joint space narrowing
6	Advanced secondary degenerative changes

In view of this, specialists have traditionally managed AVN aggressively at early stages to slow or even prevent progression to subchondral collapse.

Treatment options for early AVN are all focused on reducing oedema and preventing further destruction of the joint, therefore delaying, or avoiding the need for joint replacement.[15]

The concept that hyperbaric oxygen treatment (HBOT) could be used as a treatment for AVN can be dated back to the 1990s when its potential beneficial effects were first hypothesised.[16] Hyperbaric oxygen can temporarily restore tissue normoxia and has been shown to reduce oedema at the level of the microcirculation which may lead to reduced venous stasis.[17–20]

In recent years HBOT has been used with increasing frequency in the treatment of early Stage I and II AVN of the femoral head and femoral condyle.[21,22] Despite this, there have only been a small number of human studies evaluating the effectiveness of HBOT in AVN of the femoral head and a single study assessing AVN of the femoral condyle.[23]

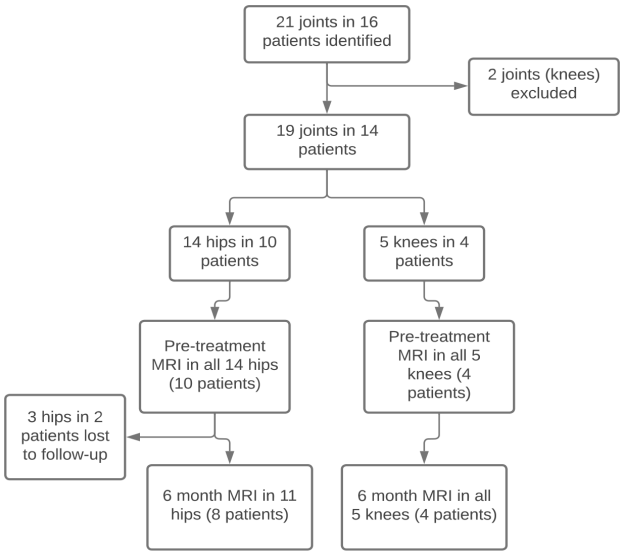
We present data collected from one centre (Fremantle Hospital Hyperbaric Medicine Unit (HMU) from November 1989 to November 2014, which transitioned to Fiona Stanley Hospital (FSH) HMU in November 2014) over the past 30 years and compare these results to those previously published and review the available literature.

Methods

Approval was obtained for data review and extraction by Governance, Evidence, Knowledge and Outcomes (GEKO) at FSH (Approval Number 42155).

A literature search of publications was performed using PubMed, with 25 relevant publications identified. Thirteen studies directly related to the use of HBOT for AVN of the femoral head and one study reported the use of HBOT for AVN of the femoral condyle.

Figure 1
Patient selection and follow-up flow diagram; MRI – magnetic resonance imaging



The FSH HMU database was searched for all cases of AVN receiving HBOT since 1989. Patients included in this study must have received at least 20 sessions of HBOT and have radiologically confirmed AVN with a pre-treatment Steinberg score of I–IV. A HBOT session was defined as treatment with 100% oxygen (O_2) at a pressure of at least 200 kPa (two atmospheres absolute [atm abs], 10 metres of seawater equivalent) for at least 60 minutes (Figure 1).

The primary outcome measure was interval change in MRI on follow-up imaging. Post-treatment MRIs were performed within six months of the last HBOT session. Secondary outcome measures included subjective improvement on follow-up (overall subjective satisfaction from one to five), the need for joint replacement surgery and complication rates.

STATISTICAL ANALYSIS

Observational results were collated on an encrypted Excel spreadsheet prior to statistical analysis. Results were analysed via IBM SPSS Statistics 28.0.1 software using ANOVA and paired *t*-tests. Significance was accepted when $P < 0.05$. The null hypothesis was that there would be no statistically significant difference in radiologic outcomes between the femoral head and femoral condyle AVN groups.

Results

We identified 21 joints in 14 patients (14 femoral heads and seven femoral condyles) treated with HBOT since

Table 2
Comparison of outcome measures between avascular necrosis (AVN) of the femoral head and femoral condyle groups; HBOT – Hyperbaric oxygen treatment; MRI – Magnetic resonance imaging; SONK – Spontaneous osteonecrosis of the knee

Outcome measure	AVN femoral head (*n* = 14)	SONK (*n* = 5)
Mean age (years)	38 (28–66)	58 (46–77)
Percentage females	36%	40%
Smoking history	8 (57%)	2 (40%)
Mean body mass index ($kg \cdot m^{-2}$)	2.3	2.2
Mean pre-HBOT Steinberg score	2.3	2.2
Mean number HBOT treatments	45 (30–76)	32 (30–38)
Stable/improved follow-up MRI	10 (71%)	5 (100%)
Satisfaction upon completion of HBOT	13 (93%)	5 (100%)
Satisfaction at six months	10 (71%)	4 (80%)

1989. Two patients were excluded (two joints); one patient had declined treatment and one failed to return after their fourth treatment. All patients were treated with a 243 kPa (2.4 atm abs) table either in a multiplace chamber (14:90:24 table – being compression to 14 metres of seawater equivalent [243 kPa] for a total of 90 minutes breathing 100% O_2 with a five-minute air-break then 24 minutes decompression on 100% O_2) or monoplace chamber (14:90:08 table).

The mean age of patients for AVN of the femoral head was 38 years (range 28–66). The age range in the femoral condyle group was greater (46–77) with a mean age of 58 years. In the AVN femoral head group 36% were female compared to 40% in the femoral condyle group. Within the AVN femoral head group, two patients (two joints) were identified as current smokers and a further five patients (six joints) were identified as ex-smokers while within the AVN femoral condyle group there were no current smokers, and two patients (two joints) were identified as ex-smokers. Amongst the smokers and ex-smokers there was a mean pack year history of 12 years within the AVN femoral head group vs 22 years amongst the AVN femoral condyle group. The mean body mass index (BMI) among the AVN femoral head cohort was 24.8 vs 27.6 $kg \cdot m^{-2}$ within the femoral condyle group. The number of HBOT administered varied between the two cohorts with the average in the AVN hip group being 45 (30–76) compared to 32 (30–38) in the femoral condyle group. Pre-treatment Steinberg score for both groups were similar (2.3 for femoral head vs 2.2 for femoral condyle). Patient demographics are shown in Table 2.

Within the femoral head group, nine of the 14 joints (64%) had stable or improved MRI scans post-treatment (within six months of completion) and on follow up after at least six months, 10 joints (71%) reported good outcomes subjectively (Table 2). Two of the 14 patients (three hips) had no follow-up MRI (one because of acute intercurrent illness and one because of the progression to joint replacement surgery). Of the AVN femoral head cohort 10 joints were followed up beyond six months (one to 10 years) with a mean follow-up of time of six years. Two joints had evidence of slight progression on MRI at 10 years. Five joints had stable or improved appearance on MRI at long term follow-up. A total of three joints (in three patients) required surgical intervention (two total hip replacements and one hip resurfacing). Of the patients requiring joint replacement surgery, all three had pre-intervention Steinberg scores of III or more. Of the 14 patients within the femoral head AVN group, three suffered from minor complications of HBOT (mild aural barotrauma). There were no serious complications documented.

Within the femoral condyle group, all five joints had stable or improved post-treatment MRI scans with four having visible improvement in oedema and/or chondral stability (Table 2). At six-month (minimum) follow-up, four of the five joints had a good subjective outcome. None of the five joints had required subsequent surgical intervention (follow-up time ranging from six months to two years). One patient sustained a Teed grade four aural barotrauma during HBOT necessitating otolaryngology consultation, but no long-term sequelae.

When the primary outcome measure between the two groups was compared, we found that 64% of the femoral head AVN group had no deterioration radiologically on follow-up MRI whereas none of the five patients in the femoral condyle group deteriorated. Subjective satisfaction at zero months and then six months were compared between the two groups. All patients (five joints) were satisfied on completion of HBOT in the femoral condyle group compared to 92%

(13 joints) in the femoral head group. At six months (four of five joints) in the femoral condyle group versus 71% (10 joints) in the femoral head group were satisfied with their outcomes. There was no statistically significant difference in primary outcome between the two groups ($P = 0.795$).

When data were combined for both groups, follow-up MRI showed that 15 joints (79%) had no deterioration radiologically with eight joints (42%) showing evidence of improvement. Subjectively, 10 patients (14 joints) (74%) were satisfied at six-month (minimum) follow-up. One patient (one joint) reported poor subjective outcome and another three patients (four joints) failed to complete the follow-up questionnaire.

Discussion

Avascular necrosis is a relatively rare condition, yet it is responsible for significant morbidity and its impact on quality of life can be profound. The secondary causes of AVN are most prevalent. Common risk factors for secondary AVN include prolonged steroid use, diabetes mellitus, alcoholism, musculoskeletal decompression sickness and sickle cell disease.[8] With diabetes rates increasing, the incidence of secondary AVN is increasing.[7]

The pathogenesis of AVN after disruption of bone microcirculation seems to be multifactorial but involves death of osteoclasts, bone marrow oedema and venous stasis.[10,24,25] It is also hypothesised that the imbalance of osteoclastic and osteoblastic cells is as a result of increased activity of receptor activator of nuclear factor-kappa B ligand (RANKL) and a comparative reduction in activity of osteoprotegerin (OPG) which leads to increased bone resorption and reduced production.[19] The consequence of these pathological processes is collapse of the necrotic bone leading to loss of normal anatomy. It is thought that HBOT acts to reduce oedema and venous stasis in compromised tissue by restoring normoxia at the tissue level and modulation of the RANKL:OPG system. It has also been shown that HBOT produces reactive oxygen and nitrogen species which initiate a multitude of anti-inflammatory pathways and induction of angiogenesis.[26] The initiation of new blood vessel formation along with suppression of inflammation may contribute to the therapeutic effect of HBOT in AVN.

Even though there appears to be a convincing biological basis for theorising that HBOT should be effective in AVN, there have been few studies. This study evaluated and compared the use of HBOT in AVN of the femoral head and femoral condyle. Despite the limitations of being a retrospective study with a small sample size, this study reported similar results for the use of HBOT in femoral AVN to other published studies. When we compare our results for AVN of the femoral head to the prospective study published by Reis et al in 2003 we found a 93% subjective improvement at six-month follow-up vs an 83% improvement in the Reis study.[16] Objective results using MRI found similar results with 79% of patients showing stable or improved MRI findings at follow-up vs 81% in Reis' study. When comparing the effectiveness of HBOT in AVN of the femoral condyle with AVN of the hip we found the results to be comparable with no significant difference though our study was too small to evaluate this reliably.

Conclusions

AVN of the femur is a debilitating disease that progresses towards subchondral articular collapse requiring surgical intervention if left untreated.[13] The results from this single centre retrospective study observed improved bone stability and prevention of disease progression on follow-up for femoral AVN treated with HBOT. This finding is comparable to other published data and suggests benefit when compared to the expected progression of disease both subjectively and radiologically.[11,12] We also observed several patients in both groups with both radiological and subjective improvement after HBOT. This study adds to the body of evidence that HBOT may have a significant role in the treatment of femoral AVN.

References

1 Ferri FF. Ferri's clinical advisor. 1st ed. Philadelphia: Elsevier; 2018. p. 166.

2 Kang JS, Park S, Song JH, Jung YY, Cho MR, Rhyu KH. Prevalence of osteonecrosis of the femoral head. J Arthroplasty. 2009;24:1178–83. doi: 10.1016/j.arth.2009.05.022. PMID: 19640674.

3 Cooper C, Steinbuch M, Stevenson R, Miday R, Watts NB. The epidemiology of osteonecrosis: findings from the GPRD and THIN databases in the UK. Osteoporos Int. 2010;21:569–77. doi: 10.1007/s00198-009-1003-1. PMID: 19547906. PMCID: PMC2832873.

4 Shah KN, Racine J, Jones LC, Aaron RK. Pathophysiology and risk factors for osteonecrosis. Curr Rev Musculoskelet Med. 2015;8:201–9. doi: 10.1007/s12178-015-9277-8. PMID: 26142896.

5 Gunes AE, Aktas S. A review of hyperbaric oxygen therapy for avascular necrosis. Acta Medica Mediterr. 2017;33:29–34. doi: 10.19193/0393-6384_2017_1_004.

6 Lafforgue P. Pathophysiology and natural history of avascular necrosis of bone. Joint Bone Spine. 2006;73:500–7. doi: 10.1016/j.jbspin.2006.01.025. PMID: 16931094.

7 Mont MA, Jones LC, Hungerford DS. Nontraumatic osteonecrosis of the femoral head: ten years later. J Bone Joint Surg Am. 2006;88:1117–32. doi: 10.2106/JBJS.E.01041. PMID: 16651589.

8 Glimcher MJ, Kenzora JE. The biology of osteonecrosis of the human femoral head and its clinical implications: II. The pathological changes in the femoral head as an organ and in the hip joint. Clin Orthop Relat Res. 1979;139:283–312. PMID: 455846.

9 Steinberg ME, Hayken GD, Steinberg DR. A quantitative system for staging avascular necrosis. J Bone Joint Surg Br. 1995;77:34–41. doi 10.1302/0301-620X.77B1.7822393.

PMID: 7822393.
10 Brown TD, Baker KJ, Brand RA. Structural consequences of subchondral bone involvement in segmental osteonecrosis of the femoral head. J Orthop Res. 1992;10:79–87. doi: 10.1002/jor.1100100110. PMID: 1727938.
11 Lespasio MJ, Sodhi N, Mont MA. Osteonecrosis of the hip: a primer. Perm J. 2019;23:18–100. doi: 10.7812/TPP/18-100. PMID: 30939270. PMCID: PMC6380478.
12 Väänänen M, Tervonen O, Nevalainen MT. Magnetic resonance imaging of avascular necrosis of the femoral head: predictive findings of total hip arthroplasty. Acta Radiol Open. 2021;10(4):20584601211008379. doi: 10.1177/20584601211008379. PMID: 35140984. PMCID: PMC8819766.
13 Mont MA, Hungerford DS. Non-traumatic avascular necrosis of the femoral head. J Bone Joint Surg Am. 1995;77:459–74. doi: 10.2106/00004623-199503000-00018. PMID: 7890797.
14 Urbaniak JR, Harvey EJ. Revascularization of the femoral head in osteonecrosis. J Am Acad Orthop Surg. 1998;6:44–54. doi: 10.5435/00124635-199801000-00005. PMID: 9692940.
15 Camporesi E, Vezzani G, Zanon V, Manelli D, Enten G, Quartesan S, et al. Review on hyperbaric oxygen treatment in femoral head necrosis. Undersea Hyperb Med. 2017;44:497–508. doi: 10.22462/11.12.2017.1. PMID: 29281187.
16 Reis ND, Schwartz O, Militianu D, Ramon Y, Levin D, Norman D, et al. Hyperbaric oxygen therapy as a treatment for stage-I avascular necrosis of the femoral head. J Bone Joint Surg Br. 2003;85:371–5. doi: 10.1302/0301-620x.85b3.13237. PMID: 12729112.
17 Camporesi EM, Bosco G. Mechanisms of action of hyperbaric oxygen therapy. Undersea Hyperb Med. 2014;41:247–52. PMID: 24984320.
18 Samara S, Dailiana Z, Chassanidis C, Koromila T, Papatheodorou L, Malizos KN, et al. Expression profile of osteoprotegerin, RANK and RANKL genes in the femoral head of patients with avascular necrosis. Exp Mol Pathol. 2014;96:9–14. doi: 10.1016/j.yexmp.2013.10.014. PMID: 24200492.
19 Vezzani G, Quartesan S, Cancellara P, Camporesi E, Mangar D, Bernasek T, et al. Hyperbaric oxygen therapy modulates serum OPG/RANKL in femoral head necrosis patients. J Enzyme Inhib Med Chem. 2017;32:707–11. doi: 10.1080/14756366.2017.1302440. PMID: 28385082.
20 Li W, Ye Z, Wang W, Wang K, Li L, Zhao D. Clinical effect of hyperbaric oxygen therapy in the treatment of femoral head necrosis: A systematic review and meta-analysis. Orthopade. 2017;46:440–6. doi: 10.1007/s00132-016-3360-8. PMID: 27928615.
21 Camporesi EM, Vezzani G, Bosco G, Mangar D, Bernasek TL. Hyperbaric oxygen therapy in femoral head necrosis. J Arthroplasty. 2010;25:118–23. doi: 10.1016/j.arth.2010.05.005. PMID: 20637561.
22 Koren L, Ginesin E, Melamed Y, Norman D, Levin D, Peled E. Hyperbaric oxygen for stage I and II femoral head osteonecrosis. Orthopedics. 2015;38:e200–5. doi: 10.3928/01477447-20150305-57. PMID: 25760507.
23 Bosco G, Vezzani G, Enten G, Manelli D, Rao N, Camporesi EM. Femoral condylar necrosis: treatment with hyperbaric oxygen therapy. Arthroplast Today. 2018;4:510–5. doi: 10.1016/j.artd.2018.02.010. PMID: 30560184. PMCID: PMC6287235.
24 Aaron RK, Dyke JP, Ciombor DM, Ballon D, Lee J, Jung E, et al. Perfusion abnormalities in subchondral bone associated with marrow edema, osteoarthritis, and avascular necrosis. Ann N Y Acad Sci. 2007;1117:124–37. doi: 10.1196/annals.1402.069. PMID: 18056039.
25 Vande Berg BE, Malghem JJ, Labaisse MA, Noel HM, Maldague BE. MR imaging of avascular necrosis and transient marrow edema of the femoral head. Radiographics. 1993;13:501–20. doi: 10.1148/radiographics.13.3.8316660. PMID: 8316660.
26 Paderno E, Zanon V, Vezzani G, Giacon TA, Bernasek TL, Camporesi EM, et al. Evidence-supported HBO therapy in femoral head necrosis: a systematic review and meta-analysis. Int J Environ Res Public Health. 2021;18:2888. doi: 10.3390/ijerph18062888. PMID: 33808951.

Conflicts of interest and funding: nil

Submitted: 28 September 2023
Accepted after revision: 13 April 2024

Survey comparing the treatment of central retinal artery occlusion with hyperbaric oxygen in Australia and New Zealand with the recommended guidelines as outlined by the Undersea and Hyperbaric Medical Society

William Emmerton[1], Neil D Banham[2], Ian C Gawthrope[2]

[1] *Department of Anaesthesia and Hyperbaric Medicine, Royal Adelaide Hospital, Adelaide, Australia*
[2] *Department of Hyperbaric Medicine, Fiona Stanley Hospital, Perth, Australia*

Corresponding author: *Dr William Emmerton, Department of Anaesthesia and Hyperbaric Medicine, Royal Adelaide Hospital, Port Road, Adelaide, SA 5000, Australia*
ORCiD: *0009-0007-0996-0728*
william.emmerton@sa.gov.au

Keywords
Blindness, sudden; Hyperbaric oxygen treatment; Hypoxia; Medical conditions and problems; Ophthalmology; Questionnaire; Vision

Abstract
(Emmerton W, Banham ND, Gawthrope IC. Survey comparing the treatment of central retinal artery occlusion with hyperbaric oxygen in Australia and New Zealand with the recommended guidelines as outlined by the Undersea and Hyperbaric Medical Society. Diving and Hyperbaric Medicine. 2024 30 June;54(2):97–104. doi: 10.28920/dhm54.2.97-104. PMID:38870951.)
Introduction: Central retinal artery occlusion (CRAO) presents suddenly causing painless loss of vision that is often significant. Meaningful improvement in vision occurs in only 8% of patients with spontaneous reperfusion. Hyperbaric oxygen treatment (HBOT) is considered to be of benefit if commenced before retinal infarction occurs. The Undersea and Hyperbaric Medical Society (UHMS) guidelines on the management of CRAO were last amended in 2019. This survey questioned Australian and New Zealand (ANZ) hyperbaric medicine units (HMUs) about the incidence of CRAO cases referred and compared their subsequent management against the UHMS guidelines.
Methods: An anonymous survey via SurveyMonkey® was sent to all 12 ANZ HMUs that treat emergency indications, allowing for multiple choice and free text answers regarding their management of CRAO.
Results: One-hundred and forty-six cases of CRAO were treated in ANZ HMUs over the last five years. Most (101/146) cases (69%) were initially treated at a pressure of 284 kPa. This was the area of greatest difference noted in CRAO management between the UHMS guidelines and ANZ practice.
Conclusions: Few ANZ HMUs strictly followed the UHMS guidelines. We suggest a more simplified management protocol as used by the majority of ANZ HMUs.

Introduction

Insufficient blood supply to the inner layers of the retina from retinal artery occlusion (RAO) (either central or branch) is rare but serious. The incidence has been reported as 0.85 cases per 100,000 but may be significantly higher due to under-reporting of this condition.[1] Central retinal artery occlusion (CRAO) presents acutely with sudden onset painless, unilateral vision loss. Vision to the affected eye is often significantly reduced, typically with no useful vision remaining if the central retinal artery is occluded. Limited field vision is common when branch retinal artery occlusion occurs. Whilst over a few days there will typically be recanalisation of the artery, by this time the retina is often irreversibly damaged from hypoxia. Meaningful improvement in vision is estimated to occur in only 8% of patients with spontaneous reperfusion.[2] Vision impairment is known to have a profound impact on a patient's quality of life.[3] For convenience, the term CRAO will be used for all cases including branch RAO.

The central retinal artery is a branch of the ophthalmic artery. An ophthalmic artery originates from each internal carotid artery. The retina has a dual blood supply, with the inner layers supplied with blood from the central retinal artery and its branches, while the choroidal circulation supplies the outer layers. Retinal cells exhibit the highest oxygen (O_2) consumption in the body by weight (13 $mL \cdot 100g^{-1} \cdot min^{-1}$), making the retina highly susceptible to ischaemia.[4] Variation in visual acuity from CRAO occurs because partial perfusion of the retina may persist in some cases. The choroid supplies 50–60% of the retina with O_2, provided there is normal ophthalmic artery perfusion.[5] In addition, 15–30% of the population has a cilioretinal artery, supplying blood to the area around the fovea.[6]

There are multiple possible causes for CRAO including thrombosis, embolus, dissection, arteritis and vasospasm. The Undersea and Hyperbaric Medical Society (UHMS) guidelines on CRAO state that an ophthalmologist should be consulted emergently in cases of suspected CRAO.[7]

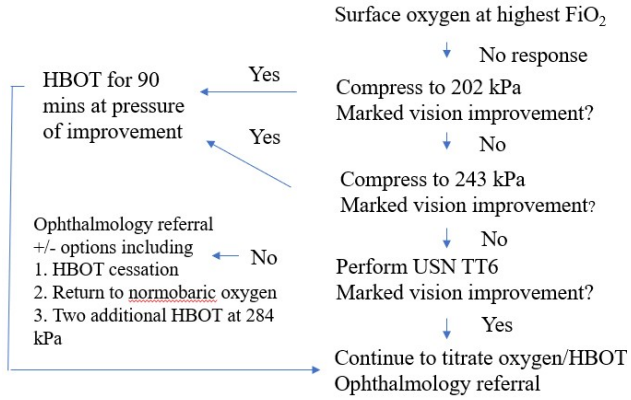
To arrive at a diagnosis of CRAO, decreased vision without improvement with pinhole examination needs to be confirmed, as well as a fundoscopic exam preferably using dilatation if there are no contraindications. Moreover, alternative diagnoses including retinal detachment or vitreous haemorrhage must also be excluded. Full work-up for CRAO includes: a full blood count (to screen for platelet disorders or infective causes); erythrocyte sedimentation rate (ESR) and C-reactive protein (to screen for giant cell arteritis); coagulation profile (fibrinogen, prothrombin time/ partial thromboplastin time [PT/PTT] , antiphospholipid antibody); lipid panel; electrocardiogram (ECG); carotid ultrasound; brain magnetic resonance imaging (MRI) and echocardiography. Of note, however, hyperbaric oxygen treatment (HBOT) should not be delayed accomplishing these diagnostic measures. Moreover, if arteritis is the suspected cause of CRAO, HBOT should still be undertaken in addition to intravenous corticosteroids.

Multiple treatments for CRAO have been reported including ocular massage, haemodilution, anterior chamber paracentesis, intravenous acetazolamide, transluminal Nd:YAG laser, intra-arterial thrombolytic therapy and intravenous fibrinolytic therapy. No significant benefit has been clearly demonstrated with any of these treatments, and moreover serious haemorrhagic sequelae may result from thrombolytic and fibrinolytic therapy, and surgical embolectomy.

Hyperbaric oxygen is considered to be of benefit for CRAO as the higher partial pressure of O_2 in arterial blood allows the peripheral collateral circulation to meet the retina's demands for O_2 while time passes before the central retinal artery recanalises. In animal models, HBOT has demonstrated the capacity to reduce both tissue oedema and ischaemia-reperfusion injury after recanalisation.[8]

Hyperbaric oxygen for CRAO is classified as American Heart Association (AHA) class IIb level of evidence.[9] Class IIb implies that the benefit of treatment is deemed to outweigh the associated risks but usefulness/efficacy is less well established by the evidence/opinion. Retrospective controlled case series have shown fair to good evidence supporting the use of HBOT for CRAO. The UHMS review reported that 66% of the 927 patients treated with HBOT experienced vision improvement after treatment.[7] A recent retrospective study from the Royal Brisbane and Women's Hospital continues to support HBOT as being beneficial and safe for CRAO.[10] There remains great difficulty in performing prospective randomised controlled trials for CRAO and HBOT, on account of the ethical considerations for a proposed trial when no alternative therapy with a similar outcome exists, and because of the relatively low incidence of the condition. The UHMS guidelines for management of CRAO offer at present the only widely available protocol. The most recent Hyperbaric textbook has used these UHMS criteria.[11] Acknowledging that there are limitations on the evidence as to how these guidelines were developed, we have used them as the best available option from which to consider the management offered by other Australian and New Zealand (ANZ) hyperbaric medicine units (HMUs).

Figure 1
Undersea and Hyperbaric Medical Society Guidelines for the acute management of central retinal artery occlusion (CRAO); FiO_2 – Fraction of inspired oxygen; HBOT – Hyperbaric oxygen treatment; mins – minutes; USN TT6 – United States Navy Treatment Table 6



UHMS GUIDELINES

The UHMS guidelines for management of CRAO (Figure 1) advise considering patients for HBOT if they present within 24 hours (h) of symptom onset.[7] This guideline however does note a few case reports where patients have had benefit from HBOT after the 24-h window had passed.

The UHMS guidelines advocate immediately commencing the highest possible fraction of inspired O_2 (FiO_2) at 1 atmosphere. If there is significant improvement within 15 minutes (mins), the patient should then have intermittent normobaric O_2 for 15 mins every hour, alternating with 45 mins of breathing room air. Visual acuity should continue to be checked after each air-breathing period, with this regimen continuing until either a fluorescein angiogram shows patency, the patient's vision remains stable on room air for 2 h, or a maximum of 96 h on intermittent supplemental O_2 therapy had been reached.

If there is no response to high fraction normobaric O_2 within 15 mins, the UHMS guidelines advocate that HBOT can be delivered for 90 mins at the pressure of the return to vision, with a maximum of United States Navy Treatment Table 6 (USN TT6) – which begins at 284 kPa / 2.8 atmospheres absolute (atm abs) for a first treatment. Initially their recommendation is compression to 2 atm abs (203 kPa) on 100% O_2. Should there be no improvement in vision at 2 atm abs by the first air-break period (or 30 minutes), they advise progressing to a pressure of 2.4 atm abs (243 kPa). If no response at 2.4 atm abs, the guidelines advise compressing

to 2.8 atm abs (284 kPa). If there were still no improvement after the first 20 mins period at 2.8 atm abs, the guidelines suggest proceeding to USN TT6. If vision had improved at 2.4 atm abs, the guidelines suggest conducting a United States Navy Treatment Table 9 (USN TT9).

Should there have been no response following completion of USN TT6, options at this point would be to either discontinue treatment, continue with normobaric O_2 at the highest possible FiO_2, or give two additional 90-minute treatments at 2.8 atm abs (284 kPa) with air-breathing periods, on a twice-daily schedule.

If the patient had return of vision during HBOT, the UHMS guidelines recommend considering inpatient monitoring and intermittent supplemental O_2. Should vision loss recur, the UHMS guidelines suggest aggressive use of intermittent normobaric O_2 as described in the initial treatment for CRAO. Alternatively, a customised HBOT protocol would be indicated to preserve retinal function until central retinal artery recanalisation occurs.

The UHMS guidelines also state that HBOT twice or three times daily may be necessary until the angiogram normalises or the patient has no further improvement for three treatments.

It should be noted that the UHMS mentions an exception to this advised regimen when CRAO results from cerebral arterial gas embolism (CAGE). The recommended treatment regimen for CAGE should be followed with a minimum of USN TT6.

For the purpose of this survey, we have used the UHMS guidelines for the management of CRAO as the benchmark against which the management by the ANZ HMUs can be compared. The UHMS guidelines were written based on what its authors considered at the time to be the best HBOT management of CRAO. With ongoing evidence adding weight to the body of knowledge already supporting HBOT for CRAO, it is important that ANZ HMUs are aware of CRAO and its management.

Methods

Approval was obtained for data review and extraction by Governance, Evidence, Knowledge and Outcomes (GEKO) at Fiona Stanley Hospital (Approval Number 42155).

All 12 Australasian HMUs that treat hyperbaric emergencies were emailed a SurveyMonkey® questionnaire for completion. The survey included a pool of nine questions that asked about their frequency of CRAO referral, their use of HBOT for CRAO, the methods by which this was delivered, as well as their ongoing management of CRAO (*Appendix 1). The survey allowed for a multiple-choice response as well as free text for further clarification or comment. Responses were analysed using SurveyMonkey® software (Momentive Inc, San Mateo, CA) for quantitative and qualitative results.

Results

CASES TREATED

There were 146 CRAO cases treated in ANZ HMUs in the 5-year period surveyed between 2017 and 2021 (Table 1 and Table 2).

TIME WINDOW FOR CRAO TREATMENT WITH HBOT

Nearly all institutions agreed that offering HBOT for CRAO patients presenting sub-acutely offered little benefit. Christchurch Hospital (CHCH) and Fiona Stanley Hospital (FSH) had a cut-off time of within 24 h but would ideally prefer < 12 h. The Royal Hobart Hospital (RHH) also had a cut off time < 24 h but preferred presentation within 8 h. Other units that had a cut off time < 24 h included: the Alfred Hospital (AH), the Royal Adelaide Hospital (RAH), the Royal Darwin Hospital (RDH), the Royal Brisbane and Women's Hospital (RBWH), the Townsville Hospital (TH) and the Wesley Hyperbaric Medicine Unit (WHMU). The RDH reported they offered HBOT if it could be initiated < 5 days from symptom onset. The Prince of Wales Hospital (POWH) offered HBOT if initiated < 24 h from symptom

Table 1

Australian and New Zealand hyperbaric facilities and the corresponding number of central retinal artery occlusion cases treated with hyperbaric oxygen over five years; AH – The Alfred Hospital; CHCH – Christchurch Hospital; FSH – Fiona Stanley Hospital; LTPH – La Trobe Private Hospital; POWH – Prince of Wales Hospital; RAH – Royal Adelaide Hospital; RBWH – Royal Brisbane and Women's Hospital; RDH – Royal Darwin Hospital; RHH – Royal Hobart Hospital; SHMU – Slark Hyperbaric Medical Unit; TH – Townsville Hospital; WHMU – Wesley Hyperbaric Medical Unit

HMU	AH	CHCH	FSH	LTPH	POWH	RAH	RBWH	RDH	RHH	SHMU	TH	WHMU	Total
Cases	1	56	17	0	15	0	27	1	16	0	10	3	146

Footnote: * Appendix 1 are available on DHM Journal's website: https://www.dhmjournal.com/index.php/journals?id=336

Table 2

Australian and New Zealand hyperbaric facilities (excluding La Trobe Private Hospital) and their responses to the central retinal artery occlusion (CRAO) questionnaire. La Trobe treated no patients and only provided a response to the time window question (< 48 hours in their case). atm abs – atmospheres absolute; BD – twice daily; Contraindications – contraindications; ED – emergency department; HBOT – hyperbaric oxygen treatment; h – hours; m – metres; NA – not applicable; Optht hal – ophthalmologist or ophthalmology service; S/B – seen by; SMO – senior medical officer; Sx – symptoms; T5 – United States Navy Treatment Table 5; T6 – United States Navy Treatment Table 6; UHMS – Undersea and Hyperbaric Medical Society; VA – visual acuity; See Table 1 for hyperbaric unit name abbreviations. See text for explanation of HBOT table abbreviations (18-60-30, 18-60-35, 14-90-30, 14-90-20, 10-90-30); in this nomenclature, the first number refers to the pressure expressed in metres of seawater, the second number refers to the duration of 100% oxygen breathing (minutes), and the third number refers to the decompression time (minutes) while still breathing 100% oxygen

Question	AH	CH	FSH	POWH	RAH	RBWH	RDH	RHH	SHMU	TH	WHMU
How many CRAO cases have you treated in the last five years?	1	56	17	10 to 15	0	27	1	16	0	10	3
Is there a time window from onset of symptoms beyond which your facility will not offer HBOT	24 h	24 h. Prefer within 12 h	Occ 24 h though usually 12 h	24 h (maybe unless "*last*" eye)	24 h	> 24 h	Nothing official (no written policy) but unlikely if > 5 days	Usually if > 24 h vision loss (unless clinical evidence that vision loss is still changing). Prefer to start HBOT within 8 h of symptom onset, if possible	No	24 h	> 24 h
What are the diagnostic criteria / minimum requirements by your facility before commencing HBOT?	Diagnosis confirmed by ophthal, duration since onset < 24 h, no response to normobaric oxygen	Diagnosis of CRAO by ophthal and within 24 h, no contraindications to HBOT	Clinical. Acute loss of vision with consistent retinal findings on fundoscopy/ absence of other cause	S/B opthal. Confirmed recent CRAO	Referral from ophthal after exam	CRAO confirmed by ophthal within 24 h of onset, no contraindications to HBOT	Low threshold to treat given what patient has to lose – so anyone referred by ophthal with diagnosis or suspicion	Diagnosis should be confirmed by an ophthal prior to HBOT. We are happy to take both CRAO and branch retinal artery occlusions. (Have also treated a couple of retinal vein occlusions)	Diagnosis and referral by ophthal. Onset within last 24 h. No response to 15 mins normobaric oxygen	Ophthal referral < 24h after onset	CRAO diagnosis by ophthal. No contraindications to HBOT
What initial treatment table do you offer for CRAO? 18-60-30 or similar, TT5, 140-90, other (please list)	60.5 (284 kPa table)	18-60-30	18-60-35 multiplace 18-60-10 monoplace	Standard 14-90-20	T6?	Sliding based on UHMS[7]	18-60-30	Tend to use Beiran's regime – 284 kPa for all treatments, 18-60-30 BD for 3 days then daily until no further improvement for 3 consecutive days	10-90-30 progressing to 14-90-30 if no improvement after 30 minutes. If no improvement after 90 mins at 243 kPa, progress to T6.	18-60-30	UHMS guidelines 14th edition (T6)[7]

Table 2 continued.

What follow-up HBOT schedule and tables do you use?	AH14 (243 kPa table)	18-60-30 or 14-90-20	18-60 x 3 over 1st 24 h then daily until plateau 3/7 or resolution	Join other patients in standard tables	10-90-30	Proportional to the initial treating pressure.	14-90-14	See answer to question 5 (above)	Would use 18-60-30 BD until plateau if responding or max 8 sessions if not	3 in 1st 24 h, then daily until plateau or resolution reached	18-60-30
Are they on high flow oxygen initially?	Yes	From diagnosis to HBO 1st treatment if possible	Usually	Pre HBOT? Don't think so	Don't know	Yes	No	Possibly – depends on whether they've come via ED or direct from ophthalmologist's rooms	They should be	Variable, unknown often.	Yes
Are they on high flow oxygen between treatments?	Maybe on oxygen between treatments	Only if vision deteriorates following treatment	No	No	No	Yes for the first 24 h with 15 mins on and 45 mins off with VA check	No	No	They should be	Yes if HBOT has produced benefit	Yes
Would the hyperbaric treatment schedule vary between physicians at the department or is there a unit consensus on treatment schedule?	Varies. In our 1 case in 5 years, we sought advice on protocol from another unit who had treated 36 cases in 3 years	Consensus on treatment now generally 18-60-30 but hyperbaric SMO retains discretion if having difficulty getting to depth etc	Unit consensus	We don't do a separate HBOT	Maybe. Don't know what others do	Unit consensus	Likely vary as limited/ no experience so little driver for policy development thus far	Generally adhere to Bieran's regime; very occasionally Murphy-Lavoie's strategy of 100% oxygen urgently at 1 ATA. Compress to 2 atm abs if no benefit. If no improvement within 30 minutes at 2 atm abs compress to 2.4. If no improvement after 20 minutes compress to 2.8 and if not improved, consider USN T6. No clear endpoint – "*until angiogram normalises*"	Unit consensus	Unit consensus	Probably variance but try to stick to UHMS 14th edition guidelines[7]
Is there a specific number of hyperbaric treatments that get offered, or does it vary according to patient response?	Varies based on response	Varies based on response. Christchurch protocol[14]	Until resolution or plateau- no benefit over 3 HBOT	Usually 5 – depends on response	3	Varies based on response – aim for at least 72 h for reperfusion	Dependent on patient response, but if no improvement after 5 then would likely cease	Varies depending on patient response and time to plateau in symptoms. Generally averages out at about 10–11 treatments per patient (167 treatments given to 16 patients over 5 years)	Should vary with patient response (see Q6)	No – according to response	Varies based on response

onset but would treat later presentations if the patient had been affected in their only eye that had vision.

DIAGNOSTIC CRITERIA/MINIMUM REQUIREMENTS BY FACILITY BEFORE COMMENCING HBOT

All HMUs agreed on requiring an ophthalmology review before accepting CRAO cases for HBOT. Ophthalmologists have the essential role of expediently confirming a diagnosis of CRAO before HMUs will accept a patient for treatment. Of note, many HMUs responses stated there needed to be no contraindication to HBOT.

INITIATION OF HIGH FLOW O_2

Not all HMUs reported using high flow O_2 as initial treatment. The RDH said they do not. Most HMUs appeared to recognise that patients should be treated with normobaric first aid O_2 in as high a fraction as possible, but some were also realistic in recognising that when first presenting for HBOT they may not yet have received O_2.

INITIAL TREATMENT TABLE

This survey has shown there are at most only three HMUs which follow the UHMS protocol strictly regarding the initial treatment table. This accounted for 30 of the 146 patients treated over the five-year period (21%). Every other HMU chose a higher initial pressure (79% of the 146 cases). The most common initial treatment pressure (used by six of the 12) was 284 kPa, used in 101 out of the total 146 cases treated (69%).

The most frequently used initial treatment schedule was 18-60-30 or similar (284 kPa / 18 metres of seawater equivalent pressure for 60 mins breathing O_2 with a 30-min decompression). Five of the 12 HMUs said they used an 18-60-30 regimen and another unit used the very similar 18-60-35 (a 35-min decompression instead of 30-min). Two HMUs used a USN TT6, and two HMUs made specific reference to the UHMS 14th edition guidelines for the management of CRAO.[7] The Slark Hyperbaric Medicine Unit (SHMU) has not treated a CRAO case within that last five years, but their proposed management stated they start with a 10-90-30 table (203 kPa / 10 metres of seawater equivalent pressure for 90 mins breathing O_2 with a 30-minute decompression) and progressed to 14-90-30 (243 kPa / 14 metres of seawater equivalent pressure for 90 mins breathing O_2 with a 30-minute decompression) if no improvement after 30 mins. If still no improvement after 90 mins at 243 kPa, they would then progress to USN TT6. This is in keeping with UHMS guidelines. The POWH's initial treatment was a 14-90-20 (243 kPa / 14 metres of seawater equivalent pressure for 90 mins breathing O_2 with a 20-minute decompression).

O_2 BETWEEN TREATMENTS

Six of 15 HMUs answered "*no*" to the question of whether patients were on high flow O_2 between treatments, with another unit saying that O_2 treatment would "*probably not*" be offered. Additionally, one unit responded "*unknown*" and another "*NA*". The AH may offer high flow O_2 between treatments, and two other HMUs offered high flow O_2 between treatments conditionally. The TH offered "*if HBOT had produced improvement*" and the CHCH offered "*only if vision deteriorates following treatment*". Three of the units offered high flow O_2 between treatments unconditionally, with the RBWH reporting that they offered for the first 24 hrs with a 15 mins on and 45 mins off regime along with visual acuity checking.

FOLLOW-UP HBOT SCHEDULE AND TABLES USED

Follow up treatment pressures varied between 203 kPa and 284 kPa. A 243 kPa exposure was the most frequently utilised treatment pressure for follow-up. The RBWH reported that their follow-up pressure would be proportional to the initial treating pressure as per the UHMS guidelines. The TH's treatment schedules included three treatments at 284 kPa during the first 24 h and then one treatment per day subsequently until a plateau or resolution reached. The SHMU instead offered two treatments per day until plateau or resolution up to a total of eight treatments maximum. The FSH utilised three HBOTs at 284 kPa in the first 24 h then daily until plateau for three days or resolution. The RHH treated with Beiran's regime with twice daily treatments for three days then daily until no further improvement for three consecutive days.[12]

DEPARTMENTAL POLICY REGARDING HYPERBARIC TREATMENT SCHEDULE

Seven of the 12 units answered that there would be unequivocal consensus between physicians on the treatment regime chosen for managing acute RAO. When variance was mentioned (as by RAH, RDH and WHMU), it seemed mostly because of low case numbers. The AH mentioned seeking advice from an international unit that had more experience treating CRAO.

NUMBER OF HYPERBARIC TREATMENTS OFFERED

Most units offered a varied schedule depending on the response of the patient to treatment. The CHCH treatment varied according to patient response and have a published protocol outlining a clear treatment regime. The FSH treatment end point was resolution or plateau of symptoms (no improvement over three HBOT). The RBWH's treatment also varied based on response, and specifically mentioned aiming for at least 72 h to allow for recanalisation. The RDH's treatment schedule varied based on response but if

no improvement after five HBOT then they would likely cease. The RHH's detailed answer was that they also varied treatment number depending on patient response and time to plateau in symptoms. They added that it generally averaged out at about 10–11 treatments per patient (167 treatments given to 16 patients over five years).

Discussion

Great variability exists in the number of CRAO cases treated with HBOT over the last five years in ANZ HMUs. This broad range of cases treated is not expected to have resulted from geographical variability in the incidence of CRAO. It is expected that there be a roughly similar incidence of CRAO for all regions. Perhaps what varied was the rate of ophthalmology referral to hyperbaric units and this in turn would depend upon this specialty's regional support of HBOT for acute CRAO. Future work could elucidate whether this is the case.

The responses regarding the time window from symptom onset for which HMUs provide HBOT identify that CRAO is a time critical emergency. Perhaps offering HBOT up to five days from symptom onset is on account of the few case reports noted in the UHMS guidelines demonstrating benefit despite late treatment. Considering the physiology, these cases may represent those that had partial retinal artery occlusion, and so irreparable damage to the retina had been spared. Some HMUs also offer HBOT beyond 24 h of symptom onset if a patient has been affected in their only eye that had vision. Certainly, preservation of vision offers significant quality adjusted life year benefits,[3] and therefore a short trial looking for any improvement may be reasonable.

If we support the theoretical basis of how HBOT works acutely for CRAO, then initial high flow O_2 should be commenced. Also, while HMU specialists may initiate this treatment after being involved in a CRAO patient's care, the emergency department must be considered the best site for initiating immediate normobaric high flow O_2 as this is where many patients will initially present.

We must note that the UHMS recommendations for the intermittent highest flow normobaric O_2 schedule of 15 min·h^{-1} was arrived at based on only three patients treated with normobaric O_2 received continuously for several hours . Patients who received interrupted high FiO_2 normobaric O_2 in fact received carbogen (5% carbon dioxide 95% O_2) which is more vasodilatory than plain O_2, theoretically improving retinal O_2 delivery. Given these issues, and with the aim of providing a simple and achievable protocol for which to follow, it may be suggested as an alternative to provide continuous high flow O_2 to patients. The initial treatment pressure of 284 kPa chosen by most ANZ HMUs has advantages over the UHMS guidelines which are complicated. Moreover, their lower recommended initial treatment pressure and subsequent increments based on treatment response may result in longer times before retinal oxygenation and therefore a delayed time until return of vision. We propose to use a more simplified approach with a higher starting pressure and less subsequent adjustments, such as that used presently at some Australasian HMUs. Starting at a higher initial pressure potentially may result in faster return of visual acuity and a minimisation of retinal ischaemic time.

It should be noted that data from 20 years' experience of O_2 toxicity seizures in patients undergoing HBOT from a single HMU demonstrate higher rates of OTS associated with higher treatment pressures. At 203 kPa, seizures occurred 2/17,512 (0.01%) or 1/8,756 treatments. The event rate for treatment at 243 kPa was 12/20,633 (0.06%) or 1/1719 treatments. At a pressure of 284 kPa, seizures occurred in 7/2,371 (0.3%) or 1/339 treatments.[13] This increase in seizure occurrence at higher treatment pressures necessitates appropriate consenting of patients as well as vigilance during treatment.

Variance in treatment schedule by specialists within a HMU seemed to correlate with infrequency of exposure to HBOT for CRAO.

Determination of the best HBOT schedule for CRAO requires ongoing research. It is our hope that this survey can serve to raise awareness of CRAO and its management with HBOT, as well as allow HMUs to consider other institutions' management and compare it against their own.

We propose a management guideline consistent with the majority of practice in Australasia as well as adapted from the UHMS guidelines and from the published CHCH as follows.[14]

- Any patient with sudden, painless vision loss suspicious for CRAO should be commenced on the highest fraction / flow of normobaric O_2 immediately and seen by an ophthalmologist urgently.
- If diagnosed with CRAO by an ophthalmologist and within the 24 h window from symptom onset, they should be immediately referred to a HMU and assessed for contraindications to HBOT. Patients affected in their only eye that has vision should be referred up to 5 days post symptom onset.
- An initial 18:60:30 treatment table or similar 284 kPa treatment should be the initial HBOT.
- With no improvement in vision after three 20 min O_2 breathing periods at 284 kPa, progression to a USN TT6 may be considered.
- Treatment should continue two or three times daily or until either resolution, clinical plateau or an angiogram confirms recanalisation / reperfusion.
- Ideally, patients should be admitted for at least the first 24 h with regular visual acuity checks.

- Visual acuity should be monitored following treatments. Should visual loss recur, high flow normobaric O_2 should be administered continuously until repeat HBOT can be arranged.
- The HMU should closely liaise with the referring ophthalmologist throughout the patient treatment schedule.

Conclusions

This survey has shown that in those centres where CRAO is treated more frequently there exists agreement in how it is managed, with most having diverged from the UHMS guidelines specifically in the initial treatment schedule offered. The more simplified approach of initially treating with a 284 kPa table offers a more pragmatic way of treating CRAO and may potentially result in a reduced retinal ischaemic time thereby increasing the chances of restoring and preserving visual acuity. Our belief is that this benefit would outweigh the small increased O_2 toxicity seizure risk associated with the higher treatment pressure.

References

1 Rumelt S, Dorenboim Y, Rehany U. Aggressive systematic treatment for central retinal artery occlusion. Am J Ophthalmol. 1999;128:733–8. doi: 10.1016/s0002-9394(99)00359-1. Erratum in: Am J Ophthalmol. 2000;130:908. PMID: 10612510.

2 Augsburger JJ, Magargal LE. Visual prognosis following treatment of acute central retinal artery obstruction. Br J Ophthalmol. 1980;64:913–7. doi: 10.1136/bjo.64.12.913. PMID: 7448144. PMCID: PMC104257.

3 Assi L, Chamseddine F, Ibrahim P, Sabbagh H, Rosman L, Congdon N, et al. A global assessment of eye health and quality of life: a systematic review of systematic reviews. JAMA Ophthalmol. 2021;139:526–41. doi: 10.1001/jamaophthalmol.2021.0146. PMID: 33576772. PMCID: PMC7881366.

4 Landers MB. Retinal oxygenation via the choroidal circulation. Trans Am Ophthalmol Soc. 1978;76:528–56. PMID: 112752. PMCID: PMC1311635.

5 Brown GC, Shields JA. Cilioretinal arteries and retinal arterial occlusion. Arch Ophthalmol. 1979;97:84–92. doi: 10.1001/archopht.1979.01020010024006. PMID: 758898.

6 Hadanny A, Maliar A, Fishlev G, Bechor Y, Bergan J, Friedman M, et al. Reversibility of retinal ischemia due to central retinal artery occlusion by hyperbaric oxygen. Clin Ophthalmol. 2016;11:115–25. doi: 10.2147/OPTH.S121307. PMID: 28096655. PMCID: PMC5207437.

7 Murphy-Lavoie H, Butler F, Hagan C. The Hyperbaric oxygen therapy committee report. Central retinal artery occlusion. In: Moon RE, editor. Hyperbaric oxygen therapy indications. 14th ed. Durham (NC): Undersea and Hyperbaric Medical Society; 2019. p. 15–30.

8 Masters TC, Westgard BC, Hendriksen SM, Decanini A, Abel AS, Logue CJ, et al. Case series of hyperbaric oxygen therapy for central retinal artery occlusion. Retin Cases Brief Rep. 2021;15:783–8. doi: 10.1097/ICB.0000000000000895. PMID: 31306292.

9 Oguz H, Sobaci G. The use of hyperbaric oxygen therapy in ophthalmology. Surv Ophthalmol. 2008;53:112–20. doi: 10.1016/j.survophthal.2007.12.002. PMID: 18348877.

10 Williamson J, Sharma A, Murray-Douglass A, Peters M, Lee L, Webb R, et al. Outcomes of hyperbaric oxygen treatment for central and branch retinal artery occlusion at a major Australian referral hospital. Diving Hyperb Med. 2023:53:224–9. doi: 10.28920/dhm53.3.224-229. PMID: 37718296. PMCID: PMC10735708.

11 Whelan HT, Kindwall EP, editors. Hyperbaric Medicine Practice. 4th ed. Florida: Best Publishing Company; 2017. p. 852–5.

12 Beiran I, Goldenberg I, Adir Y, Tamir A, Shupak A, Miller B. Early hyperbaric oxygen therapy for retinal artery occlusion. Eur J Ophthalmol. 2001;11:345–50. doi: 10.1177/112067210101100405. PMID: 11820305.

13 Banham ND. Oxygen toxicity seizures: 20 years' experience from a single hyperbaric unit. Diving Hyperb Med. 2011;41:202–10. PMID: 22183697.

14 Elder MJ, Rawstron JA, Davis M. Hyperbaric oxygen in the treatment of acute retinal artery occlusion. Diving Hyperb Med. 2017;47:233–8. doi: 10.28920/dhm47.4.233-238. PMID: 29241233. PMCID: PMC6706338.

Submitted: 25 March 2024
Accepted after revision: 19 April 2024

Clinical utility of dipstick urinalysis in assessing fitness to dive in military divers, submariners, and hyperbaric personnel

Arne Melessen[1], Thijs T Wingelaar[1], Pieter-Jan AM van Ooij[1]

[1] *Royal Netherlands Navy Diving and Submarine Medical Center, Den Helder, the Netherlands*

Corresponding author: *Dr Thijs Wingelaar, Royal Netherlands Navy Diving and Submarine Medical Center, Rijkszee and Marinehaven, 1780 CA Den Helder, the Netherlands*
ORCiD: *0000-0001-7740-7392*
tt.wingelaar@mindef.nl

Keywords
Diving; Fitness to dive; Haematuria; Screening; Urology

Abstract
(Melessen A, Wingelaar TT, van Ooij PJAM. Clinical utility of dipstick urinalysis in assessing fitness to dive in military divers, submariners, and hyperbaric personnel. Diving and Hyperbaric Medicine. 2024 30 June;54(2):105–109. doi: 10.28920/dhm54.2.105-109. PMID: 38870952.)
Introduction: Routine dipstick urinalysis is part of many dive medical assessment protocols. However, this has a significant chance of producing false-positive or false-negative results in asymptomatic and healthy individuals. Studies evaluating the value of urinalysis in dive medical assessments are limited.
Methods: All results from urinalysis as part of dive medical assessments of divers, submarines, and hyperbaric personnel of the Royal Netherlands Navy from 2013 to 2023 were included in this study. Additionally, any information regarding additional testing, referral, or test results concerning the aforementioned was collected.
Results: There were 5,899 assessments, resulting in 46 (0.8%) positive dipstick urinalysis results, predominantly microscopic haematuria. Females were significantly overrepresented, and revisions resulted in significantly more positive test results than initial assessments. Lastly, almost half of the cases were deemed fit to dive, while the other half were regarded as temporarily unfit. These cases required additional testing, and a urologist was consulted three times.
Conclusions: To our knowledge, this is the most extensive study evaluating urinalysis in dive medical assessments. In our military population, the incidence of positive test results is very low, and there have not been clinically relevant results over a period of 10 years. Therefore, routinely assessing urine in asymptomatic healthy military candidates is not cost-effective or efficacious. The authors advise taking a thorough history for fitness to dive assessments and only analysing urine when a clinical indication is present.

Introduction

When immersed or submersed, the human body is exposed to unique environmental factors that require specific physiological adaptations.[1] However, certain pre-existing medical conditions may interfere with these compensatory mechanisms, increasing the risk of adverse diving events.[2] It is, therefore, strongly recommended that professional divers undergo a medical examination to determine their fitness to dive.[3,4]

While cardiovascular and pulmonary disease can predispose a diver to severe diving-related illnesses, other organ systems can cause significant problems when diving.[1,2] Regarding the urogenital tract, renal calculus disease, commonly known as kidney stones, can cause incapacitating symptoms. However, until symptoms reveal themselves, microscopic haematuria can be the only sign found when screening 'healthy' subjects.[5] However, haematuria can also be found in athletes, especially in non-contact sports and running, and has little clinical significance.[6,7] Aside from haematuria, dipstick urinalysis can also be used to screen for diabetes mellitus (glucose) or urinary tract infections (nitrite or leukocyte esterase), all of which can have a severe impact on diving safety but rarely present without symptoms. There is no consensus in the field of urology regarding the added value of dipstick urinalysis in asymptomatic individuals.[8] The European Diving Technology Committee guideline recommends routine dipstick urinalysis for blood, protein, and glucose; however, false-positive and false-negative results are typical with this test.[8,9]

In the Netherlands, dipstick urinalysis is required by legislation as part of a medical assessment for fitness to dive; however, its role in such a screening program has not been evaluated.[10] Although this method is highly sensitive in detecting haematuria or glucosuria, its sensitivity for detecting proteinuria is much lower.[11] As a result, dipstick urinalysis should not be the sole test to identify renal target organ damage. False-positive results can trigger costly and potentially harmful procedures such as cystoscopy, while false negatives may create a false sense of safety

among subjects.[12] Using a test with these limitations when screening a generally healthy population, such as occupational or military divers, warrants an assessment of its cost-effectiveness. To our knowledge, a single study (only appearing as a conference abstract) was conducted on this matter, which concluded urinalysis is not cost-effective and has little contribution to diving safety.[13]

This retrospective study endeavours to ascertain dipstick urinalysis' clinical value and cost-effectiveness in conjunction with subsequent referrals from medical assessments of military divers' fitness to dive. We hypothesise that the routine use of dipstick urinalysis in these assessments rarely identifies clinically relevant disease.

Methods

The methods for handling medical information comply with national and European legislation and the guidelines of the Association of Universities in the Netherlands.

CONTEXT

The Royal Netherlands Navy Diving Medical Center is responsible for the medical well-being of the Dutch armed forces' divers, submariners, and hyperbaric personnel. As mentioned in the introduction, the aforementioned group is subjected to annual medical assessments as part of national legislation.

DATA COLLECTION

Subjects gave written informed consent at the time of their dive medical examination consent to use their data for scientific research. Subjects that refused reuse of their data were excluded from the study. All assessments in a 10-year time frame between 2013 and 2023 were eligible for inclusion. Data from urinalysis and baseline characteristics and outcomes of the assessments were extracted from the medical records. The dipstick urinalysis results were coded into five groups: fit to dive, temporary fit to dive, temporary unfit to dive, unfit to dive, and 'other'. This last group includes divers who withdrew from the assessment. This is relevant, as an 'unfit' result from an assessment can have legal or financial consequences for the candidate; many candidates choose to withdraw from the assessment process when a 'fit' result is unlikely. As part of the outcome of the assessments, details such as repeated testing or referral to a urologist were recorded.

DATA ANALYSIS

All data were recorded in a database. Binary data were tested using χ^2 or Fisher's exact tests (or the Fisher-Freeman-Halton test when contingency tables are more extensive than 2 x 2). Continuous data were tested using unpaired *t*-tests or Mann-Whitney U, depending on the normality of the data. Statistical analyses were performed using SPSS Statistics for Windows software (IBM Corp; Armonk, NY: 2022, version 29.0), with $P < 0.05$ defined as statistically significant.

Results

In total, 5,899 medical assessments were performed; about two-thirds were divers, a quarter were hyperbaric personnel, and the rest were submariners. The median age was 32 yr (interquartile range [IQR] 27–40 yr) and 92.8% were male, with 10.5% smokers. About one-fifth were initial assessments (i.e., someone being medically cleared for the first time); the rest were revisions. More details can be found in Table 1.

In this population, 46 cases (0.8%) had a positive result on dipstick urinalysis. Notably, this was significantly more likely in female candidates (Fisher's exact test; $P = 0.004$). Age, height, weight, and smoking status were not significantly different in the positive cases when compared to the total population. Divers were significantly over represented and submariners were underrepresented in this case series, with a *P*-value of 0.007 when tested with a Fisher-Freeman-Halton exact test. Of note, the ratio between divers and hyperbaric personnel was not significantly different when submariners were excluded from the analysis. Lastly, a positive urinalysis result was significantly less present in initial assessments (χ^2; $P = 0.010$), with only two positive tests in 1,129 initial assessments (0.17%).

Of the total population, about two-thirds were deemed fit to dive. Of the remaining one-third, the majority fell in the 'other' category (as explained in the methods section). Interestingly, all 'temporarily unfit' verdicts ($n = 21$) were due to a positive urine test, which represented about half of the cases with a positive result on urinalysis. Aside from a small group, the other half of the cases with a positive urine sample were deemed fit to dive. The differences in results of the diving medical assessment were statistically significant (χ^2; $P < 0.001$)

The relation between the fitness to dive results and the results of the dipstick urinalysis is displayed in Table 2. Erythrocytes were found in more than half of the cases. None of the urinalysis results were significantly more present in any of the fitness outcome groups when tested using Fisher-Freeman-Halton exact tests. Additional investigations were performed in 27 cases (59%) of the 46 positive urinalysis results. Note that these 46 cases belonged to 28 individuals, meaning some had positive test results on multiple assessments (up to five in one case). Of the 27 cases where additional investigations were performed, five were deemed fit to continue diving, 21 were temporarily unfit, and one candidate withdrew from the assessment. Three cases were referred to a urologist, who cleared the diver after additional investigations (repeated urinalysis and cystoscopy in one case). Regarding the individuals with

Table 1
Baseline characteristics and results of diving medical assessments; data are number (%) or median (interquartile range [IQR])

Parameter	Total (n = 5,899)	Cases (n = 46)	P-value
Baseline characteristics			
Sex	5,473 male (92.8%)	37 male (80.4%)	0.004
Age (yrs)	32 (IQR 27–40)	30 (IQR 27–39)	0.540
Height (cm)	183 (IQR 178–188)	181.5 (IQR 173.7–185.2)	0.241
Weight (kg)	85 (IQR 79–92)	79.5 (IQR 71.7–84.2)	0.701
Non-smoking	5,280 (89.5%)	38 (82.6%)	0.142
Type			
Diver	3812 (64.6%)	38 (82.6%)	0.007
Submariner	656 (11.1%)	0	
Hyperbaric personnel	1,431 (24.3%)	8 (17.4%)	
Assessment			
Initial	1,129 (19.1%)	2 (4.3%)	0.010
Revision	4,770 (80.9%)	44 (95.7%)	
Result			
Fit	3,965 (67.2%)	22 (47.8%)	< 0.001
Temporarily fit	352 (6.0%)	0	
Temporarily unfit	21 (0.4%)	21 (45.7%)	
Unfit	91 (1.5%)	0	
Other	1,470 (25.0%)	3 (6.5%)	

Table 2
Influence of urinalysis result on fitness to dive; none of the tested parameters showed statistically significant differences between the result categories (using the Fisher-Freeman-Halton exact test)

Parameter	Fit (n = 22)	Temporarily unfit (n = 21)	Other (n = 3)
Protein	4	3	0
Erythrocytes	15	12	1
Haemoglobin	0	2	0
Leukocyte esterase	5	2	2
Nitrite	2	1	0
Glucose	0	2	0
Ketones	1	0	0
Bilirubin	2	1	0
Urobilirubin	1	2	0

positive test results that were deemed fit for diving; in this retrospective study if it could not be determined whether the positive dipstick was missed by the clinician, or it was noted by the physician but failed to take action accordingly, or perhaps due to other reasons.

Discussion

Our evaluation of nearly 6,000 dive medical assessments of military divers, submariners, and hyperbaric personnel showed a low incidence (0.8%) of positive urinalysis test results. Moreover, these positive test results had limited effect on the end result of the assessment, with almost half of the candidates being cleared for diving and the other half being regarded as temporarily unfit for diving. Repeating urinalysis, additional investigations, or referral to a urologist were performed in these cases without identifying clinically significant disease. Female candidates were overrepresented in the identified cases.

In general, false-positive and false-negative test results are a major issue with screening asymptomatic, healthy, and relatively young individuals with an instrument of limited sensitivity and specificity – and this is also the case in dipstick urinalysis, even though the range of these characteristics varies in different studies.[14] While more advanced techniques, such as imaging (ultrasonography or computer tomography; for nephro- or urolithiasis) or blood analysis (for diabetes) generally may have better test characteristics, there is still a risk of false-positive and false-negative test results with a very low *a priori* probability of disease.[15] Moreover, these instruments can have more impact on the assessment regarding associated costs or harm for the candidate (i.e., radiation in CT-imaging or an invasive test), with an unknown reduction of incorrect test results.

The incidence of positive test results on urinalysis is lower than found in a retrospective study amongst pilots, with the caveat that our population was slightly younger.[16] This, in combination with a generally non-smoking population, could explain the lower incidence of microscopic haematuria

than in the general population.[17] We found a slightly higher incidence of positive results on urinary dipstick analysis in females than in males. However, this is also seen in the general population, commonly associated with cystitis (e.g., with positive nitrite or leukocyte esterase), in contrast to our female population with mainly microscopic haematuria.[18] While this can be related to the menstrual cycle, we feel that we cannot rule out exertion haematuria in our population.[6] Therefore, the authors suggest taking a thorough history for dive medical assessments and only analysing urine when a clinical indication is present.

While urinary dipstick analysis is relatively cheap (generally less than $5 per test), the expenses associated with additional investigations and 'operational downtime' for a diver should also be considered. The latter is particularly relevant for our armed forces but is likely to also be of concern for commercial diving operations. Without clinically relevant findings over a ten-year period, the cost-effectiveness is unfavourable, as was also concluded by the previously mentioned study.[13] We would like to encourage the scientific community to repeat our study, perhaps even prospectively, to validate our findings and discuss the value of urinalysis in asymptomatic divers and hyperbaric personnel.

STRENGTHS AND LIMITATIONS

To our knowledge, this is the largest study to date evaluating the utility of urinalysis in dive medical assessments. While the results strongly indicate that urinalysis is of little value for dive medical assessments, some limitations must be addressed.

Firstly, our population of military personnel has been medically assessed at least once (when entering the service, several units require additional medical screenings) and are of above-average physical fitness. This may have reduced the incidence, and thus the *a priori* chance, of urinary calculi or diabetes. Therefore, our results may not be transferable to other populations, such as commercial or recreational divers.

Secondly, while we could include almost 6,000 assessments, it remains a retrospective analysis of our database. Diabetes, renal calculus disease, and other diseases are the subject of active inquiry when taking a history. However, candidates could have forgotten or withheld information in the dive medical assessment, masking the true incidence of these diseases. Additionally, these data cannot accurately determine the false-negative test characteristic of dipstick urinalysis. This could have been overcome by combining our database with the database of the military general practitioners. However, this would have generated a substantial administrative burden due to European privacy legislation. We feel the effect of this shortcoming is minimal, as we have a good relationship with our diving and submarine community, but it cannot be entirely ruled out.

Lastly, the number of 'unfit' divers in our population is very low compared to other studies. This is most likely due to the aforementioned option to withdraw from the assessment, resulting in an 'other' result. It is, therefore, perhaps best to regard 'other' as 'unfit' when interpreting these results. The three candidates in the group with positive test results on urinalysis that were in the 'other' category would have been 'unfit' for other reasons (two cases with an insufficient pulmonary function test, one case was not physically fit enough and scored too low on the exercise ergometry). Therefore, we feel this has not affected the interpretation or conclusion of the present study.

Conclusions

This retrospective study covering 10 years of data on dive medical assessments in military divers, submariners, and hyperbaric personnel showed an incidence of 0.8% of positive test results on urinalysis. Almost half of the cases could be cleared right away; the other half were regarded temporarily unfit for diving and generally required retesting or additional investigations, after which they were deemed fit to dive. Therefore, routinely assessing urine in asymptomatic healthy candidates is neither cost-effective nor clinically useful. The authors advise taking a thorough history for fitness to dive assessments and only analysing urine when a clinical indication is present.

References

1 Mitchell SJ, Bennett MH, Moon RE. Decompression sickness and arterial gas embolism. N Engl J Med. 2022;386(13):1254–64. doi: 10.1056/NEJMra2116554. PMID: 35353963.

2 Bosco G, Rizzato A, Moon RE, Camporesi EM. Environmental physiology and diving medicine. Front Psychol. 2018;9:72. doi: 10.3389/fpsyg.2018.00072. PMID: 29456518. PMCID: PMC5801574.

3 Wendling J, Elliott D, Nome T, editors. Fitness to dive standards. Guidelines for medical assessment of working divers. Biele-Biene: European Diving Technology Committee; 2003. [cited 2024 Jan 15]. Available from: http://edtc.org/wp-content/uploads/2020/05/EDTC-Fitnesstodivestandard-2003.pdf.

4 Health and Safety Executive. Medical examination and assessment of working divers (MA1); 2023. [cited 2024 Jan 15]. Available from: https://www.hse.gov.uk/pubns/ma1.htm2023.

5 Nagendra V, Dhande R, Mishra G, Reddy NG, Gowda H. Hematuria as a sign of kidney stone disease evaluated using computed tomography: a review. Cureus. 2023;15(4):e38064. doi: 10.7759/cureus.38064. PMID: 37252589. PMCID: PMC10212727.

6 Lippi G, Sanchis-Gomar F. Exertional hematuria: definition, epidemiology, diagnostic and clinical considerations. Clin Chem Lab Med. 2019;57:1818–28. doi: 10.1515/cclm-2019-0449. PMID: 31188754.

7 Varma PP, Sengupta P, Nair RK. Post exertional hematuria. Ren Fail. 2014;36:701–3. PMID: 24865509.

8 Krogsbøll LT. Guidelines for screening with urinary dipsticks differ substantially – a systematic review. Dan Med J. 2014;61(2):A4781. PMID: 24495888.

9 Simerville JA, Maxted WC, Pahira JJ. Urinalysis: A comprehensive review. Am Fam Physician. 2005;71:1153–62. PMID: 15791892.
10 Working under pressure foundation. Guideline occupational health assessment: Working under positive pressure and diving [in Dutch: Keuringsrichtlijn Arbeidsgezondheidskundig Onderzoek Werken onder Overdruk en Duikarbeid]. Pijnacker, the Netherlands: Working Under Pressure Foundation; 2021. [cited 2024 Jan 15]. Available from: https://www.arbocataloguswoo.nl/images/SWOD/pdf/NL/SWOD-ARBOCAT-WoO-Keuring-CAT003_1-2021-rev4-aug-2021.pdf.
11 Zamanzad B. Accuracy of dipstick urinalysis as a screening method for detection of glucose, protein, nitrites and blood. East Mediterr Health J. 2009;15:1323–8. PMID: 20214148.
12 Dutch Society for Urology. Hematuria. Utrecht: Dutch Association of Medical Specialists; 2023. [cited 2024 Jan 15]. Available from: https://www.nvu.nl/kwaliteitsbeleid/richtlijnen/actuele-richtlijnen/.
13 Toppen W, Smith C, Castellano T, Grover I, Sadler C. Cost effectiveness of urinalyses in occupational diver clearance. Undersea Hyperb Med. 2023;50(2):214. [Abstract].
14 Rodgers M, Nixon J, Hempel S, Aho T, Kelly J, Neal D, et al. Diagnostic tests and algorithms used in the investigation of haematuria: systematic reviews and economic evaluation. Health Technol Assess. 2006;10(18):iii-iv, xi–259. PMID: 16729917.
15 Al-Shawi MM, Aljama NA, Aljedani R, Alsaleh MH, Atyia N, Alsedrah A, Albardi M. The role of radiological imaging in the diagnosis and treatment of urolithiasis: a narrative review. Cureus. 2022;14(12):e33041. doi: 10.7759/cureus.33041. PMID: 36589703. PMCID: PMC9795962.
16 Froom P, Ribak J, Tendler Y, Cyjon A, Gross M. Asymptomatic microscopic hematuria in pilots. Aviat Space Environ Med. 1987;58:435–7. PMID: 3593146.
17 Sharp VJ, Barnes KT, Erickson BA. Assessment of asymptomatic microscopic hematuria in adults. Am Fam Physician. 2013;88:747–54. PMID: 24364522.
18 Hooton TM. Clinical practice. Uncomplicated urinary tract infection. N Engl J Med. 2012;366(11):1028–37. doi: 10.1056/NEJMcp1104429. PMID: 22417256.

Conflicts of interest and funding: nil

Submitted: 15 January 2024
Accepted after revision: 24 March 2024

Review articles

Effects of CO_2 on the occurrence of decompression sickness: review of the literature

Lucile Daubresse[1], Nicolas Vallée[2], Arnaud Druelle[1], Olivier Castagna[2], Régis Guieu[3], Jean-Eric Blatteau[1]

[1] *Department of hyperbaric and diving medicine. Hôpital d'instruction des armées Sainte-Anne. Toulon armées, France*
[2] *Resident operational underwater research team, Institut de recherche biomédicale des armées, Toulon armées, France*
[3] *Center for cardiovascular and nutrition research, Aix-Marseille University, Marseille, France*

Corresponding author: *Professor Jean-Eric Blatteau, Department of hyperbaric and diving medicine (SMHEP). Hôpital d'instruction des armées Sainte-Anne. 83800 Toulon armées, France*
jean-eric.blatteau@intradef.gouv.fr

Keywords
Bubbles; Carbogen; Carbon dioxide; Decompression illness; Diving; Hyperbaric; Hypercapnia; Hypobaric

Abstract
(Daubresse L, Vallée N, Druelle A, Castagna O, Guieu R, Blatteau J-E. Effects of CO_2 on the occurrence of decompression sickness: review of the literature. Diving and Hyperbaric Medicine. 2024 30 June;54(2):110–119. doi: 10.28920/dhm54.2.110-119. PMID: 38870953.)

Introduction: Inhalation of high concentrations of carbon dioxide (CO_2) at atmospheric pressure can be toxic with dose-dependent effects on the cardiorespiratory system or the central nervous system. Exposure to both hyperbaric and hypobaric environments can result in decompression sickness (DCS). The effects of CO_2 on DCS are not well documented with conflicting results. The objective was to review the literature to clarify the effects of CO_2 inhalation on DCS in the context of hypobaric or hyperbaric exposure.

Methods: The systematic review included experimental animal and human studies in hyper- and hypobaric conditions evaluating the effects of CO_2 on bubble formation, denitrogenation or the occurrence of DCS. The search was based on MEDLINE and PubMed articles with no language or date restrictions and also included articles from the underwater and aviation medicine literature.

Results: Out of 43 articles, only 11 articles were retained and classified according to the criteria of hypo- or hyperbaric exposure, taking into account the duration of CO_2 inhalation in relation to exposure and distinguishing experimental work from studies conducted in humans.

Conclusions: Before or during a stay in hypobaric conditions, exposure to high concentrations of CO_2 favors bubble formation and the occurrence of DCS. In hyperbaric conditions, high CO_2 concentrations increase the occurrence of DCS when exposure occurs during the bottom phase at maximum pressure, whereas beneficial effects are observed when exposure occurs during decompression. These opposite effects depending on the timing of exposure could be related to 1) the physical properties of CO_2, a highly diffusible gas that can influence bubble formation, 2) vasomotor effects (vasodilation), and 3) anti-inflammatory effects (kinase-nuclear factor and heme oxygenase-1 pathways). The use of O_2-CO_2 breathing mixtures on the surface after diving may be an avenue worth exploring to prevent DCS.

Introduction

At atmospheric pressure, inhalation of carbon dioxide (CO_2) can quickly become toxic depending on the concentration of inhaled CO_2. In ambient air, the level of CO_2 is about 400 ppm) or 0.04 kPa at atmospheric pressure (101.3 kPa). From 0.2 kPa (2,000 ppm or 0.2% of CO_2 at atmospheric pressure), clinical manifestations may appear with headaches, shortness of breath or tachycardia. At high concentrations (10,000 ppm or 1%), around 1 kPa of CO_2 at atmospheric pressure, consciousness disorders may occur. For these reasons, the European limit value not to be exceeded in occupational medicine is a maximum exposure per day of eight hours at 0.5 kPa at atmospheric pressure (5,000 ppm).[1]

Elevation of blood CO_2 levels endogenously or exogenously defines hypercapnia, which corresponds to an arterial CO_2 pressure ($PaCO_2$) above 6 kPa (45 mmHg). To avoid this situation, the body adapts by increasing its ventilatory response and activating its buffer systems. These physiological adaptations allow the removal of excess CO_2 and thus maintain a stable blood pH.

During hyperbaric exposure, hypercapnia can occur by several mechanisms: either by inhalation of higher CO_2 levels due to equipment failure, or by a disturbance in ventilatory control leading to hypoventilation (induced by increased ventilatory work or physical exercise).[2] It's important to note that some divers, including rebreather divers, appear to develop less sensitivity to CO_2 over time. This tolerance to hypercapnia, fostered by constant hyperoxia during immersion and adaptation to excessive ventilatory work, reduces the ventilatory drive induced by the normal response to increasing CO_2 levels.[3,4]

Hypercapnia appears to be the most frequent biochemical accident involving military rebreathers. A study of 30 years of accidents during rebreather use in the French Navy found that 68% related to gas toxicities, of which 60% were related to hypercapnia.[5] This hypercapnia occurs with rebreathers that use hyperoxic mixes, which protect against the onset of decompression sickness (DCS), but this use can lead to specific inflammatory responses.[6]

In addition, hypercapnia has been shown to potentiate the narcotic effects of nitrogen.[7] Symptoms of narcosis, including loss of consciousness, may be increased by exercise in hypercapnia.[8] Hypercapnia has also been shown to potentiate the neurological toxicity of oxygen, with observations of hyperoxic convulsive seizures occurring in combat swimmers using closed-circuit oxygen equipment. Most of these dives were long and sustained. At the end of the dive, the soda-lime cartridge filtered CO_2 less efficiently, resulting in higher inspired CO_2 levels.[5,9,10] The potentiation of oxygen toxicity effects is thought to be mediated in part by the vasodilatory action of CO_2 on cerebral arteries.[11]

Scuba diving also exposes divers to the risk of decompression sickness (DCS) if the removal of supersaturated inert gases from blood or body tissues during decompression is not performed properly. Increased CO_2 levels in the air or breathing mixture during underwater and hyperbaric exposure could also contribute to this type of accident. In fact, CO_2 may play a role in bubble formation and growth.[12,13] This hypothesis was raised during an investigation following a series of neurological diving accidents in 2020 at the French Army Diving Training Centre. Eight subjects developed neurological symptoms consistent with DCS after a training dive.[14]

Given the exceptional nature of this unprecedented group of accidents, both in terms of incidence and clinical presentation, an investigation was carried out to identify the contributing factors. In particular, all changes related to the 'COVID-19' context implemented in the organisation of this course were analysed in detail, as well as the environmental or individual causes[15] that could be at the origin of the onset of neurological clinical symptoms. The retention of CO_2 and the inhalation of part of it, linked to the sanitary conditions (wearing of a protective mask), was a possible explanation, based on the hypothesis of the activation of gaseous nuclei by CO_2 before diving.[13]

It appears that the increased risk of DCS is rather poorly documented and seems to be related only to the situation of CO_2 exposure during bottom time.[16] On the other hand, different or even opposite effects are observed when CO_2 exposure occurs during the decompression phase.[17] In view of these divergent results, we felt it was important to review all published studies on the subject, concerning both hyperbaric and hypobaric exposures, based on experimental data or studies conducted in humans.

The aim of this study is to clarify the effect of CO_2 inhalation on the occurrence of decompression sickness as a function of the duration and concentration of inhaled CO_2 relative to hypobaric or hyperbaric exposure. We define low concentrations of inhaled CO_2 as a $PiCO_2$ of less than 1 kPa (equivalent to 1% of inhaled CO_2 at surface pressure) and high concentrations as a $PiCO_2$ of 1 kPa or more.

Methods

INCLUSION CRITERIA

This study focuses on available clinical or experimental data based on CO_2-enriched mixtures and does not address hypercapnia issues related to endogenous production.

We considered all experimental animal studies or descriptive human studies performed under hyper- or hypobaric conditions that evaluated the effect of CO_2 on bubble formation, denitrogenation, or the occurrence of DCS. The MEDLINE and PubMed search engines were used with the following keywords: carbon dioxide, nitrogen, decompression sickness, decompression illness, bubble, denitrogenation, diving. We did not limit the bibliographic search by publication date or language.

We have also included documents from specialist books on underwater and hyperbaric medicine and aeronautical medicine, as well as archival documents from specialist websites.

Results

SELECTION OF ARTICLES

Forty-three articles were identified based on the inclusion criteria, of which 31 were from MEDLINE or PubMed and 12 from other sources. Thirty-two articles were excluded. The decision on the retention of articles was taken by consensus of a number of authors on the basis of criteria of relevance to the topic. A total of 11 articles were included in the review (Figure 1).

Figure 1
PRISMA flow diagram to show study selection

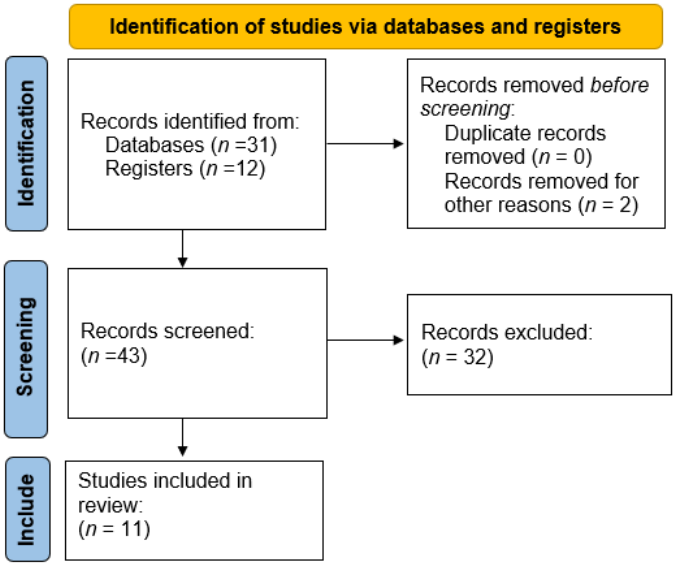


Table 1
Classification of CO_2 studies according to exposure and type of study

Type of exposure	Effects studied	Author's name & year	Type of study
Hypobaric	Effects of elevated CO_2 prior to exposure	Harris et al. 1945	Animal
		Andicochea et al. 2019	Human
	Effects of CO_2 elevation before and during exposure	Hill et al. 1994	Animal
		Katuntsev et al. 1994	Human
Hyperbaric	Effects of elevated CO_2 prior to exposure	Seddon, 1997	Animal
	Effects of elevated CO_2 during exposure	Mano et al. 1978	Human
	Effects of elevated CO_2 during decompression	Margaria et al. 1950	Human
		Bell et al. 1986	Human
		Gennser et al. 2014	Animal
	Effects of elevated CO_2 during exposure and just before decompression	Gennser et al. 2008	Animal
		Huang et al. 2018	Animal

The 11 articles selected were classified according to the criteria of hypo or hyperbaric exposure, taking into account the timing of CO_2 inhalation in relation to exposure and distinguishing between experimental work and studies carried out in humans (Table 1).

STUDIES DURING HYPOBARIC EXPOSURE

Effects of inhaling high concentrations of CO_2 prior to hypobaric exposure in animals

In 1944, Harris et al. conducted several animal model studies by exposing frogs to rapid depressurisation (2–10 minutes) to simulated altitudes of 10,000–70,000 ft for 30 minutes.[18] On return to atmospheric pressure, the number of bubbles formed was analysed by a venous sampling method. These experiments determined the levels of depressurisation and muscle stimulation in the frogs necessary to observe bubble formation.

The animals were then subjected to very high levels of CO_2 inhalation ranging from 25 to 70 kPa for 1.5 hours and up to 4 hours prior to depressurisation.

The authors demonstrated the concept of CO_2 as a facilitator of bubble formation. It greatly increased the ease with which bubbles can be initiated and may be responsible for their rapid growth in the early stages of development.

Effects of inhaling high concentrations of CO_2 before and during hypobaric exposure in animals

Hill et al. conducted an animal study in 1994, in which seven goats were repeatedly exposed to hypobaric exposure at equivalent altitudes of 5,000–33,000 ft for 30 min.[19] The rate of depressurisation was 19 kPa·min^{-1}. The protocol involved inhalation of O_2–CO_2 mixtures before and during the hypobaric exposure. Before the exposure, the mixtures breathed for 15 min contained 0 to 6.1 kPa of CO_2. Throughout the exposure, the mixtures breathed contained 0 to 4 kPa CO_2.

The risk of decompression events was assessed by measuring precordial circulating bubbles during hypobaric exposure.

When CO_2 levels were increased before and during hypobaric exposure, no significant changes in the number of circulating bubbles were observed. According to the authors, this negative result may be related to insufficient numbers or too short periods of CO_2 exposure before depressurisation.

Effects of inhaling high concentrations of CO_2 before and during hypobaric exposure in humans

Katuntsev et al. conducted a study to evaluate the effect of CO_2 on the occurrence of DCS during hypobaric exposures simulating extravehicular activity protocols.[20]

They exposed 46 healthy male volunteers to simulated altitudes of 21,325 to 26,574 ft for up to six hours. During the hypobaric exposure, the subjects performed a calibrated intermittent exercise. The subjects breathed a 97% O_2–3% CO_2 mixture for two hours prior to depressurisation. Inhalation of this mixture was maintained during the hypobaric exposure. A total of 106 experimental exposures were performed while breathing 3% O_2–CO_2 versus 101 control exposures breathing pure O_2. The subjects who inhaled the CO_2-enriched mixture showed a decrease in mean blood pH values from 7.40 to 7.37 and an increase in $PaCO_2$ from 5.26 to 5.82 kPa.

The incidence of joint pain DCS was significantly higher in the CO_2-exposed group before and during depressurisation than in the control group, with 67.9% DCS versus 32.7%, respectively.

Effects of inhaling low concentrations of CO_2 prior to hypobaric exposure in humans

In 2019, Andicochea reported cognitive symptoms suggestive of altitude DCS in six US Army aviators.[21] This involved exposure to high altitudes of 30,000–41,000 feet with a rapid depressurisation protocol. Of the nine pilots who underwent this procedure, six experienced cognitive dysfunction including difficulty concentrating, a feeling of psychic slowing down, and paraesthesias in the limbs. Four of the six symptomatic pilots received hyperbaric chamber treatment. The six symptomatic pilots had been exposed several hours before the flight to a slightly elevated level of CO_2 (900 ppm on average, i.e., 0.09 kPa) in their briefing room which was poorly ventilated. The three other pilots who were briefed in another room with better ventilation (560 ppm on average, i.e., 0.056 kPa) and who followed the same protocol did not show any symptoms.

According to the authors, chronic intoxication with 1,000 ppm CO_2 prior to a rapid ascent could have an effect on the occurrence of high-altitude DCS.

STUDIES DURING HYPERBARIC EXPOSURES

Effects of inhaling high concentrations of CO_2 prior to hyperbaric exposure in animals

Seddon conducted a series of experiments to determine the relationship between the pressure at which a goat can become saturated and the maximum depth from which it can then safely escape from a simulated submarine.[22] One of the aims of the study was to assess the effect of prior exposure to a CO_2-enriched environment and its impact on the incidence of decompression sickness and bubble formation. He compared several groups of animals exposed to a high inspired pressure of CO_2 (2.5 kPa) for 23 hours before being subjected to a very rapid compression-decompression protocol simulating an escape procedure at equivalent depths of 240 to 270 metres (787 to 886 ft). In the group maintained at atmospheric pressure and then subjected to an escape procedure at 270 m, none of the 20 animals showed any signs of DCS. The bubble scores of the animals exposed to CO_2 were slightly higher than those of the animals maintained in air, but the difference was not significant.

Seddon's results do not support the hypothesis of increased bubble formation and DCS following normobaric exposure to a CO_2-enriched environment prior to an aggressive escape procedure dive.

Effects of inhaling high concentrations of CO_2 during hyperbaric exposure in humans

The study carried out by Mano and d'Arrigo in 1978 was a retrospective descriptive study of 84 tunnel boring machines involved in the construction of the Tokyo Bay Subway which lasted five months.[16] The authors noted that DCS was only observed at pressures above 273.5 kPa (2.7 atmospheres absolute) and working times of 5.5 to 6 hours maximum.

At the start of the project, the working chambers were not ventilated. For ambient pressures between 304 and 324 kPa, the ambient CO_2 level was between 1.8 and 2.3% ($PiCO_2$ max = 7.36 kPa). Out of 2,430 exposures carried out under these conditions, there were 74 cases of joint pain DCS (90% involving the knee), i.e., an incidence of 3.05%.

Table 2
Number of joint pain decompression sickness (DCS) cases as a function of CO_2 exposure based on data from Mano and d'Arrigo (1978)[16]; Max – maximum; $PiCO_2$ – inspired pressure of CO_2

Pressures (kPa)	Ventilation	Ambient CO_2 (%)	Max $PiCO_2$ (kPa)	Exposures (*n*)	DCS (*n* %)
300–320	No	1.8–2.3	7.36	2,430	74 (3.05%)
320–340	Yes	0.3–0.8	2.70	3,951	38 (0.96%)

At the end of the work, the rooms were ventilated, the ambient CO_2 level was between 0.3 and 0.9% at an ambient pressure of between 324 and 344.5 kPa ($PiCO_2$ max = 3 kPa). Out of 3,951 exposures, 38 DCS were reported, i.e., an incidence of 0.96% of DCS (Table 2).

The authors highlighted the increased risk of DCS as a function of CO_2 levels in the hyperbaric environment.

Effects of inhaling high concentrations of CO_2 during decompression in humans

In 1950, Margaria and Sendroy exposed four male volunteer divers to a hyperbaric environment at 203 kPa for four hours before decompressing to atmospheric pressure within one minute.[17] Immediately upon returning to the surface, the divers breathed either 100% O_2, O_2 with 3% CO_2 or O_2 with 5% CO_2 in a chamber at 25°C, while seated at rest. Exhaled gas samples were collected in a Douglas bag every 10 to 15 minutes to determine their composition using the Van Slyke and Sendroy method. This method, described by Van Slyke in 1927, consists of measuring the proportion of oxygen and carbon dioxide contained in a gas using a manometric method. The amount of N_2 eliminated (denitrogenation curve) up to two hours after the dive was extrapolated from these measurements.

The results showed a significant increase of 20% in exhaled N_2 when breathing O_2 with 5% CO_2 compared to breathing pure O_2. No clinical symptoms were reported. The pH remained stable with an increase in ventilation in the subjects exposed to the O_2/CO_2 mixture.

The authors expressed interest in breathing a 5% CO_2 95% O_2 mixture at atmospheric pressure after a hyperbaric exposure, to increase the elimination of nitrogen and thereby reduce the occurrence of DCS.

However, in a relevant animal study, Gennser et al. investigated the ability of gases breathed after surfacing to reduce the initial bubble load.[23] Animals breathing oxygen, carbogen (5% CO_2, 95% O_2), or air were compared. Thirty-two goats were subjected to a dry simulated submarine escape profile to and from 240 meters (2.5 MPa). On surfacing, they breathed air (control), oxygen or carbogen for 30 minutes. Bubbles were assessed by audio Doppler, using the Kisman Masurel (KM) scale. There was no significant difference between groups in the median peak KM grade. On the other hand, oxygen showed significantly faster bubble resolution than carbogen and air. It follows that this study did not confirm the value of carbogen breathing during post-surfacing decompression in order to reduce bubbles.

The Bell et al. study, published in 1986, was a prospective study of 65 healthy volunteer divers during a saturation dive.[24] Divers were exposed to either 172 or 182 kPa ambient pressure for 48 hours before being decompressed to atmospheric pressure at a rate of 0.5 $m \cdot min^{-1}$. During decompression, one group of 30 divers breathed nitrox (40% O_2), while the other group of 35 divers breathed nitrox (38% O_2) with 2% CO_2. At the end of the dive, the effect of decompression was assessed by repeated measurement of precordial circulating bubbles, assessed at rest and after movement, during the six hours following hyperbaric exposure, also noting the possible occurrence of DCS within 24 hours.

The study showed no difference in the incidence of DCS between the two groups. None of the 20 subjects exposed to 172 kPa showed any symptoms. However, there were two cases of DCS in both groups exposed to 182 kPa. The main finding of the study concerns the number of circulating bubbles which was lower in the O_2-CO_2-N_2 breathing group with a significant reduction of 55% of the bubble levels (following movement) for divers diving at 172 kPa and 30% (after movement) for those diving at 182 kPa.

The authors expressed a real interest in breathing a CO_2-enriched mixture during decompression in order to reduce the formation of circulating bubbles and thus the risk of DCS.

Effects of inhaling high concentrations of CO_2 before and during decompression in animals

Gennser et al. performed two experiments on goats to determine the influence of breathing gases on the number of circulating bubbles after a submarine simulated escape.[25] In the experiment of interest, goats breathed either 100% O_2, 97.5% (n = 12), O_2-CO_2 2.5% (Carbogen) (n = 8) or air (n = 10) for 15 min after a six hour period at 100 kPa (~10 metres of seawater). Next, an evacuation profile from a submarine at a depth of 240 m was simulated (compression in 24 s followed by decompression at 2.75 $m \cdot sec^{-1}$). Finally, circulating bubbles were measured in each group for 6 h. The number of DCS cases was recorded for each group. The

results showed that circulating bubbles decreased (in number and duration) only in the group pre-exposed to 100% O_2. Only one case of CNS DCS occurred, in the carbogen group. Two animals (also in the carbogen group) suffered from oxygen convulsions. Three fatal events due to pulmonary barotrauma were observed in the 100% O_2 and air groups.

The idea of adding CO_2 to O_2 was that the vasodilatory effect of CO_2 would speed up the elimination of nitrogen, particularly in the CNS. However, this study does not confirm the value of adding carbogen prior to decompression to reduce bubbles and limit the occurrence of DCS. In addition, the vasodilatory effect favours the onset of oxygen-induced convulsions.

In 2018, Huang et al. published an abstract of an animal study investigating the effect of inhaling high levels of CO_2 before the start of decompression on the occurrence of DCS.[26] To do this, the authors exposed rats to 608 kPa for one or two hours with rapid decompression in five min to induce DCS. The rats were divided into three groups and breathed a mixture of 3% CO_2 and 97% air for either 10 min, 30 min or 60 min before the start of decompression. The authors then analysed the histological lung lesions induced by post-decompression bubble formation. The number of animals per group is not given.

They showed that rats that breathed the gas mixture for 10 min just before the onset of decompression had a lower DCS mortality with less decompression-induced lung damage compared to rats that breathed the CO_2-enriched gas mixtures for 30 min or 60 min of hyperbaric exposure.

The authors suggested that a short period of hypercapnia, just before decompression, would have a specific anti-inflammatory effect and thus protect against inflammatory lung lesions associated with decompression sickness. The protective effect of CO_2 would be related to an effect that is independent of the known effects on bubble and nitrogen elimination, but which was not studied in this study.

A summary of these studies is provided in Table 3.

Discussion

HYPOBARIC CONDITIONS

Studies in hypobaric conditions have shown that CO_2 has a predominantly detrimental effect on the risk of DCS at high altitude. This is particularly the case when CO_2 is inhaled prior to depressurisation.

This analysis of articles confirms that the occurrence of hypercapnia prior to depressurisation is a factor that favours the increase in the formation and volume of circulating bubbles and de facto, the risk of the occurrence of a DCS.[27]

On the other hand, there are no mechanisms associated with a change in pH due to CO_2. In fact, in an organism without underlying pathology, $PaCO_2$ is compensated by hyperventilation and activation of the body's buffer systems to maintain a stable pH. Katuntsev found no pH disturbance despite high inhaled CO_2 concentrations.[20]

HYPERBARIC CONDITIONS

CO_2 breathed during time spent at the bottom may have a detrimental effect, as suggested by Mano's observational study, which found an increased incidence of DCS when tunnels were poorly ventilated.[16]

In contrast, several studies in healthy volunteers support a beneficial effect when exposure to elevated CO_2 occurs during decompression.

Margaria et al. were interested in the possible potentiating effect of CO_2 on denitrogenation.[17] This study is the only one to have measured the elimination of nitrogen in humans after breathing an over-oxygenated mixture enriched with CO_2 following hyperbaric exposure. In this study, the measurement of circulating bubbles was not performed and only the measurement of respiratory N_2 elimination was considered. The approach is particularly interesting as it shows a possible beneficial effect of CO_2 when exposure takes place during decompression. The addition of CO_2 to oxygen appeared to be more effective than inhalation of 100% O_2, which could be of practical interest in optimising denitrogenation procedures and thus safety in diving currently based on the use of 100% O_2. Indeed, pre- or post-dive oxygen inhalation is known to have a beneficial effect on nitrogen elimination and protection against DCS events during diving[28,29] and is increasingly used in recreational and professional diving to improve denitrogenation in the context of deep or repetitive dives.

Bell's study also goes in this direction, although the results did not show a reduction in the incidence of DCS, they did note a reduction in circulating bubbles when divers breathed CO_2-enriched air during decompression.[23] However, Gennser's animal study[23] did not confirm the value of carbogen breathing after surfacing following a simulated submarine escape in order to reduce bubble formation and DCS.

HYPOTHESES ON THE RELEVANT EFFECTS OF INHALED CO_2

Physical effects on gas phases

CO_2 is a fat-soluble, highly diffusible gas that may affect the bubble phenomenon via an increase in the growth of gas nuclei and bubbles when the concentration of dissolved CO_2 increases.[12,13,27,30] Gennser et al. speculated that CO_2 inhalation under pressure would promote bubble formation due to the high diffusibility of CO_2.[25]

Table 3
Summary of the different effects of CO_2 as a function of pressure conditions, CO_2 exposure phase and CO_2 levels; DCS – decompression sickness

Exposure	Author, year	CO_2 inhalation phase	CO_2 %	Type of study	Conclusion
Hypobaric	Harris, 1945	Before and during depressurisation	25–70% (25–70 kPa)	Animal	**Deleterious effect:** Increase bubble formation
	Hill, 1944	Before and during depressurisation	3.5–46% (3.5–4.6 kPa)	Animal *n* = 7	**Not significant**
	Katuntsev, 1994	Before depressurisation	3% (3 kPa)	Male *n* = 46	**Deleterious effect**: Increase in DCS occurrence
	Andicochea, 2019	Before depressurisation	~0.1% (0.1 kPa)	Male *n* = 9	
Hyperbaric	Seddon, 1997	Before hyperbaric exposure	2.5% (2.5 kPa)	Animal *n* = 20	**Not significant** on DCS occurence. Slight increase in circulating bubbles
	Mano, 1978	During the hyperbaric exposure	See Table 2	Male See Table 2	**Deleterious effect**: Increase in DCS occurrence
	Margaria, 1950	After surfacing	5% (5 kPa)	Male *n* = 4	**Beneficial effect:** Accelerated denitrogenation
	Gennser, 2014	After surfacing	5% (5 kPa)	Animal *n* = 32	**Not significant** compared to air or oxygen for reducing circulating bubbles. Faster resolution with O_2
	Bell, 1986	During decompression (from saturation dive)	2% (3.6 kPa at 182 kPa)	Male *n* = 65	**Beneficial effect:** Reduction of circulating bubbles compared to air
	Gennser, 2008	(15 min) Before decompression	2.5% (5 kPa at 200 kPa)	Animal *n* = 30	**Not significant** compared to air for reducing circulating bubbles. O_2 more effective in reducing bubbles. **Deleterious effect:** Promotes oxygen convulsions
	Huang, 2018	During (and 10 min before) decompression	3% (18 kPa)	Animal	**Beneficial effect:** Improvement of lung damage induced by bubble formation

Vasomotor effects

In 1990, Bailliart measured changes in carotid artery flow in healthy subjects exposed to 5% CO_2.[31] They found a 30% increase in primary carotid artery flow due to an acceleration of the circulatory flow. Vascular reactivity during CO_2 inhalation has also been studied at the cerebral level by magnetic resonance imaging in healthy volunteers breathing a gas containing 5% CO_2, 21% O_2 and 74% N_2.[32] The study showed rapid cerebral vasodilation during CO_2 inhalation with rapid normalisation at the end of exposure.

Lambertsen et al. in 1955 observed that adding 2% to CO_2 to inhaled oxygen significantly shortened the time to onset of hyperoxic convulsions.[33] In his experiment, where he had humans breathing oxygen at 355 kPa, the PCO_2 at the onset of convulsions was low at 3.06 kPa (23 mmHg). The most likely hypothesis is that the vasodilatory effect of CO_2 outweighs the vasoconstrictive effect of oxygen.

In an attempt to improve decompression Gennser et al. tried to counteract the vasoconstrictive effect of oxygen with the vasodilatory effect of CO_2 by adding CO_2 to oxygen. As previously mentioned, this had no beneficial effect on decompression and hyperoxic crises occurred.[25]

In the context of hyperbaric exposure, the vasodilatory effect of CO_2 appears to have an unfavourable effect on the risk of DCS occurrence by increasing the inert gas load on the tissues during bottom time. Nevertheless, the effects of CO_2 combined with oxygen in the form of carbogen may be of interest in preventing DCS under certain conditions, and may be an avenue for improving surface decompression. It is important to continue research into the administration of carbogen on the surface, as studies are few and contradictory.[17,23]

Acid-basic effects and anti-inflammatory properties

Acid-base balance is maintained by the combined action of ventilation and the buffering effect of bicarbonates.[34] The body adapts to elevated concentrations of inhaled CO_2 by hyperventilating.[35,36] Exposure to higher concentrations of CO_2 (> 5%) will exceed the regulatory capacity of the organism, leading to disruption of acid-base balance, respiratory acidosis and blood hypercapnia. The severity of these effects depends on the duration of exposure, the CO_2 level and the basal state of the exposed subject.[37,38]

In addition to the effects described above, inhalation of high concentrations of CO_2 appears to activate anti-inflammatory processes. The work of Huang et al. in the DCS animal model suggests an anti-inflammatory effect with amelioration of lung damage when exposure to 3% of inspired CO_2 occurs immediately before and during the decompression phase.[26] The work of this same team has also explored these anti-inflammatory and anti-apoptotic effects in other models of acute lung injury, which would be mediated by hypercapnic acidosis with activation of heme oxygenase-1 anti-oxidant enzyme (HO-1) and inhibition of nuclear factor (NF)-κB signaling.[39,40] This work must be set against that of Katuntsev,[20] who found no variation in pH despite high concentrations of inhaled CO_2.

Therapeutic effects

The therapeutic properties of CO_2 are already being used in the form of an inhaled carbogen. This gas, usually composed of 95% oxygen and 5% CO_2, has long been used to treat sudden deafness.[41] Carbogen induces vasodilation and increased blood flow compared to pure oxygen alone. Measurements of PO_2 and PCO_2 carried out, mainly in the retina of animals under normobaric conditions, show an improvement in O_2 diffusion during carbogen breathing. CO_2 promotes the release of O_2 by haemoglobin (Bohr effect) which contributes to a better tissue oxygen delivery.[42]

In addition, CO_2-induced vasodilation in carbogen may also contribute to better O_2 utilisation and delivery through increased blood flow compared to pure oxygen.[43–45]

In 2009, a Cochrane review was conducted on 189 patients to assess the efficacy of different vasodilators in the treatment of sensorineural hearing loss.[41] Twenty-six patients received Carbogen. The only side effect reported was a feeling of heaviness in the head in five patients, which resolved spontaneously when the treatment was stopped.

These effects of CO_2 combined with oxygen in the form of carbogen may be of interest in the prevention of decompression sickness, in certain post-surfacing conditions. In fact, the vasodilatation and hyperventilation induced by CO_2 could favour denitrogenation with a better elimination of N_2 by the respiratory route. The anti-inflammatory effects could also contribute to a better tolerance of the bubble phenomenon during decompression. However, as previously mentioned, cerebral vasodilation can promote the onset of cerebral oxygen toxicity, which makes it dangerous to use during submersion.

Conclusions

In conclusion, we note that all the studies conducted in the context of hypobaric exposure suggest a detrimental effect of CO_2 on bubble formation and the occurrence of DCS.

In the context of hyperbaric exposures, the effects appear to be related to the duration of exposure, with adverse effects observed when the CO_2 exposure occurs before or during the bottom time, whereas beneficial effects are observed when the exposure occurs after decompression. Overall, there are very few studies on this topic, and human studies are rare and old. The studies presented do not answer the initial question of whether a low dose of CO_2 before diving can increase the

risk of DCS. Only the study on American aviators suggests this, but under hypobaric conditions.[21]

It should be noted that the effect of CO_2, particularly at low doses prior to hyperbaric exposure, has not been reported in the literature.

Given the lack of data on this point, we believe it is important to experimentally investigate the effects of chronic CO_2 exposure prior to hyperbaric exposure.

Furthermore, most studies inferring a possible beneficial effect of CO_2 in the decompression phase are observational and small. Further experimental work is required to confirm this effect and its mechanism(s).

The effect of carbogen inhalation (95% O_2 and 5% CO_2) after decompression could be studied with an aim of optimising decompression procedures. This could help to improve surface decompression procedures in specific contexts such as saturation diving evacuation procedures, submarine rescue or technical deep diving with rebreathers.

References

1 INRS. Institut national de recherche et de sécurité pour la prévention des accidents du travail et des maladies professionnelles. Intoxication by inhalation of carbon dioxide. Dossier médico-technique. Documents pour le médecin du travail, N°79, 3rd quarter. 1999.

2 Anthony G, Mitchell S. Respiratory physiology of rebreather diving. In: Pollock NW, Sellers SH, Godfrey JM, editors. Rebreathers and scientific diving. Proceedings of NPS/NOAA/DAN/AAUS June 16-19, 2015, Workshop. Durham, NC: 2016. p. 66–79.

3 Hyacinthe R, Giry P, Battesti A. Effets de l'entrainement et du conditionnement ventilatoires sur le comportement respiratoire du plongeur à 46 ATA. Bull MEDSUBHYP. 1983;2(2):9–16.

4 Badier M. Hypercapnie. In : Broussolle B, Meliet JL, Coulange M. Physiologie et médecine de la plongée, 2e éd. Paris: Ellipse Edition Marketing; 2006. p. 306–12.

5 Gempp E, Louge P, Blatteau JE, Hugon M. Descriptive epidemiology of 153 diving injuries with rebreathers among French military divers from 1979 to 2009. Mil Med. 2011;176:446–50. doi: 10.7205/milmed-d-10-00420. PMID: 21539168.

6 Arya AK, Balestra C, Bhopale VM, Tuominen LJ, Räisänen-Sokolowski A, Dugrenot E, et al. Elevations of extracellular vesicles and inflammatory biomarkers in closed circuit scuba divers. Int J Mol Sci. 2023;24:5969. doi: 10.3390/ijms24065969. PMID: 36983042. PMCID: PMC10053377.

7 Hesser CM, Adolfson J, Fagraeus L. Role of CO_2 in compressed-air narcosis. Aerosp Med. 1971;42:163–8. PMID: 5547162.

8 Lanphier EH. Carbon dioxide poisoning. In: Waite CL, editor. Case histories of diving and hyperbaric accidents. UHMS Publication No. 0-930406-12-5. Bethesda (MD): Undersea and Hyperbaric Medical Society; 1988. p. 199–213.

9 Arieli R, Moskovitz Y. Humidity does not affect central nervous system oxygen toxicity. J Appl Physiol (1985). 2001;91:1327–33. doi: 10.1152/jappl.2001.91.3.1327. PMID: 11509532.

10 Eynan M, Daskalovic YI, Arieli Y, Arieli R, Shupak A, Eilender E, et al. Training improves divers' ability to detect increased CO_2. Aviat Space Environ Med. 2003;74:537–45. PMID: 12751583.

11 Schmetterer L, Findl O, Strenn K, Graselli U, Kastner J, Eichler HG, et al. Role of NO in the O_2 and CO_2 responsiveness of cerebral and ocular circulation in humans. Am J Physiol. 1997;273(6):R2005–12. doi: 10.1152/ajpregu.1997.273.6.R2005. PMID: 9435655.

12 Ishiyama A. Analysis of gas composition of intravascular bubbles produced by decompression. Bull Tokyo Med Dent Univ. 1983;30(2):25–35. PMID: 6418399.

13 Blatteau JE, Souraud JB, Gempp E, Boussuges A. Gas nuclei, their origin, and their role in bubble formation. Aviat Space Environ Med. 2006;77:1068–76. PMID: 17042253.

14 Daubresse L, Amara J, Grau M, De Maistre S, Cassourret G, Lehot H, et al. Occurrence of a series of unusual cases of neurological symptoms during training dives in a context of preventive measures related to SarsCov2. Bull MEDSUBHYP. 2022;31(2):77–85.

15 Imbert J-P, Egi SM, Germonpré P, Balestra C. Static metabolic bubbles as precursors of vascular gas emboli during divers' decompression: a hypothesis explaining bubbling variability. Front Physiol. 2019;10:807. doi: 10.3389/fphys.2019.00807. PMID: 31354506. PMCID: PMC6638188.

16 Mano Y, D'Arrigo JS. Relationship between CO_2 levels and decompression sickness: implications for disease prevention. Aviat Space Environ Med. 1978;49:349–55. PMID: 637787.

17 Margaria R, Sendroy J Jr. Effect of carbon dioxide on rate of denitrogenation in human subjects. J Appl Physiol. 1950;3:295–308. doi: 10.1152/jappl.1950.3.6.295. PMID: 14794592.

18 Harris M, Berg WE, Whitaker DM, Twitty VC, Blinks LR. Carbon dioxide as a facilitating agent in the initiation and growth of bubbles in animals decompressed to simulated altitudes. J Gen Physiol. 1945;28:225–40. doi: 10.1085/jgp.28.3.225. PMID: 19873416. PMCID: PMC2142667.

19 Hill RC, Miller CW, Tucker A. Influence of carbon dioxide on venous gas emboli production during altitude decompression in goats. Aviat Space Environ Med. 1994;65:139–43. PMID: 8161324.

20 Katuntsev V, Poleshchuk P, Kazakova R. The effect of hypercapnia on the decompression sickness risk during simulated extravehicular activity. Aerosp Med. 1994;103:734–8.

21 Andicochea CT, Henriques ME, Fulkerson J, Jay S, Chen H, Deaton T. Elevated environmental carbon dioxide exposure confounding physiologic events in aviators? Mil Med. 2019;184(11-12):e863–7. doi: 10.1093/milmed/usz092. PMID: 31038172.

22 Seddon FM. Safe to escape curve animal studies: August 1993 to February 1997. Defense Research Agency report DERA/SSES/CR971023/1.0. London, UK: Defence Evaluation and Research Agency; 1997.

23 Gennser M, Loveman G, Seddon F, Thacker J, Blogg SL. Oxygen and carbogen breathing following simulated submarine escape. Undersea Hyperb Med. 2014;41:387–92. PMID: 25558547.

24 Bell PY, Harrison JR, Page K, Summerfield M. An effect of CO_2 on the maximum safe direct decompression to 1 bar

from oxygen-nitrogen saturation. Undersea Biomed Res. 1986;13:443–55. PMID: 3101259.
25 Gennser M, Blogg SL. Oxygen or carbogen breathing before simulated submarine escape. J Appl Physiol (1985). 2008;104:50–6. doi: 10.1152/japplphysiol.00465.2007. PMID: 17975127.
26 Huang K-L, Peng C-K, Chu S-J. Hypercapnic acidosis attenuates decompression sickness-induced lung injury. Asian Pacific Society of Respirology. 2018;23:5–89.
27 Hodes R, Larrabee M. The relation between alveolar carbon dioxide tension and susceptibility to decompression sickness. Am J Physiol. 1946;147:603–15. doi: 10.1152/ajplegacy.1946.147.4.603. PMID: 20277052.
28 Pontier JM, Lambrechts K. Effect of oxygen-breathing during a decompression-stop on bubble-induced platelet activation after an open-sea air dive: oxygen-stop decompression. Eur J Appl Physiol. 2014;114:1175–81. doi: 10.1007/s00421-014-2841-x. PMID: 24563091.
29 Castagna O, Gempp E, Blatteau JE. Pre-dive normobaric oxygen reduces bubble formation in scuba divers. Eur J Appl Physiol. 2009;106:167–72. doi: 10.1007/s00421-009-1003-z. PMID: 19219451.
30 Gireesan S, Pandit AB. Modeling the effect of carbon-dioxide gas on cavitation. Ultrason Sonochem. 2017;34:721–8. doi: 10.1016/j.ultsonch.2016.07.005. PMID: 27773299.
31 Bailliart O, Marotte H, Normand H, Martineaud JP, Durand J. Variations du débit de la carotide primitive et de ses branches lors de modifications de la composition en O_2 et en CO_2 du gaz alvéolaire. Arch Int Physiol Biochim. 1990;98:179–92. PMID: 1707614. French.
32 Liu P, De Vis JB, Lu H. Cerebrovascular reactivity (CVR) MRI with CO_2 challenge: a technical review. Neuroimage. 2019;187:104–15. doi: 10.1016/j.neuroimage.2018.03.047. PMID: 29574034. PMCID: PMC6150860.
33 Lambersten CJ, Ewing JH, Kough RH, Gould R, Stroud MW 3rd. Oxygen toxicity, arterial and internal jugular blood gas composition in man during inhalation of air, 100% O_2 and 2% CO_2 in O_2 at 3.5 atmospheres of ambient pressure. J Appl Physiol. 1955;8:255–63. doi: 10.1152/jappl.1955.8.3.255. PMID: 13271251.
34 Mannée DC, Fabius TM, Wagenaar M, Eijsvogel MMM, de Jongh FHC. Reproducibility of hypercapnic ventilatory response measurements with steady-state and rebreathing methods. ERJ Open Res. 2018;4(1):00141–2017. doi: 10.1183/23120541.00141-2017. PMID: 29492407. PMCID: PMC5824331.
35 Alexander JK, West JR, Wood JA, Richard DW. Analysis of the respiratory response to carbon dioxide inhalation in varying clinical states of hypercapnia, anoxia, and acid-base derangement. J Clin Invest. 1955;34:511–32. doi: 10.1172/JCI103100. PMID: 14367506. PMCID: PMC438656.
36 Maresh CM, Armstrong LE, Kavouras SA, Allen GJ, Casa DJ, Whittlesey M, et al. Physiological and psychological effects associated with high carbon dioxide levels in healthy men. Aviat Space Environ Med. 1997;68:41–5. PMID: 9006881.
37 Permentier K, Vercammen S, Soetaert S, Schellemans C. Carbon dioxide poisoning: a literature review of an often forgotten cause of intoxication in the emergency department. Int J Emerg Med. 2017;10(1):14. doi: 10.1186/s12245-017-0142-y. PMID: 28378268. PMCID: PMC5380556.
38 Van der Schrier R, van Velzen M, Roozekrans M, Sarton E, Olofsen E, Niesters M, et al. Carbon dioxide tolerability and toxicity in rat and man: a translational study. Front. Toxicol. 2022;4:1001709. doi: 10.3389/ftox.2022.1001709. PMID: 36310693. PMCID: PMC9606673.
39 Wu SY, Wu CP, Kang BH, Li MH, Chu SJ, Huang KL. Hypercapnic acidosis attenuates reperfusion injury in isolated and perfused rat lungs. Crit Care Med. 2012;40:553–9. doi: 10.1097/CCM.0b013e318232d776. PMID: 21946657.
40 Wu SY, Li MH, Ko FC, Wu GC, Huang KL, Chu SJ. Protective effect of hypercapnic acidosis in ischemia-reperfusion lung injury is attributable to upregulation of heme oxygenase-1. PLoS One. 2013;8(9):e74742. doi: 10.1371/journal.pone.0074742. PMID: 24040332. PMCID: PMC3769390.
41 Agarwal L, Pothier DD. Vasodilators and vasoactive substances for idiopathic sudden sensorineural hearing loss. Cochrane Database of Systematic Reviews. 2009;2009(4):CD003422. doi: 10.1002/14651858.CD003422.pub4. PMID: 19821308. PMCID: PMC7170414.
42 Pournaras JA, Poitry S, Munoz JL, Pournaras CJ. Occlusion veineuse rétinienne expérimentale: effet de l'inhalation de carbogène sur la PO_2 prérétinienne [Experimental branch vein occlusion: the effect of carbogen breathing on preretinal PO_2]. J Fr Ophtalmol. 2003;26:813–8. PMID: 14586222. French.
43 Rosengarten B, Spiller A, Aldinger C, Kaps M. Control system analysis of visually evoked blood flow regulation in humans under normocapnia and hypercapnia. Eur J Ultrasound. 2003;16:169–75. doi: 10.1016/s0929-8266(02)00070-8. PMID: 12573785.
44 Petropoulos IK, Pournaras JA, Munoz JL, Pournaras CJ. Effect of carbogen breathing and acetazolamide on optic disc PO_2. Invest Ophthalmol Vis Sci. 2005;46:4139–46. doi: 10.1167/iovs.05-0258. PMID: 16249491.
45 Chung CK, Linsenmeier RA. Effect of carbogen (95% O_2/5% CO_2) on retinal oxygenation in dark-adapted anesthetized cats. Curr Eye Res. 2007;32(7-8):699–707. doi: 10.1080/02713680701459250. PMID: 17852195.

Conflicts of interest and funding: nil

Submitted: 11 April 2023
Accepted after revision: 7 May 2024

The role of routine cardiac investigations before hyperbaric oxygen treatment

Connor TA Brenna[1,2], Marcus Salvatori[1,3,4], Shawn Khan[1], George Djaiani[1,3,4], Simone Schiavo[1,3,4], Rita Katznelson[1,3,4]

[1] *Department of Anesthesiology & Pain Medicine, University of Toronto, Toronto, Ontario, Canada*
[2] *Department of Physiology, University of Toronto, Toronto, Ontario, Canada*
[3] *Hyperbaric Medicine Unit, Toronto General Hospital, Toronto, Ontario, Canada*
[4] *Department of Anesthesia and Pain Management, University Health Network, Toronto, Ontario, Canada*

Corresponding author: *Dr Rita Katznelson, Toronto General Hospital, 200 Elizabeth St, Toronto, ON M5G 2C4, Canada*
rita.katznelson@uhn.ca

Keywords
Cardiac complications; Echocardiography; Electrocardiography; Hyperbaric oxygen therapy; Risk assessment

Abstract

(Brenna CTA, Salvatori M, Khan S, Djaiani G, Schiavo S, Katznelson R. The role of routine cardiac investigations before hyperbaric oxygen treatment. Diving and Hyperbaric Medicine. 2024 30 June;54(2):120–126. doi: 10.28920/dhm54.2.120-126. PMID: 38870954.)

Cardiac complications are a rare but potentially serious consequence of hyperbaric oxygen treatment (HBOT), resulting from increased blood pressure and decreased heart rate and cardiac output associated with treatment. These physiologic changes are generally well-tolerated by patients without preexisting cardiac conditions, although those with known or undetected cardiac disease may be more vulnerable to treatment complications. Currently, there are no universally accepted guidelines for pre-HBOT cardiac screening to identify these patients at heightened risk, leading to variability in practice patterns. In the absence of HBOT-specific evidence, screening protocols might be adapted from the diving medicine community; however, given the important differences in physiological stressors, these may not be entirely applicable to patients undergoing HBOT. Traditional cardiac investigations such as electro- and echo-cardiograms are limited in their ability to detect relevant risk modifying states in the pre-HBOT patient, stymieing their cost-effectiveness as routine tests. In the absence of strong evidence to support routine cardiac investigation, we argue that a comprehensive history and physical exam – tailored to identify high-risk patients based on clinical parameters – may serve as a more practical screening tool. While certain unique patient groups such as those undergoing dialysis or with implanted cardiac devices may warrant specialised assessment, thorough evaluation may be sufficient to identify many patients unlikely to benefit from cardiac investigation in the pre-HBOT setting. A clinical decision-making tool based on suggested low-risk and high-risk features is offered to guide the use of targeted cardiac investigation prior to HBOT.

Introduction

Hyperbaric oxygen treatment (HBOT) has several unique effects on human physiology, resulting from the combination of breathing pure (100%) oxygen and exposure to heightened pressure.[1] These effects serve as therapeutic mechanisms for its use in the treatment of a variety of medical conditions, but are also responsible for treatment complications in a rare minority of patients undergoing HBOT. As with other medical interventions, treatment decisions are made on the basis of a relative balance of expected benefits and risks, and these are estimated by way of thorough patient evaluation (e.g., to identify those at greatest risk) in combination with the best available evidence (e.g., to quantify or ameliorate that risk).

Currently, there are no widely accepted guidelines for screening patients prior to the initiation of HBOT. In the absence of expert recommendations, this process is usually undertaken at the discretion of individual providers. Typically, the initial assessment includes a thorough history and physical examination to substantiate the indication for which HBOT is considered, as well as other potentially relevant medical comorbidities and/or known contraindications to treatment. Many centres also routinely perform pre-HBOT screening with chest X-ray and/or pulmonary function testing to rule out pre-existing airways disease, which may portend an increased risk of pulmonary complications of HBOT,[2] although we have previously demonstrated the limited utility of these investigations in low-risk patient population.[3,4] Similarly, many centres including our own have been performing cardiac investigations such as electrocardiograms (ECGs) or echocardiograms as a matter of routine,[5] although the utility and value of these tests in the pre-HBOT setting has not been previously characterised.

Cardiac investigations in fitness-to-dive testing

The diving medicine community has been more methodical in developing and operationalising standard fitness-to-dive assessments, and these have undoubtedly influenced pre-HBOT screening practices. For example, the South Pacific Underwater Medicine Society has articulated clear guidelines for cardiac evaluation, including the performance of an ECG for all diving candidates older than age 45, as well as more comprehensive tests like cardiac stress tests, computed tomography angiograms, or echocardiograms for those with higher cardiovascular risk.[6] For others, a focused questionnaire is accepted as a reasonable screening tool.[7] Many hyperbaric medical units have conformed to similar practices; however, the relevant cardiac risks of diving do not necessarily extend to hyperbaric treatment, calling into question whether screening practices should be shared without modification between these communities.

Cardiac conditions are the second most common cause of diving-related deaths.[8,9] However, these are largely attributed to increased myocardial oxygen demand during the metabolically taxing activity of swimming, in combination with increases in both cardiac preload (resulting from immersion-induced increases in central venous return) and afterload (resulting from cold-induced peripheral vasoconstriction).[8] Thus, fitness-to-dive assessments focus on the detection of coronary artery disease (CAD) to identify divers who cannot tolerate the additional cardiac demands associated with exertion under pressure.[9,10] However, the metabolic demands of HBOT are minimal and, with greater dissolved oxygen in the blood, the risk of acute coronary syndrome (ACS) during treatment is very small. On the contrary, HBOT has been proposed as a treatment for ACS and small trials suggest morbidity and mortality benefits.[11] Some have also argued for cardiac screening in the fitness-to-dive assessment to detect a patent foramen ovale,[12] which may serve as a direct conduit for small venous nitrogen bubbles (formed while surfacing) to enter the systemic circulation as paradoxical gas emboli.[12–14] However, this is not widely practiced and, similarly to CAD, the concern is not relevant to HBOT. Therefore, HBOT providers should tailor cardiac investigations according to modifiable risks material to HBOT.

Cardiac effects of hyperbaric oxygen treatment

While the presence of CAD is less informative of cardiac risk in the context of hyperbaric medicine, HBOT does have several known effects on cardiovascular function.[15] In the peripheral circulation, high partial pressures of oxygen cause transient vasoconstriction which increases left ventricular afterload, as well as peripheral vascular resistance and arterial blood pressure (ABP).[16] Suggested mechanisms include the formation of reactive oxygen species which interfere with nitric oxide's vasodilating effect, and/or hyperoxic inhibition of prostaglandin synthesis.[17] This can be clinically relevant for patients with hypertension, although the effect is generally small: recent studies demonstrate that HBOT is associated with an average increase of ABP by 4–11 mmHg, with larger changes in systolic than diastolic components.[16,18] The existing literature has demonstrated that patients with preexisting hypertension may experience greater increases in ABP during HBOT, while there is more controversy surrounding the cumulative effects of long treatment courses on this haemodynamic parameter.[16,18]

The other major cardiac effect of HBOT relates to heart rate (HR), which decreases due to both oxygen-dependent and oxygen-independent physiologic mechanisms.[15] Bradycardia appears to result predominately from indirect effects of HBOT on the heart (e.g., mediated by baroreceptor activation),[19] possibly compounded by direct effects of pressure on the myocardium.[20,21] An ordinary bradycardic response to HBOT may be a decrease in HR of approximately 20%, occurring gradually over the course of treatment.[17,19] Coronary perfusion is also decreased during HBOT, but this is balanced by a decrease in myocardial work and demand.[15,22] The reduction in HR is associated with, and possibly the main cause of a decrease in cardiac output (CO) for some patients.

Previous studies have reported a decrease in CO between 8% and 18% during HBOT.[23–25] However, for many patients, haemodynamic compensation can limit the impact of these changes. For example, bradycardia facilitates better ventricular filling during diastole, increasing left ventricle (LV) preload and maintaining stroke volume.[15] Recent studies have even reported that HBOT may improve LV ejection fraction (LVEF) for some patients without cardiac symptoms,[26] and increase global longitudinal strain to improve LV systolic function recovery in patients suffering from post-COVID-19 syndrome.[27] Furthermore, because the dissolved oxygen content of blood increases dramatically during HBOT, tissue oxygen requirements can be met despite a decreased CO.

However, patients with heart failure may have limited reserve to compensate for decreases in CO, and may experience further deterioration of prior LV dysfunction during HBOT, including the development of acute pulmonary oedema immediately after HBOT.[28,29] One explanatory hypothesis may involve the relative decrease in oxygen tension immediately following HBOT, leading to acute heart strain and a transient increase in physiological stress. This may affect cardiac function; however, the impact of this return to normoxia on cardiac strain has not yet been well characterised in the literature. Vincent and colleagues performed a retrospective review of 23 patients with a past medical history of heart failure and reduced LVEF (< 40%), and reported that two patients experienced acute heart failure within 24 hours of HBOT.[30] Nevertheless, both

cases included significant potential confounding features such as takotsubo cardiomyopathy and septic shock, and current evidence suggests that pulmonary oedema is unlikely to be triggered by HBOT alone in the absence of other predisposing factors. These findings are consistent with our own data suggesting that a minority of patients with heart failure may experience deterioration of symptoms following HBOT.[25] Consequently, heart failure may not be an absolute contraindication to HBOT; however, caution and close monitoring of these patients are warranted.[25,30]

Cardiac investigations for hyperbaric oxygen treatment

In accordance with the principle "*do no harm*", cardiac screening before HBOT should be based on the balance of expected risks and benefits. The various haemodynamic changes of HBOT appear to be well tolerated by patients with no preexisting cardiac disease.[31] Over the past decade, our major North American HBOT referral centre in Toronto, Canada has performed approximately 26,000 treatments: in our experience, we have not observed any unexpected cardiac complications among patients without a previously known cardiac history. However, identifying those at heightened risk remains an important challenge for the mitigation of cardiac complications, and severe hypertension, advanced CAD, and symptomatic heart failure appear to be relevant conditions.

In the broader clinical arena, it is recognised that screening tests are widely misused (i.e., implemented when they will not change management).[32] For example, the resting 12-lead ECG has very limited application in detecting arrhythmias or other cardiac pathology in otherwise healthy individuals. The sensitivity of an ECG for the diagnosis of left ventricular hypertrophy is a mere 7%.[33] Electrocardiographic criteria alone are not reliable for the confirmation or exclusion of important heart disease,[34] particularly the presence or absence of suspected heart failure. Transthoracic echocardiography is a preferred test for the detection of heart failure,[35] but a low incidence of heart failure in the general population[36] limits the cost-effectiveness of this test as a routine screening tool. Blood tests such as N-terminal pro b-type natriuretic peptide (NT-proBNP) have been applied in the diagnosis of heart failure, but are similarly limited as a first-line screening tool due to a lack of consensus regarding diagnostic thresholds.[37]

The value proposition of routinely applying any investigation with limited predictive value comes into question when considering the major expense associated with population screening. Choosing Wisely presents Canadian guidelines aimed at limiting unnecessary testing in the perioperative context,[38] which currently recommend that asymptomatic, low-risk patients undergoing non-cardiac surgery are not subjected to a baseline ECG,[39–41] resting echocardiography,[42,43] or cardiac stress testing.[44–47]

In contrast, a detailed history and physical exam may be the most reliable and cost-effective screening tools for heart failure. For example, a large cross-sectional diagnostic accuracy study of 721 patients (of whom 29% had heart failure) demonstrated a strong predictive model using nine key pieces of data collected from a patient history and physical exam. Those data included: age, history of CAD, pulse rate and rhythm, displaced apex beat, rales or heart murmur on auscultation, increased jugular vein pressure, and the use of loop diuretics.[48] Furthermore, rapid bedside screening tests, when performed correctly, can detect LV dysfunction with respectable accuracy. For example, a single Valsalva maneuver (specificity 91%, sensitivity 69%)[49] or hepatojugular reflex (specificity 96%, sensitivity 12%)[50] can be performed in under one minute to assess for heart failure.

Suggested guidelines

Currently, there is no robust evidence relating to the use of any cardiac investigations prior to HBOT. There is a pressing need for future studies to characterise the efficacy and cost-effectiveness of available cardiac tests in the pre-HBOT context. In the meantime, we suggest a pragmatic approach and offer a practical clinical risk tool drawing on the available literature surrounding risk factors for the development of congestive heart failure,[51] the diagnostic utility of information acquired through history and physical examination,[48,49] guidelines for perioperative cardiovascular risk assessment[38,52] and for the management of known heart failure,[53] and clinical intuition (Figure 1). This tool is presented in the form of a questionnaire which stratifies patients as low- or high-risk with respect to modifiable cardiac risk and is intended to support decisions to either pursue or forego cardiac investigations prior to HBOT. This tool will require further internal and external validation.

Limitations and future directions

There are several important caveats for any clinical risk assessment tool. Principally, it should augment but not replace the clinical judgement of a hyperbaric physician. Unique circumstances may present special cardiac risks deserving of pre-HBOT investigations. One example of a potentially high-risk group is patients undergoing dialysis, given their unique risks of fluid overload and electrolyte disturbance. Investigations may stand to inform management of these patients, as significant fluid overload would favor performing HBOT immediately after dialysis sessions, rather than immediately before them. Another example is patients with implanted devices like permanent pacemakers, defibrillators, or intrathecal pumps, for which pre-treatment device interrogation is extremely important as some of these devices may bear unique risks of fire hazard or damage during exposure to HBOT.[54,55] Finally, some indications for HBOT may be intricately associated with increased cardiovascular risk. For instance, carbon monoxide poisoning is itself associated with myocardial ischaemia and LV dysfunction;[56] however, the urgency and likely benefit of HBOT in this scenario would take priority over a delayed approach to facilitate cardiac risk assessment.

Figure 1

Clinical decision-making questionnaire; a questionnaire based on current evidence to support clinicians and patients in the decision to pursue or forego cardiac investigations prior to hyperbaric oxygen treatment. [1] During a Valsalva manoeuvre (forced expiratory effort against a closed airway), a transient increase in systolic blood pressure is normal. While auscultating the brachial pulse, both persistent Korotkoff sounds throughout this manoeuvre and failure of Korotkoff sounds to resume after conclusion of the Valsalva are considered abnormal. [2] A positive hepatojugular reflex is defined by an increase in jugular venous pressure of at least 3 cm, sustained for at least 15 seconds, signifying that the right ventricle cannot accommodate the augmented venous return. [3] Four metabolic equivalents is the approximate intensity of activities like light housework/yardwork, climbing a flight of stairs, or walking on level ground at 4 miles·hour^{-1}. [4] Unexplained weight increase greater than 1 kg·day^{-1} or 2 kg·week^{-1} is considered suspicious for heart failure

The role of cardiac investigations to elucidate cardiovascular risks prior to HBOT remains poorly defined. Future directions for this work should focus on robust clinical studies characterising the contributions of specific cardiac tests to decisions of whether to proceed or not with HBOT. Another important aspect of pre-HBOT testing is the evaluation of the cost-effectiveness of these investigations. Finally, for risk stratification to be successful, the cardiac risks of HBOT must be better understood. Current evidence suggests that acute decompensation of existing heart failure happens in a rare minority of patients undergoing HBOT, but it is not well understood why some patients decompensate while others do not, or how to predict which patients would benefit from tailored care or the consideration of alternative therapies.

Conclusions

The marginal benefit of incorporating cardiac screening investigations in the pre-HBOT care of all patients is likely to be low. While there is a paucity of evidence to guide decision-making with respect to screening for relevant cardiac disease, the existing literature demonstrates that HBOT is tolerated without complication by most patients. Specifically, normotensive patients who are not in heart failure have a very low risk of HBOT-related cardiac complications. In the absence of high-quality evidence, patients with known heart failure may benefit from limited cardiac investigations prior to HBOT, and optimal monitoring of cardiac function during and after HBOT should be ensured. For those patients without a history of heart disease, a meticulous history and physical exam should suffice prior to HBOT. Patients identified as potentially high-risk for undiagnosed cardiac dysfunction may benefit from a targeted cardiac assessment in order to answer a specific clinical question, when this will factor into decision-making and allow HBOT to be performed in the safest possible conditions.

References

1 Thom SR. Hyperbaric oxygen – its mechanisms and efficacy. Plast Reconstr Surg. 2011;127(Suppl 1):131–41. doi: 10.1097/PRS.0b013e3181fbe2bf. PMID: 21200283. PMCID: PMC3058327.

2 Kirby JP, Snyder J, Schuerer DJE, Peters JS, Bochicchio GV. Essentials of hyperbaric oxygen therapy: 2019 review. Mo Med. 2019;116:176–9. PMID: 31527935. PMCID: PMC6690283.

3 Brenna CTA, Khan S, Djaiani G, Buckey JC, Katznelson R. The role of routine pulmonary imaging before hyperbaric oxygen treatment. Diving Hyperb Med. 2022;52:197–207. doi: 10.28920/dhm52.3.197–207. PMID: 36100931. PMCID: PMC9731143.

4 Brenna CTA, Khan S, Djaiani G, Au D, Schiavo S, Wahaj M, et al. Pulmonary function following hyperbaric oxygen therapy: a longitudinal observational study. PLoS One. 2023;18(5):e0285830. doi: 10.1371/journal.pone.0285830. PMID: 37256885. PMCID: PMC10231819.

5 Dey D, Kochhar HR, Rao KN, Venkatesh S, Verma R. The rationale of carrying out specific investigations prior to hyperbaric oxygen therapy. Indian J Aerosp Med. 2013;57(1):56–65.

6 Jepson N, Rienks R, Smart D, Bennett MH, Mitchell SJ, Turner M. South Pacific Underwater Medicine Society guidelines for cardiovascular risk assessment of divers. Diving Hyperb Med. 2020;50:273–7. doi: 10.28920/dhm50.3.273-277. PMID: 32957130. PMCID: PMC7819720.

7 Glen S, White S, Douglas J. Medical supervision of sport diving in Scotland: reassessing the need for routine medical examinations. Br J Sports Med. 2000;34:375–8. doi: 10.1136/bjsm.34.5.375. PMID: 11049148. PMCID: PMC1756251.

8 Lynch JH, Bove AA. Diving medicine: a review of current evidence. J Spec Oper Med. 2009;9(4):72–9. doi: 10.55460/H2N1-5QHN. PMID: 20112651.

9 Caruso J, Bove A, Uguccioni D, Ellis J, Dovenbarger J, Bennett P. Recreational diving deaths associated with cardiovascular disease: epidemiology and recommendations for pre-participation screening. Undersea Hyperb Med. 2001;28(Suppl):75–6. [cited 2023 Oct 14]. Available from: https://www.uhms.org/uhm-search/supplement-2001/viewdocument/3243.html.

10 Greenland P, Alpert JS, Beller GA, Benjamin EJ, Budoff MJ, Fayad ZA, et al. 2010 ACCF/AHA guideline for assessment of cardiovascular risk in asymptomatic adults: a report of the American College of Cardiology Foundation/American Heart Association Task Force on Practice Guidelines. J Am Coll Cardiol. 2010;56(25):e50–103. doi: 10.1016/j.jacc.2010.09.001. PMID: 21144964.

11 Bennett MH, Lehm JP, Jepson N. Hyperbaric oxygen therapy for acute coronary syndrome. Cochrane Database Syst Rev. 2015;2015(7):CD004818. doi: 10.1002/14651858.CD004818.pub4. PMID: 26202854. PMCID: PMC8101090.

12 Wilmshurst PT. The role of persistent foramen ovale and other shunts in decompression illness. Diving Hyperb Med. 2015;45:98–104. PMID: 26165532.

13 Lier H, Hering R, Schroeder S. Diving and patent foramen ovale: time for a change in fitness to dive certifications? Clin J Sport Med. 2005;15:205–7. doi: 10.1097/01.jsm.0000168076.74497.ed. PMID: 16003031.

14 Germonpré P, Lafère P, Portier W, Germonpré FL, Marroni A, Balestra C. Increased risk of decompression sickness when diving with a right-to-left shunt: results of a prospective single-blinded observational study (the "carotid doppler" study). Front Physiol. 2021;12:763408. doi: 10.3389/fphys.2021.763408. PMID: 34777020. PMCID: PMC8586212.

15 Mathieu D, Favory R, Collet F, Linke JC, Wattel F. Physiologic effects of hyperbaric oxygen on hemodynamics and microcirculation. In: Mathieu D, editor. Handbook on hyperbaric medicine. Dordrecht: Springer Netherlands; 2006. p. 75–101. doi: 10.1007/1-4020-4448-8_6.

16 Schiavo S, Djaiani C, DeBacker J, Albertini L, Santa Mina D, Buryk-Iggers S, et al. Magnitude and clinical predictors of blood pressure changes in patients undergoing hyperbaric oxygen therapy: a retrospective study. Int J Environ Res Public Health. 2020;17(20):7586. doi: 10.3390/ijerph17207586. PMID: 33086495. PMCID: PMC7589597.

17 Schipke JD, Muth T, Pepper C, Schneppendahl J, Hoffmanns M, Dreyer S. Hyperoxia and the cardiovascular system: experiences with hyperbaric oxygen therapy. Med Gas Res. 2022;12(4):153–7. doi: 10.4103/2045-9912.337997. PMID: 35435427. PMCID: PMC9074980.

18 Heyboer M Rd, Wojcik SM, Smith G, Santiago W. Effect

of hyperbaric oxygen therapy on blood pressure in patients undergoing treatment. Undersea Hyperb Med. 2017;44:93–9. doi: 10.22462/3.4.2017.2. PMID: 28777899.

19 Demchenko IT, Zhilyaev SY, Moskvin AN, Krivchenko AI, Piantadosi CA, Allen BW. Baroreflex-mediated cardiovascular responses to hyperbaric oxygen. J Appl Physiol. 2013;115:819–28. doi: 10.1152/japplphysiol.00625.2013. PMID: 23823147.

20 Fagraeus L, Linnarsson D. Autonomic origin of heart rate fluctuations at the onset of muscular exercise. J Appl Physiol. 1976;40:679–82. doi: 10.1152/jappl.1976.40.5.679. PMID: 931893.

21 Doubt TJ, Evans DE. Effects of hyperbaric oxygen exposure at 31.3 ATA on spontaneously beating cat hearts. J Appl Physiol Respir Environ Exerc Physiol. 1983;55:139–45. doi: 10.1152/jappl.1983.55.1.139. PMID: 6885563.

22 Savitt MA, Rankin JS, Elberry JR, Owen CH, Camporesi EM. Influence of hyperbaric oxygen on left ventricular contractility, total coronary blood flow, and myocardial oxygen consumption in the conscious dog. Undersea Hyperb Med. 1994;21:169–83. PMID: 8061558.

23 Pisarello JB, Clark JM, Lambertsen CJ, Gelfand R. Human circulatory responses to prolonged hyperbaric hyperoxia in Predictive Studies V. Proceedings of the Ninth International Symposium on Underwater and Hyperbaric Physiology. Undersea and Hyperbaric Medical Society; 1987. [cited 2023 Sep 4]. Available from: https://ntrs.nasa.gov/citations/19890066329.

24 Weaver LK, Howe S, Snow GL, Deru K. Arterial and pulmonary arterial hemodynamics and oxygen delivery/extraction in normal humans exposed to hyperbaric air and oxygen. J Appl Physiol (1985). 2009;107(1):336–45. doi: 10.1152/japplphysiol.91012.2008. PMID: 19407250.

25 Schiavo S, Brenna CTA, Albertini L, Djaiani G, Marinov A, Katznelson R. Safety of hyperbaric oxygen therapy in patients with heart failure: a retrospective cohort study. PLoS One. 2024;19(2):e0293484. doi: 10.1371/journal.pone.0293484. PMID: 38330042. PMCID: PMC10852233.

26 Leitman M, Efrati S, Fuchs S, Hadanny A, Vered Z. The effect of hyperbaric oxygenation therapy on myocardial function. Int J Cardiovasc Imaging. 2020;36:833–40. doi: 10.1007/s10554-020-01773-0. PMID: 31953651.

27 Leitman M, Fuchs S, Tyomkin V, Hadanny A, Zilberman-Itskovich S, Efrati S. The effect of hyperbaric oxygen therapy on myocardial function in post-COVID-19 syndrome patients: a randomized controlled trial. Sci Rep. 2023;13(1):9473. doi: 10.1038/s41598-023-36570-x. PMID: 37301934. PMCID: PMC10257166.

28 Weaver LK, Churchill S. Pulmonary edema associated with hyperbaric oxygen therapy. Chest. 2001;120(4):1407–9. doi: 10.1378/chest.120.4.1407. PMID: 11591590.

29 Obiagwu C, Paul V, Chadha S, Hollander G, Shani J. Acute pulmonary edema secondary to hyperbaric oxygen therapy. Oxf Med Case Reports. 2015;2015(2):183–4. doi: 10.1093/omcr/omv002. PMID: 25988073. PMCID: PMC4370014.

30 Vincent J, Ross M-K, Pollock NW. Effect of hyperbaric oxygen treatment on patients with reduced left ventricular ejection fraction. Diving Hyperb Med. 2021;51:256–63. doi: 10.28920/dhm51.3.256-263. PMID: 34547776. PMCID: PMC8608446.

31 Molénat F, Boussuges A, Grandfond A, Rostain JC, Sainty JM, Robinet C, et al. Haemodynamic effects of hyperbaric hyperoxia in healthy volunteers: an echocardiographic and Doppler study. Clin Sci (Lond). 2004;106:389–95. doi: 10.1042/CS20030293. PMID: 14641106.

32 Grimes DA, Schulz KF. Uses and abuses of screening tests. Lancet. 2002;359(9309):881–4. doi: 10.1016/S0140-6736(02)07948-5. PMID: 11897304.

33 Levy D, Labib SB, Anderson KM, Christiansen JC, Kannel WB, Castelli WP. Determinants of sensitivity and specificity of electrocardiographic criteria for left ventricular hypertrophy. Circulation. 1990;81:815–20. doi: 10.1161/01.cir.81.3.815. PMID: 2137733.

34 Khan NK, Goode KM, Cleland JGF, Rigby AS, Freemantle N, Eastaugh J, et al. Prevalence of ECG abnormalities in an international survey of patients with suspected or confirmed heart failure at death or discharge. Eur J Heart Fail. 2007;9:491–501. doi: 10.1016/j.ejheart.2006.11.003. PMID: 17218150.

35 Cheitlin MD, Alpert JS, Armstrong WF, Aurigemma GP, Beller GA, Bierman FZ, et al. ACC/AHA Guidelines for the Clinical Application of Echocardiography. Circulation. 1997;95:1686–744. doi: 10.1161/01.cir.95.6.1686. PMID: 9118558.

36 Davies M, Hobbs F, Davis R, Kenkre J, Roalfe AK, Hare R, et al. Prevalence of left-ventricular systolic dysfunction and heart failure in the Echocardiographic Heart of England Screening study: A population based study. Lancet. 2001;358(9280):439–44. doi: 10.1016/s0140-6736(01)05620-3. PMID: 11513906.

37 Ozturk TC, Unluer E, Denizbasi A, Guneysel O, Onur O. Can NT-proBNP be used as a criterion for heart failure hospitalization in emergency room? J Res Med Sci. 2011;16:1564–71. PMID: 22973364. PMCID: PMC3434897.

38 Drop the pre-op: A toolkit for reducing unnecessary visits and investigations in pre-operative clinics. Canada: Choosing Wisely; 2019. [cited 2023 Sep 20]. Available from: https://choosingwiselycanada.org/wp-content/uploads/2017/07/CWC_Pre-Op_Toolkit_v1.2_2017-07-12.pdf.

39 Liu LL, Dzankic S, Leung JM. Preoperative electrocardiogram abnormalities do not predict postoperative cardiac complications in geriatric surgical patients. J Am Geriatr Soc. 2002;50:1186–91. doi: 10.1046/j.1532-5415.2002.t01-1-50303.x. PMID: 12133011.

40 Mathis MR, Naughton NN, Shanks AM, Freundlich RE, Pannucci CJ, Chu Y, et al. Patient selection for day case-eligible surgery: identifying those at high risk for major complications. Anesthesiology. 2013;119:1310–21. doi: 10.1097/ALN.0000000000000005. PMID: 24108100.

41 van Klei WA, Bryson GL, Yang H, Kalkman CJ, Wells GA, Beattie WS. The value of routine preoperative electrocardiography in predicting myocardial infarction after noncardiac surgery. Ann Surg. 2007;246:165–70. doi: 10.1097/01.sla.0000261737.62514.63. PMID: 17667491. PMCID: PMC1933558.

42 Halm EA, Browner WS, Tubau JF, Tateo IM, Mangano DT. Echocardiography for assessing cardiac risk in patients having noncardiac surgery. Study of Perioperative Ischemia Research Group. Ann Intern Med. 1996;125:433–41. doi: 10.7326/0003-4819-125-6-199609150-00001. PMID: 8779454.

43 Wijeysundera DN, Beattie WS, Karkouti K, Neuman MD, Austin PC, Laupacis A. Association of echocardiography before major elective non-cardiac surgery with postoperative survival and length of hospital stay: population based cohort study. BMJ. 2011;342:d3695. doi: 10.1136/bmj.d3695. PMID: 21724560. PMCID: PMC3127454.

44 Fleisher LA, Fleischmann KE, Auerbach AD, Barnason SA, Beckman JA, Bozkurt B, et al. 2014 ACC/AHA guideline on perioperative cardiovascular evaluation and management of patients undergoing noncardiac surgery: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines. Circulation. 2014;130(24):e278–333. doi: 10.1161/CIR.0000000000000105. PMID: 25085962.

45 Kristensen SD, Knuuti J, Saraste A, Anker S, Bøtker HE, Hert SD, et al. 2014 ESC/ESA Guidelines on non-cardiac surgery: cardiovascular assessment and management: The Joint Task Force on non-cardiac surgery: cardiovascular assessment and management of the European Society of Cardiology (ESC) and the European Society of Anaesthesiology (ESA). Eur Heart J. 2014;35(35):2383–431. doi: 10.1093/eurheartj/ehu282. PMID: 25086026.

46 Etchells E, Meade M, Tomlinson G, Cook D. Semiquantitative dipyridamole myocardial stress perfusion imaging for cardiac risk assessment before noncardiac vascular surgery: A meta-analysis. J Vasc Surg. 2002;36:534–40. doi: 10.1067/mva.2002.126563. PMID: 12218978.

47 Sgura FA, Kopecky SL, Grill JP, Gibbons RJ. Supine exercise capacity identifies patients at low risk for perioperative cardiovascular events and predicts long-term survival. Am J Med. 2000;108:334–6. doi: 10.1016/s0002-9343(99)00465-9. PMID: 11014727.

48 Kelder JC, Cramer MJ, van Wijngaarden J, van Tooren R, Mosterd A, Moons KGM, et al. The diagnostic value of physical examination and additional testing in primary care patients with suspected heart failure. Circulation. 2011;124(25):2865–73. doi: 10.1161/CIRCULATIONAHA.111.019216. PMID: 22104551.

49 Shamsham F, Mitchell J. Essentials of the diagnosis of heart failure. Am Fam Physician. 2000;61:1319–28. PMID: 10735340.

50 Iwata H, Miwa Y, Ikehara Y, Yodoshi T, Ueda S. The clinical value of hepatojugular reflux on congestive heart failure: a meta-analysis. J Gen Fam Med. 2022;23:393–400. doi: 10.1002/jgf2.574. PMID: 36349209. PMCID: PMC9634136.

51 He J, Ogden LG, Bazzano LA, Vupputuri S, Loria C, Whelton PK. Risk factors for congestive heart failure in US men and women: NHANES I epidemiologic follow-up study. Arch Intern Med. 2001;161:996–1002. doi: 10.1001/archinte.161.7.996. PMID: 11295963.

52 Smilowitz NR, Berger JS. Perioperative cardiovascular risk assessment and management for noncardiac surgery: a review. JAMA. 2020;324:279–90. doi: 10.1001/jama.2020.7840. PMID: 32692391.

53 Heidenreich PA, Bozkurt B, Aguilar D, Allen LA, Byun JJ, Colvin MM, et al. 2022 AHA/ACC/HFSA guideline for the management of heart failure: a report of the American College of Cardiology/American Heart Association Joint Committee on Clinical Practice Guidelines. Circulation. 2022;145(18):e895–1032. doi: 10.1161/CIR.0000000000001063. PMID: 35363499.

54 Schiavo S, Brenna CTA, Bhatia A, Middleton WJ, Katznelson R. Clinical considerations for implanted neurological devices in patients undergoing hyperbaric oxygen therapy: a case report and review of manufacturer guidelines. Int J Environ Res Public Health. 2023;20(9):5693. doi: 10.3390/ijerph20095693. PMID: 37174212. PMCID: PMC10177826.

55 Kot J. Medical devices and procedures in the hyperbaric chamber. Diving Hyperb Med. 2014;44:223–7. PMID: 25596835. [cited 2023 Oct 14]. Available from: https://dhmjournal.com/images/IndividArticles/44Dec/Kot_dhm.44.4.223-227.pdf.

56 Garg J, Krishnamoorthy P, Palaniswamy C, Khera S, Ahmad H, Jain D, et al. Cardiovascular abnormalities in carbon monoxide poisoning. Am J Ther. 2018;25(3):e339–48. doi: 10.1097/MJT.0000000000000016. PMID: 24518173.

Conflicts of interest and funding: nil

Submitted: 14 October 2023
Accepted after revision: 16 February 2024

Diving and Hyperbaric Medicine Journal copyright statement 2024

Case reports

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

Andrew P Colvin[1], Ryan Hogg[2], Peter T Wilmshurst[3]

[1] *Tunnelmed Services Ltd, Dunblane, United Kingdom*
[2] *TRHA Ltd, Surlingham, United Kingdom*
[3] *Royal Stoke University Hospital, Stoke on Trent, United Kingdom*

Corresponding author: *Dr Andrew Colvin, Tunnelmed Services Ltd, Rokeby House, 27 Doune Road, Dunblane, FK15 9AT, United Kingdom*
andrew.colvin@tunnelmed.co.uk

Keywords
Bubbles; Compressed air work; Decompression sickness; Hyperbaric tunnel work; Migraine aura; Oxygen decompression; Persistent (patent) foramen ovale

Abstract

(Colvin AP, Hogg R, Wilmshurst PT. Shunt-mediated decompression sickness in a compressed air worker with an atrial septal defect. Diving and Hyperbaric Medicine. 2024 30 June;54(2):127–132. doi: 10.28920/dhm54.2.127-132. PMID: 38870955.)
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

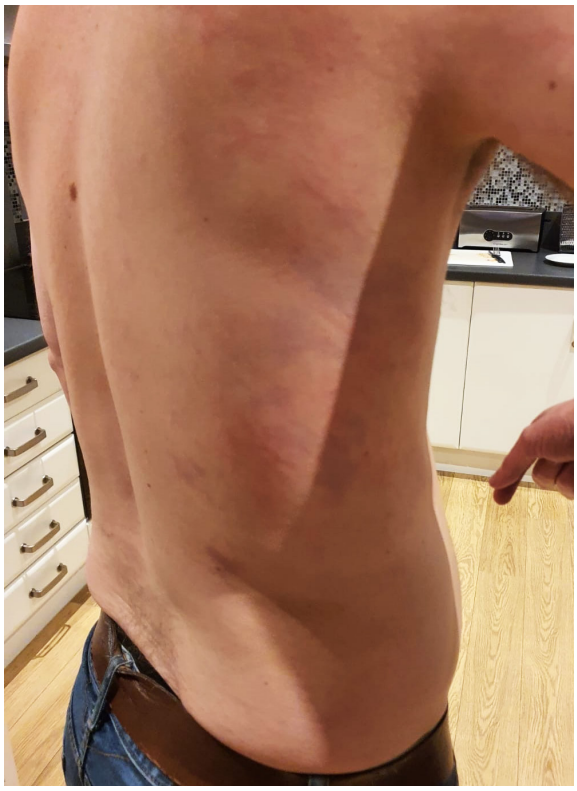


Figure 2
Skin rash over left shoulder approximately three hours after oxygen decompression

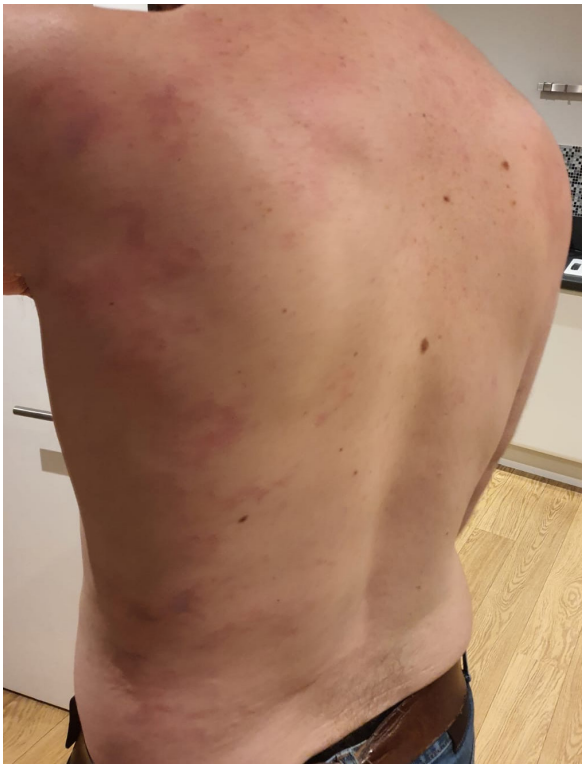
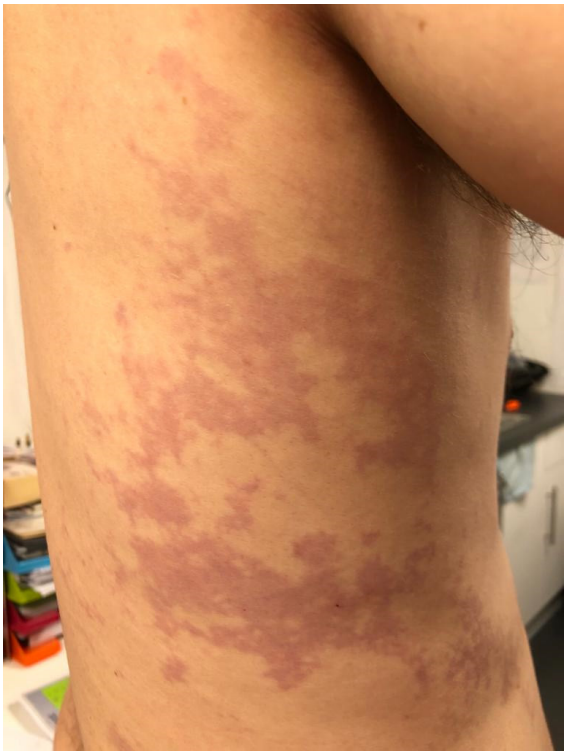


Figure 3
Skin rash approximately six hours 50 minutes after oxygen decompression



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.

References

1 Flook V, Lamont DR. Decompression risk factors in compressed air work: options for risk reduction. Second international conference on engineering and health in compressed air work, Oxford, 2002. Thomas Telford Ltd; 2003. doi: 10.1680/eahicaw.32545.0003.

2 Lamont D, Booth R. Acute decompression illness in UK tunnelling. Proceedings of the Institution of Civil Engineers. 2006;159:185–191. doi: 10.1680/cien.2006.159.4.185.

3 RR171 - Human factors in decompression sickness in compressed air workers in the United Kingdom 1986-2000. HSE Research Report 171. HMSO; 2003. Available from: https://www.hse.gov.uk/research/rrhtm/rr171.htm.

4 Wilmshurst PT. The role of persistent foramen ovale and other shunts in decompression illness. Diving Hyperb Med. 2015;45:98–104. PMID: 26165532. [cited 2024 Mar 24]. Available from: https://dhmjournal.com/images/IndividArticles/45June/Wilmshurst_dhm.45.2.98-104.pdf.

5 The Society of Physiology and Subaquatic and Hyperbaric Medicine in the French Language and The French Society of Occupational Medicine; Recommendations for good practice: Responsibility for health at work for those who work in hyperbaric conditions. Chapter 3. The paraclinical assessment in cardiology; the right-left circulatory shunts. Second ed; 2018.

6 Kütting B, Tomandl B, Drexler H. Prevention of work-related decompression illness events by detection of a cardiac right-to-left shunt. Scand J Work Environ Health 2004;30:331–3. doi: 10.5271/sjweh.803. PMID: 15458018.

7 Colvin AP, Slocombe R, Buchanan J, Lamont D. Application for HSE approval to use alternative decompression procedures. Second international conference on engineering and health in compressed air work. Oxford, 2002. Thomas Telford Ltd; 2003. doi: 10.1680/eahicaw.32545.0009.

8 Kisman K, Masurel G. Method for evaluating circulating bubbles detected by means of the Doppler ultrasonic method using the 'K.M. code'. (English translation of 283 CERTSM 1983). Toulon: Centre d'Etudes et de Recherches Techniques Sous-Marines; 1983.

9 Wilmshurst PT, Pearson MJ, Walsh KP, Morrison WL. Relationship between right-to-left shunts and cutaneous decompression illness. Clin Sci. 2001;100:539–42. PMID: 11294694.
10 Wilmshurst P, Nightingale S. Relationship between migraine and cardiac and pulmonary right-to-left shunts. Clin Sci (Lond). 2001;100:215–20. PMID: 11171291.
11 Wilmshurst P, Pearson M, Nightingale S. Re-evaluation of the relationship between migraine and persistent foramen ovale and other right-to-left shunts. Clin Sci (Lond). 2005;108:365–7. doi: 10.1042/CS20040338. PMID: 15574125.
12 Smart D, Mitchell S, Wilmshurst P, Turner M, Banham N. Joint position statement on persistent foramen ovale (PFO) and diving. South Pacific Underwater Medicine Society (SPUMS) and the United Kingdom Sports Diving Medical Committee (UKSDMC). Diving Hyperb Med. 2015;45:129–31. PMID: 26165538. [cited 2024 Mar 24]. Available from: https://dhmjournal.com/images/IndividArticles/45June/Smart_dhm.45.2.129-131.pdf.

Conflicts of interest and funding: nil

Submitted: 20 September 2023
Accepted after revision: 24 March 2024

Hyperbaric oxygen treatment in bilateral orchiopexy and post-circumcision haematoma in a thrombocytopenic patient with Noonan syndrome

Dilşad Dereli[1], Selahattin Çakiroğlu[2], Ayse Aydan Köse[3], Baran Tokar[1]

[1] *Pediatric Urology, Eskişehir Osmangazi University, Turkey*
[2] *Department of Underwater Medicine and Hyperbaric Medicine, Eskişehir Yunusemre State Hospital, Turkey*
[3] *Plastic and Reconstructive Surgery, Eskişehir Osmangazi University, Turkey*

Corresponding author: *Dr Dilşad Dereli, Pediatric Urology, Eskişehir Osmangazi University, Turkey*
derelidilsad@gmail.com

Keywords
Case reports; Children; Haematology; Hyperbaric oxygenation; Injuries; Surgery

Abstract

(Dereli D, Çakiroğlu S, Köse AA, Tokar B. Hyperbaric oxygen treatment in bilateral orchiopexy and post-circumcision haematoma in a thrombocytopenic patient with Noonan syndrome. Diving and Hyperbaric Medicine. 2024 30 June;54(2):133–136. doi: 10.28920/dhm54.2.133-136. PMID: 38870956.)
Hyperbaric oxygen treatment (HBOT) can be utilised for necrotising soft tissue infections, clostridial myonecrosis (gas gangrene), crush injuries, acute traumatic ischaemia, delayed wound healing, and compromised skin grafts. Our case was a 17-month-old male patient with Noonan syndrome, idiopathic thrombocytopenic purpura, and bilateral undescended testicles. Haematoma and oedema developed in the scrotum and penis the day after bilateral orchiopexy and circumcision. Ischaemic appearances were observed on the penile and scrotal skin on the second postoperative day. Enoxaparin sodium and fresh frozen plasma were started on the recommendation of haematology. Hyperbaric oxygen treatment was initiated considering the possibility of tissue necrosis. We observed rapid healing within five days. We present this case to emphasise that HBOT may be considered as an additional treatment option in patients with similar conditions. To our knowledge, no similar cases have been reported in the literature.

Introduction

Noonan syndrome is an autosomal dominant syndrome occurring in 1 in 1,000–2,500 live births, attributed to mutations in the PTPN11 gene. It is characterised by short stature, a low hairline on the nape of the neck, a webbed neck, cubitus valgus, pectus excavatum, and cardiac anomalies. Additionally, haematological issues have been documented in affected individuals, with bleeding disorders being of particular concern. Thrombocytopenia, Von Willebrand disease, and platelet dysfunction may manifest, leading to varying degrees of bleeding abnormalities. Such haemostatic system disorders can provoke post-operative complications including haematoma formation.

Case report

Informed consent was obtained from the patient's parents for the publication of the case report and photographs of the patient.

A 17-month-old male patient with Noonan syndrome was admitted to the paediatric urology clinic for bilateral undescended testicles and circumcision. Physical examination revealed characteristic features of Noonan syndrome, including low-set ears, a high palate, almond-shaped eyes, and a pointed chin. On urological examination, both testicles were palpable at the entrance of the inguinal canal. Scrotal ultrasound showed that the right testicle was 11 x 5 x 7 mm (0.26 ml), and the left testicle was 9 x 5 x 11 mm (0.25 ml), with no significant difference in parenchymal echogenicity between them. The patient was under haematological follow up due to idiopathic thrombocytopenic purpura (ITP). Chromosomal analysis confirmed a 46XY karyotype with a mutation in the PTPN11 gene.

Bilateral orchiopexy and circumcision were performed uneventfully. On the first postoperative day, the patient experienced a minor haemorrhage at the circumcision site, which was managed with local application of tranexamic acid. Although the bleeding ceased upon follow-up, haematoma and oedema developed in the scrotum and penile skin. Dressings were applied using soft paraffin-saturated gauze with chlorhexidine acetate BP. Ischaemic changes were noted on the penile skin and scrotum on the second postoperative day (see Figures 1 and 2).

Hyperbaric oxygen treatment (HBOT) was initiated promptly. The patient received 100% oxygen at 243 kPa (2.4 atmospheres absolute) for 120 minutes per session.

Figure 1
Postoperative day one; haematoma initially appeared

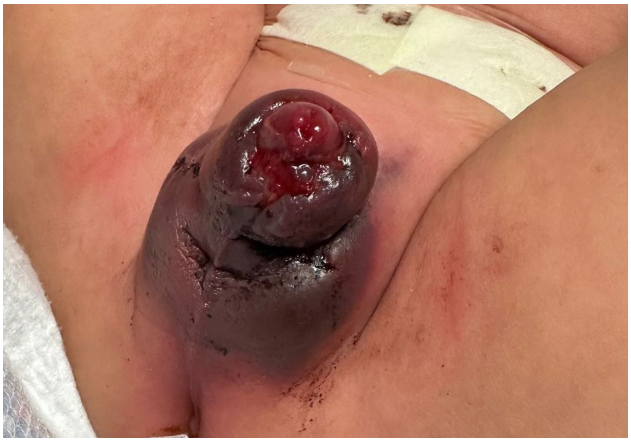


Figure 2
Postoperative day two; progression to suspicious necrosis

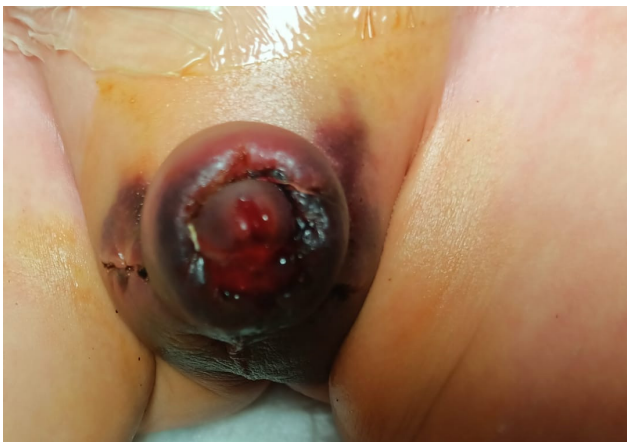


Figure 3
Postoperative day three; first day of hyperbaric oxygen treatment

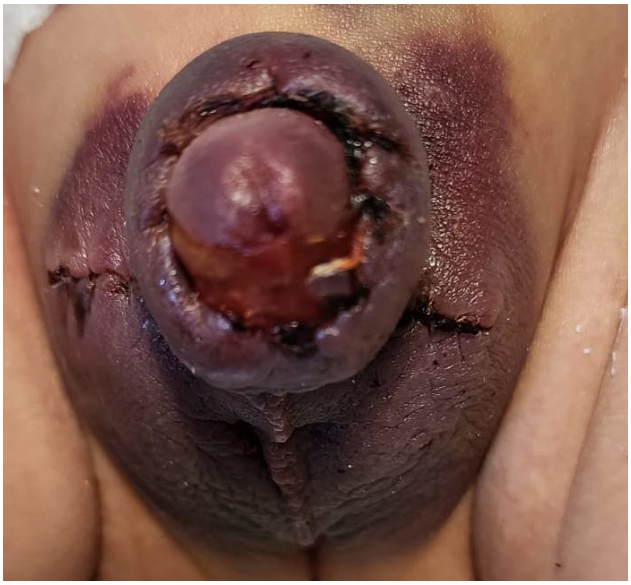
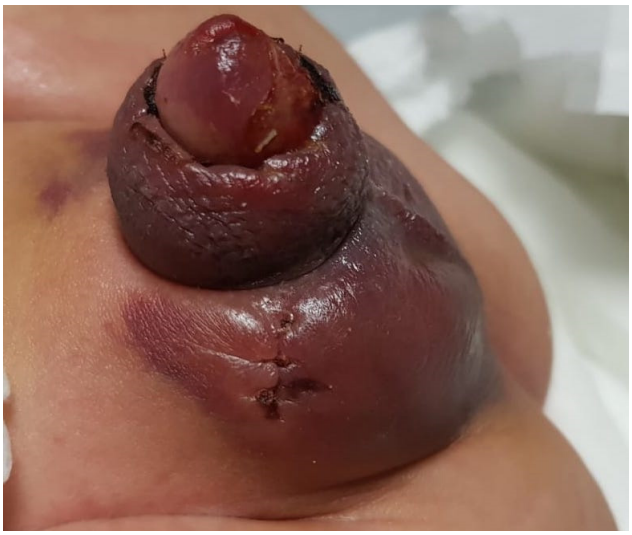


Figure 4
Postoperative day four and second day of hyperbaric oxygen treatment; a significant improvement was observed in the haematoma



After the initial HBOT session, three additional sessions were completed within the first 24 hours. Subsequent improvement in ischaemic changes was observed after the fourth session. Hyperbaric oxygen was continued once daily for five days thereafter (see Figures 3–7). Concurrently, the patient was given 10 ml·kg^{-1} fresh frozen plasma and 1 mg·kg^{-1}·day^{-1} enoxaparin sodium (low molecular weight heparin) for five days. The patient was discharged at the seventh day with complete wound healing (Figure 8)

Discussion

Hyperbaric oxygen treatment involves administration of 100% oxygen in a closed chamber at pressures higher than sea level, delivered via a mask, hood, or endotracheal tube.[1] It increases the dissolved oxygen content in the blood plasma and provides hyperoxygenation to tissues that have increased oxygen demand or reduced supply. This increase in blood oxygen content and partial pressure also compensates for arterial vasoconstriction caused by hyperoxia. It has been shown to promote vascular proliferation by increasing vascular endothelial growth factor elaboration and stem cell mobilisation as well as enhancing host defense against infections and regulating the anti-inflammatory response.[2,3]

In paediatric patients, HBOT is used for necrotising soft tissue infection, clostridial myonecrosis (gas gangrene), crush injuries, and acute traumatic ischaemia. One study[4] reported that HBOT was associated with favorable functional and cosmetic outcomes in penile repair after urethral and glans penis reconstruction following penile amputation, while another[5] demonstrated positive results with HBOT following microsurgery in a replanted penis after penile amputation.

Figure 5
Postoperative day five and third day of hyperbaric oxygen treatment

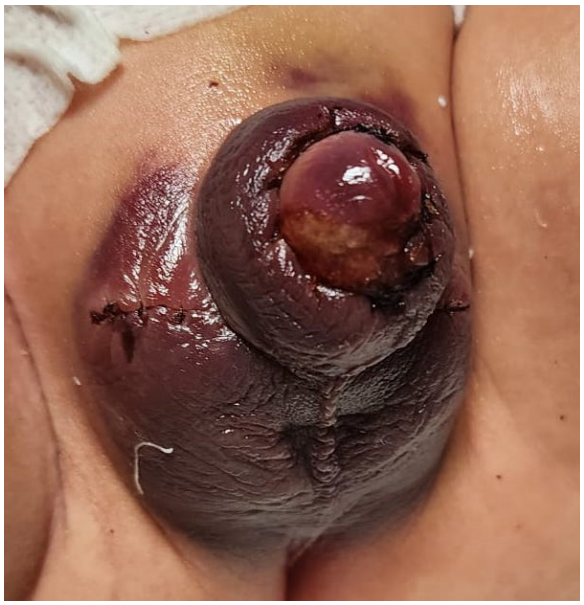


Figure 6
Postoperative day six and fourth day of hyperbaric oxygen treatment

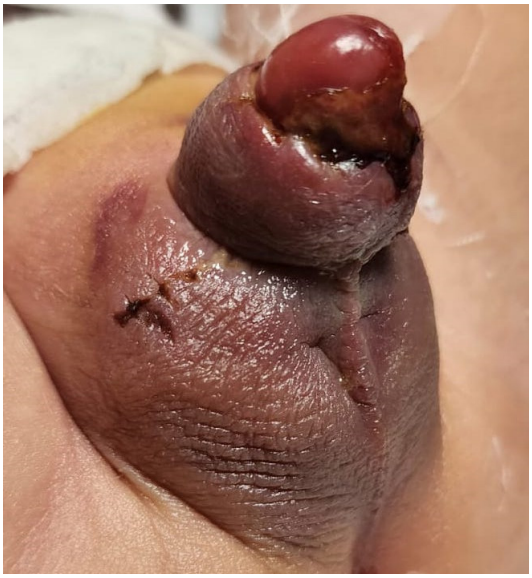


Figure 7
Postoperative day seven and fifth day of hyperbaric oxygen treatment

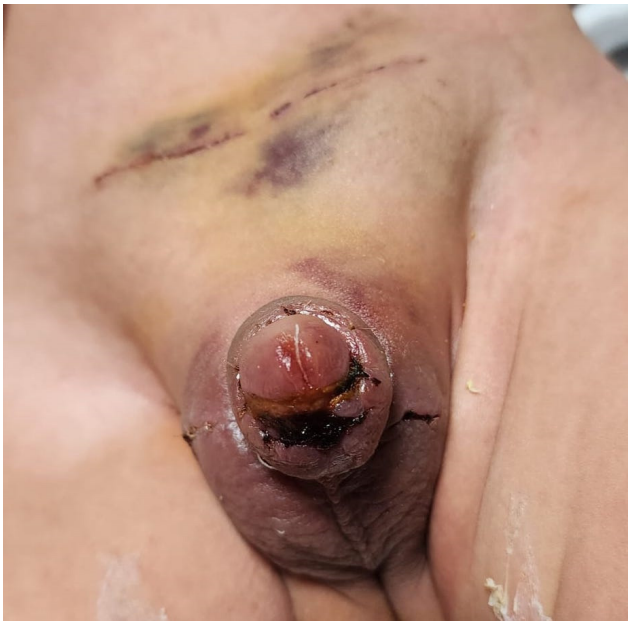
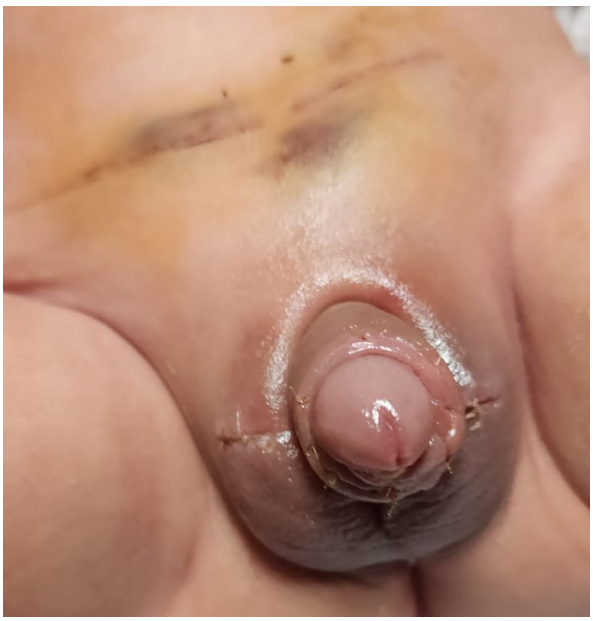


Figure 8
Postoperative day eight; complete resolution of haematoma was achieved



In the present case, HBOT was initiated to overcome the ischaemic complication of scrotum oedema, ecchymosis and haematoma of the penis and scrotum. We achieved complete tissue recovery without necrosis. By presenting this case, we aim to contribute to the existing literature on the use of HBOT in similar clinical scenarios. We believe that the anti-oedema effects of HBOT improved oxygen levels allowing complete recovery without tissue loss.

Conclusions

We cannot be certain that HBOT materially altered the outcome in the present case. Nevertheless, the contemporaneous improvement seen after institution of HBOT suggests there may have been some benefit. Moreover, HBOT might be considered in treatment of similar cases which, due to their sporadic occurrence, are never likely to be the subject of large studies.

References

1 Sahni T, Singh P, John MJ. Hyperbaric oxygen therapy: current trends and applications. J Assoc Physicians India. 2003;51:280–4. PMID: 12839352.

2 Milovanova TN, Bhopale VM, Sorokina EM, Moore JS, Hunt TK, Hauer-Jensen M, et al. Hyperbaric oxygen stimulates vasculogenic stem cell growth and differentiation *in vivo*. J Appl Physiol (1985). 2009;106:711–28. doi: 10.1152/japplphysiol.91054.2008. PMID: 19023021. PMCID: PMC2644249.

3 Jain KK. HBO Therapy in infections. In: Jain KK, editor. Textbook of hyperbaric medicine. Switzerland: Springer; 2017. p. 155–70.

4 Faydaci G, Uğur K, Osman C, Sermin S, Bilal E. Amputation of glans penis: a rare circumcision complication and successful management with primary anastomosis and hyperbaric oxygen therapy. Korean J Urol. 2011;52:147–9. doi: 10.4111/kju.2011.52.2.147. PMID: 21379434. PMCID: PMC3045722.

5 Zhong Z, Dong Z, Lu Q, Li Y, Lv C, Zhu X, et al. Successful penile replantation with adjuvant hyperbaric oxygen treatment. Urology. 2007;69:983.e3–5. doi: 10.1016/j.urology.2007.02.024. PMID: 17482954.

Conflicts of interest and funding: nil

Submitted: 31 January 2024
Accepted after revision: 30 March 2024

World as it is

Drinker driver flyer diver

Gerard Laden[1], Bruce Mathew[1]

[1] *Clinical Hyperbaric Facility, Hull and East Riding Hospital, Anlaby, UK*

Corresponding author: *Gerard Laden. Clinical Hyperbaric Facility, Hull and East Riding Hospital, Anlaby, UK*
ORCID: *0009-0008-0820-8291*
gerard.laden@mimirmarine.com

Keywords
Diving; Inert gas; Narcosis; Nitrogen; Scuba

Abstract

(Laden G, Mathew B. Drinker driver flyer diver. Diving and Hyperbaric Medicine. 2024 30 June;54(2):137–139. doi: 10.28920/dhm54.2.137-139. PMID: 38870957.)
Blood alcohol concentrations above defined levels are detrimental to cognitive performance. Empirical and published evidence suggest that nitrogen narcosis is analogous to alcohol intoxication with both impairing prefrontal cortex function. Nitrogen narcosis is also known to have been a factor in fatal accidents. To examine the effects of nitrogen narcosis, a recent publication used the Iowa Gambling Task tool, to simulate dynamic real-life risky decision-making behaviour. If the reported outcomes are corroborated in larger rigorously designed studies it is likely to provide further evidence that divers may well experience the negative effects of a 'narcotic agent', even at relatively shallow depths. These deleterious effects may occur regardless of diving experience, aptitude or professional status. In 1872, English law made it an offence to be 'drunk' whilst in charge of horses, carriages, cattle and steam engines. Understanding the danger was easy, establishing who is 'drunk' in the eyes of the court required a legal definition. Driving above a 'legal limit' for alcohol was made illegal in the United Kingdom in 1967. The limit was set at 80 milligrams of alcohol per 100 millilitres of blood. It took just short of one hundred years to get from first introducing a restriction to specific activities, whilst under the influence of alcohol, to having a clear and well-defined enforceable law. The question surely is whether our modern society will tolerate another century before legally defining safe parameters for nitrogen narcosis?

Introduction

It is widely accepted that a blood alcohol concentration above defined levels is detrimental to cognitive performance. Many countries have introduced a statutory upper limit of blood alcohol concentration for driving and a 'lower' upper limit for selected occupations for example: pilots, cabin crew, air traffic controllers and train drivers. Diving whilst under the influence of alcohol is also a bad idea.[1]

Empirical and published evidence suggest that nitrogen narcosis is analogous to alcohol intoxication with both states impairing prefrontal cortex function.[2] These deleterious effects may occur regardless of diving experience, aptitude or professional status. Multiple diving agencies have reported nitrogen narcosis as a contributing factor in fatal accidents.[3–6]

The medical literature is replete with information about the potential physiological and pathological consequences of breathing gases at increased partial pressures.[7] This includes nitrogen, oxygen, carbon dioxide, carbon monoxide and even helium. Examining the effect of nitrogen narcosis on divers is certainly not new. The literature contains many studies including those examining the effect at pressures less than thirty metres of sea water (msw) and a randomised controlled trial examining air breathing at 30 msw compared to a twenty percent oxygen-helium mixture and oxygen enriched air breathing.[8,9] Most studies to-date are more qualitative than quantitative (often involving arithmetic and reaction times and the self-reporting by participants) all require interpretation to appreciate their cognitive (i.e., decision-making) significance in the divers actual environment.[4] One study recently explored a quantitative EEG metric to measure the effects of nitrogen narcosis.[10] If the approach described can be operationally developed it would have the important potential to inform the diver in real time of early cognitive impairment. Their proposed cognitive monitoring system has far-reaching applications, one example being pilots when artificial intelligence or ground crew could take over in the event of objective evidence of cognitive compromise, another is deep recreation diving.

Narcosis in diving

In the December 2023 issue of *Diving and Hyperbaric Medicine*, Pauliina Ahti and Jan Wikgren, report using the well-known Iowa gambling task (IGT) research tool as a psychological assessment of diver's decision-making whilst

they were breathing air at two different depths: 5 and 30 metres of fresh water (mfw).[11] They noted a statistically significant difference in the IGT scores with the diver at 30 mfw revealing "*impaired cognitive function*" (i.e., taking 'riskier' decisions) than the divers at 5 mfw. Considering other variables, they attribute the difference to nitrogen narcosis. What is different in the Ahti, paper is that the cognitive assessment tool is well known and accepted and can be used to simulate dynamic real-life 'decision-making' and particularly 'risky' decision-making behaviour.[12,13] When examining risk and decision making an individual's motivational system needs also consideration, the Ahti study controlled for this influence.[14,15]

Accepting that the Ahti study involved small numbers, if the reported outcomes are corroborated in larger rigorously designed studies it is likely to provide further evidence that divers may well experience the negative effects of a 'narcotic agent', even at relatively shallow depths and introduce something of a regulatory conundrum for the diving industry ranging from the sport scuba diving instructor through to the offshore oil and gas professional and the military. The Ahti study appears to provide reliable quantitative data concerning decision-making and risk taking which indicates that even at shallow depths, a 'professional' diver undertaking paid work may well be under the influence of a 'narcotic' agent, that measurably, detrimentally impairs decision making.

Different organisations offer different advice concerning the risks of nitrogen narcosis, with recommended maximum depths for air diving typically ranging from 20 to 40 msw. The United Kingdom Health and Safety Executive, stipulates the maximum depth for breathing compressed air or other mixtures of oxygen and nitrogen as 50 msw. The effect of nitrogen as a narcotic agent at depth varies widely with notable between-and within-individual sensitivity. This may also be the case with the diver's subjective versus objective appreciation of narcosis. Just as you would not ask a person under the influence of alcohol to complete a work task 'risk assessment', so too the diver at depth, suffering from the effects of nitrogen narcosis, is compromised.

Alcohol intoxication vs nitrogen narcosis

Returning to the comparison of nitrogen narcosis and alcohol intoxication. The question often asked is whether self-regulation is adequate.[1] Surely, we already have the answer? Eventually government regulatory authorities, such as the United Kingdom's Health and Safety Executive are going to have to address the 'nitrogen narcosis' question possibly by defining what is and is not acceptable in respect of being under the influence of a narcotic agent in the workplace. Nitrox may help, however unlike alcohol consumption abstinence from nitrogen as depth increases is often not a practical option.

In many countries there are no employment laws concerning the consumption of alcohol at work. Nevertheless, all employers have a legal duty to ensure the health, safety and welfare of their employees (including the military). In other words, if you knowingly allow an employee under the influence of alcohol, drugs or a known narcotic agent to continue working, and this places the employee or others at risk, you could be liable. Moreover, the underwriters of 'employer's liability' insurance are likely to want to better understand the risk they are being asked to underwrite. Scuba diving was pioneered in the early 1940's. In 1984 Wilmshurst first reported a fatality resulting from immersion pulmonary oedema (IPO) and by 1989 had publishing a case series.[16] Forty years on IPO is now considered the most common cause of death in divers with many past cases having arguably wrongly been classified as drowning. Similarly, one is prompted to ask the question as to how many past diving deaths should really have been considered due to nitrogen narcosis causing poor or 'risky' decision making?

A 'duty of care' is generally defined as 'to take all measures that are reasonable in the circumstances to ensure participants will be safe in participating in the relevant activity'. Sports diving service providers generally assume that divers accept the risks involved. The legal maxim is "*Volenti non fit injuria*", meaning "*to a willing person, it is not a wrong*". That is, by diving one is accepting an assumption of risk.

As is often the case following any serious accident, a signed liability waiver or release statement is likely to be challenged as a defence. In any event being willing to accept a risk raises another conundrum. Is there any possibility of obtaining 'informed' consent from a diver? For the depth-time profiles common in air diving, it appears that defining an individual's susceptibility and response to nitrogen as a consequence of descent to depth may be similar to the wide 'within' and 'between' subjects' variability of bubble production from ascending. A random probability distribution that can be analysed statistically but may not be accurately predicted.[17]

One of the earliest known reports of what we now know to be nitrogen narcosis was by the French physician Colladon in 1826, however it wasn't until 1935 just over 100 years later when Behnke identified nitrogen narcosis as the likely cause.[18,19] In 1872, English law made it an offence to be 'drunk' whilst in charge of horses, carriages, cattle and steam engines. Understanding the danger was easy but establishing who is 'drunk' in the eyes of the court, required legal definition. Driving above a legal limit for alcohol was only made illegal in the United Kingdom by The Road Safety Act of 1967. The limit was initially set at 80 milligrams of alcohol per 100 millilitres of blood or a 0.08% blood alcohol concentration. It took just short of one hundred years to get from first introducing a restriction to specific activities whilst under the influence of alcohol to having a clear and well-defined enforceable law. The problem with conundrums is that they are often hard to resolve. Maximum safe depths

for air diving of: 20, 30, 40 and 50 metres of sea water, have all been advocated in academic publications, by training organisations and government agencies for the mitigation of nitrogen narcosis. Clarity of thinking surrounding nitrogen narcosis is needed and will come from challenging the certainty of the advice being offered.

References

1 Sheldrake S, Pollock NW. Alcohol and diving. In: Steller D, Lobel L, editors. Diving for Science 2012. Proceedings of the American Academy of Underwater Sciences 31st Symposium. Dauphin Island (AL): AAUS; 2012.

2 Hobbs M. Subjective and behavioural responses to nitrogen narcosis and alcohol. Undersea Hyperb Med. 2008;35:175–84. PMID: 18619113.

3 Tillmans F. DAN Annual Diving Report. 2020 ed. A report on 2018 diving fatalities, injuries, and incidents. Durham (NC): Divers Alert Network; 2021. [cited 2023 Feb 16]. Available from: https://www.ncbi.nlm.nih.gov/books/NBK582514/.

4 Clark JE. Moving in extreme environments: inert gas narcosis and underwater activities. Extrem Physiol Med. 2015;4:1. doi: 10.11186/s13728-014-0020-7. PMID: 25713701. PMCID: PMC4337274.

5 Michalodimitrakis E, Patsalis A. Nitrogen narcosis and alcohol consumption – a scuba diving fatality. J Forensic Sci. 1987;32:1095–7. PMID: 3612064.

6 Vann R, Lang M. Recreational diving fatalities. Undersea Hyperbaric Med. 2011;38:257–60. PMID: 21877554.

7 Edge CJ, Wilmshurst PT. The pathophysiology of diving diseases. BJA Educ. 2021;21(9):343–8. doi: 10.1016/j.bjae.2021.05.003. PMID: 34447581. PMCID: PMC8377235.

8 Paulton EC, Catton MJ, Carpenter A. Efficiency at sorting cards in compressed air. Brit J Industry Med. 1964;21:242. doi: 10.1136/oem.21.3.242. PMID: 14180485. PMCID: PMC1038362.

9 Bennett PB, Poulton EC, Carpenter A, Catton MJ. Efficiency at sorting cards in air and a 20 per cent oxygen-helium mixture at depths down to 100 feet and in enriched air. Ergonomics. 1967;10:53–62. doi: 10.1080/00140136708930839. PMID: 6036474.

10 Vrijdag XCE, van Waart H, Pullon RM, Sames C, Mitchell SJ, Sleigh JW. EEG functional connectivity is sensitive for nitrogen narcosis at 608 kPa. Scientific Reports. 2022;12(1):4880. doi: 10.1038/s41598-022-08869-8. PMID: 35318392. PMCID: PMC8940999.

11 Ahti PA, Wikgren J. Rapture of the deep: gas narcosis may impair decision-making in scuba divers. Diving Hyperb Med. 2023;53:306–312. doi:10.28920/dhm53.4.306-312. PMID: 38091589. PMCID: PMC10944662.

12 Chiu YC, Huang JT, Duann JR, Lin CH. Editorial: twenty years after the Iowa gambling task: rationality, emotion, and decision-making. 2017;8:2353. Front Psychol. doi: 10.3389/fpsyg.2017.02353. PMID: 29422876. PMCID: PMC5788943.

13 Buelow MT, Suhr JA. Construct validity of the Iowa gambling task. Neuropsychol Rev. 2009;19:102–14. doi: 10.1007/s11065-009-9083-4. PMID: 19194801.

14 Biersner RJ, Hall DA, Linaweaver PG, Neuman TS. Diving experience and emotional factors related to the psychomotor effects of nitrogen narcosis. Aviat Space Environ Med. 1978;49:959–62. PMID: 678246.

15 Löfdahl P, Andersson D, Bennett M. Nitrogen narcosis and emotional processing during compressed air breathing. Aviat Space Environ Med. 2013;84:17–21. doi: 10.3357/ASEM.3277.2013. PMID: 23304994.

16 Wilmshurst PT, Nuri M, Crowther A, Webb-Peplow MM. Cold-induced pulmonary oedema in scuba divers and swimmers and subsequent development of hypertension. Lancet. 1989;1:62–65. doi: 10.1016/s0140-6736(89)91426-8. PMID: 2562880.

17 Doolette DJ, Murphy FG. Within-diver variability in venous gas emboli (VGE) following repeated dives. Diving Hyperb Med. 2023;53:333–9. doi: 10.28920/dhm53.4.333-339. PMID: 38091593. PMCID: PMC10944664.

18 Unsworth IP. Inert gas narcosis-an introduction. Postgrad Med J. 1966;42:378–85.

19 Behnke AR. Thomson RM, Motley EP. Psychological affects from breathing air at 4 atmospheres pressure. Am J Physiol. 1935;112:554–8.

Conflicts of interest and funding: nil

Submitted: 22 February 2024
Accepted after revision: 7 May 2024

Notices and news

EUBS notices and news and all other society information can be found on:
http://www.eubs.org/

EUBS Notices and News

EUBS2024 Scientific Meeting on Diving and Hyperbaric Medicine

The 48th EUBS Annual Scientific Meeting will be held in Brest, France, from 16–20 September 2024.

Every year this event is the opportunity for researchers, healthcare professionals, underwater and hyperbaric medicine specialists and physiologists from all over the world, to get together in a friendly atmosphere to share their latest studies and research to expand the knowledge in our field.

The scientific programme is expected to be of a high standard allowing to open new paths in research and opportunities for collaborations. Conferences, posters and exhibitions will constitute the core of this meeting, and special attention will be paid to young investigators. A public session dedicated to science popularisation will also be organised.

Nestled in one of the most beautiful bays of France, Brest is a city oriented towards the ocean. Social events will be chosen to let you discover its great maritime natural and historic heritage.

The organising committee, which is comprised of the members of the ORPHY laboratory at Université de Bretagne Occidentale (UBO), are delighted to welcome you to participate in this meeting and to contribute to its success. Even though the 'early bird' registration rates are no longer available, there is still time for you to register for EUBS2024, be sure to book your flight/train/hotel and register now. Your friends will be there too.

Visit the dedicated conference website for all info and registration: https://eubs2024.sciencesconf.org/

EUBS Elections – Member-at-Large

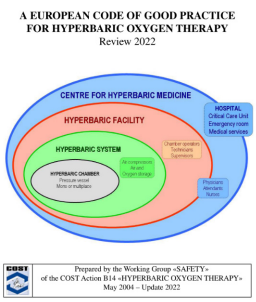
Around the time of publication of this issue of DHM, the election process for the 2024 ExCom Member-at-Large of EUBS will have been started.

We will be saying goodbye to Dr Oscar Camacho (Porto, Portugal) as Member-at-Large 2020. ExCom extends its thanks to Oscar for the work he did in ExCom.

Candidates for the position of Member-at-Large 2024 will be placed on the EUBS website with a picture and short CV, and you should, by the time this journal issue is published, have received an internet ballot by email allowing you to cast your vote. If you have not received this email yet, please notify us at secretary@eubs.org, and we will work with you to find out the reasons why. As the system works via email, it is possible the message ended up in your spam folder. There may be other reasons but usually, we are able to solve them.

European Code of Good Practice in HBO Therapy (ECGP): Free download

The 2022 revision of this important document has been published in DHM Journal 53-4 Supplement. It is an Open Access text that can be freely distributed.



The ECGP is probably the most important document for hyperbaric centres in Europe, as it details the minimum of requirements for operation (be it personnel, equipment or procedures) of any medical centre serving hyperbaric therapies. While this code does not replace any national regulations, it is intended to be a reference document for European countries to provide guidelines, regulations, and standards in all fields of hyperbaric medicine.

Please download this document from the DHM website or via the EUBS website Endorsed Documents and Guidelines page (http://www.eubs.org/?page_id=227).

Website and social media

As always, please visit the EUBS Website (www.eubs.org) for the latest news and updates.

On the 'Research Page' (http://www.eubs.org/?page_id=284) you will be able to find information on planned and recruiting clinical trials.

While we value the membership contributions of all our members (after all, members are what constitutes our Society), EUBS ExCom would specifically like to thank our Corporate Members for their support to the Society. You can find their names, contact information and logo's on the Corporate Members page under menu item 'The Society'. Please follow our Facebook, Twitter and Instagram account. While we will continue to use our 'EUBS Website News' email messages as a way to communicate important information directly to our EUBS members, Twitter and Instagram will be used to keep both members and non-members updated and interested in our Society.

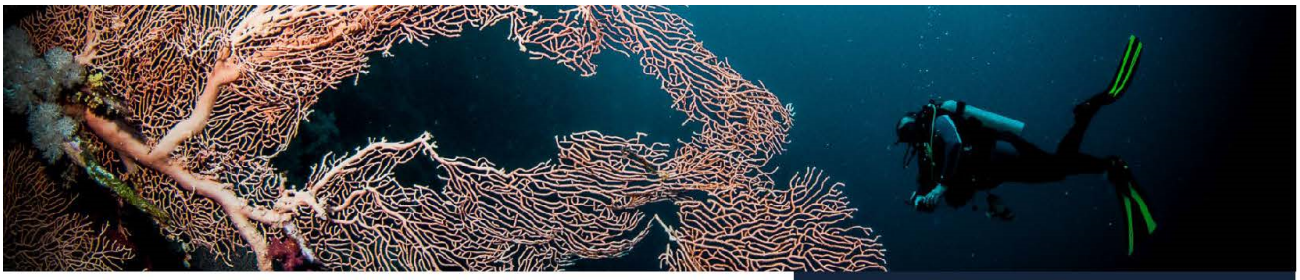
Here are the links to bookmark and follow:

Facebook: https://www.facebook.com/European-Underwater-and-Baromedical-Society-283981285037017/
X (formerly Twitter): @eubsofficial
Instagram: @eubsofficial

The

website is at
http://www.eubs.org/
Members are encouraged to log in and keep their personal details up to date.

The latest issues of *Diving and Hyperbaric Medicine* are via your society website login.



The British Hyperbaric Association (BHA) is holding its 2-day Annual Conference in the Kingsley Suite, Canham Turner Building, University of Hull Cottingham Rd HU6 7RX, Wednesday 6 and Thursday 7 November 2024.

The theme **"Nitrogen Narcosis and Bubbles"** provides an opportunity for all involved in diving and diving medicine to acquire, maintain and develop their professional profile.

Each day has registered for 6 CPD points

The program is designed for a wide range of participants including: Occupational, Emergency Department, ICU and Basics Doctors, Prehospital Responders, Nurses, Paramedics, dive systems Life Support Technicians, persons with an interest in the Physiology and Medicine of Diving and importantly **Divers themselves**

Abstracts for oral presentation are welcome, applications should be 250 words or less and submitted to BHA.Conference@mimirmarine.com on or before 14 October 2024.

Registration & payment

https://www.BHA-conference2024.com
Credit / Debit Card / Paypal / by Phone

Attending 6th & 7th Nov:	£ 400
6th Nov only:	£ 200
7th Nov only:	£ 200
Nurses, Divers, Students Non-Medics (per day):	£ 150
Conference Dinner:	£ 70
Dinner Guests:	£ 50

Contact us on +44(0)1482 672 462
BHA.Conference@mimirmarine.com

The current program includes the following speakers:

DAY 1 – 6TH NOV

Towards Gas Narcosis Monitoring in Compressed Gas Diving. Dr Xavier Vrijdag. Department of Anesthesiology at the University of Auckland.

Nitrogen Narcosis, It's a Risky Business. Pauliina Ahti. Centre for Interdisciplinary Brain Research, Department of Psychology, University of Jyväskylä. Finland.

Nitrogen Narcosis, never any hangover, or? Mikael Gennser MD PhD. Division of Environmental Physiology. Royal Institute of Technology, Sweden.

Acclimatisation to Diving: A Systematic Review. Dr Jan Risberg. Norway

Fatality Reporting International Database
Dr. Frauke Tillmans DAN USA Research Director

DAY 2 – 7TH NOV

History and Evaluation of Intra-vascular Bubble Detection and Scoring. Lesley Blogg. BSc (hons), PhD

Bubbles detected, or not, now what? Mikael Gennser MD PhD. Division of Environmental Physiology. Royal Institute of Technology, Sweden.

National Network Acute Interventional Neuroradiology
Dr Paul Maliakal. Consultant in diagnostic & Interventional Neuroradiology.

National Network Treatment of Arterial Gas Embolism
Dr Pieter Bothma Consultant in Anaesthesia and Intensive Care.

AGE from shallow depth escape training Dr Jan Risberg.

The Paediatric Patient. Jaqui Painter Hull Hyperbaric Unit

Conference Website and **Registration:** www.BHA-conference2024.com
Video hook-up is available to overseas delegates, contact: BHA.Conference@mimirmarine.com

MIMIR MARINE

NEMHS

South Pacific Underwater Medicine Society

Notices and news

SPUMS notices and news and all other society information can be found on:
https://spums.org.au/

President's report

Neil Banham

The 52nd SPUMS Annual Scientific Meeting (ASM) has just been held at the Pearl Resort, Pacific Harbour, Fiji from Sunday 12 May – Friday 17 May 2024.

Conference theme: *A plunge into recreational diving and diver health*

Convenors: David Smart and Neil Banham (Scientific Convenor)

The ASM was a great success with 108 full Registrants and 147 attendees overall including Guest Registrants and family members. Pleasingly, there was a high number of first-time attendees, who were acknowledged at the start of the conference, as was Cathy Meehan who was attending her 32nd consecutive ASM.

Our Keynote Speaker was Dr Peter Wilmshurst, a British cardiologist who some will remember from our highly successful 2014 Bali ASM, which culminated in the publication of the SPUMS and the United Kingdom Sports Diving Medical Committee (UKSDMC) Joint Position Statement (JPS) on persistent foramen ovale (PFO) and diving in 2015.[1]

Peter is a world authority on PFO and diving as well as immersion pulmonary oedema (IPO), reporting the first case. Peter, due to unforeseen circumstances, had to join the ASM virtually and thanks to the wonders of technology and the assistance of Ivan Whippy and Deb Dickson-Smith, it proceeded as though Peter was with us in person. Peter joined for the entire ASM, a stoic effort considering the 11 hour time difference with the UK, meaning that he commenced participating at 3am his time. Thanks again Peter.

Our supporting speakers Dr John Lippmann (Snorkelling deaths / Shark attacks on divers in Australia) and Professor Simon Mitchell (Update on Decompression Illness) both presented talks of very high quality. Thanks Simon and John and to all other speakers. The conference room remained full for the entire ASM, reflecting the high quality of all speakers and their topics.

Workshops were held with a view to update the JPS on PFO and diving and to develop one for return for diving (or not!) following an episode of IPO, as well as diver information for both. There was great participation from the floor about each Statement, meaning that we can further develop a JPS for these soon, with a view to publication in *Diving and Hyperbaric Medicine* and on the SPUMS website, by the end of this year.

I would like to thank our Convenor, Clinical Professor David Smart, for his huge efforts in making our ASM a fantastic success as well as thank this year's ASM travel provider, Diveplanit, dive provider Aqua-Trek Fiji and the Pearl Resort.

The venue for our 53rd ASM in 2025 has been decided. The options considered were Bali, Palau and the Philippines, with Bali being chosen as the preferred destination by a majority of SPUMS ExCom members.

Xavier Vrijdag and Hanna van Waart have volunteered to be Bali ASM Convenors.

The proposed conference theme for SPUMS 2025 is "*Oxygen: Too little, too much or just right*".

Preliminary dates are 18–23 May 2025.

Venue: Ramayana Candidasa, Bali, Indonesia.

Thanks Hanna and Xavier.

Consideration for future venues for the 2026 and 2027 SPUMS conferences were canvassed at the ASM. Popular options were Palau and the Maldives, but a decision is yet to be made. Please advise me re other suitable ideas for a venue and/ or if you wish to Convene. Any proposed venue should have a conference room seating at least 100 pax and the capacity to cater for at least 60 divers at one time.

David Smart and I have updated the SPUMS ASM Convenor Manual such that organising future ASMs is made much easier. Thank you, David.

The ANZHMG Introductory Course in Diving and Hyperbaric Medicine will be next held February/March

2025, again in Fremantle. The 2024 course was fully subscribed, and a great success. Many thanks to Ian Gawthrope the course coordinator and to all faculty who gave up precious time to contribute.

https://spums.au/index.php/education/spums-approved-courses-for-doctors.

Scholarships for trainees to attend this course are available thanks to the generosity of the Australasian Diving Safety Foundation ADSF). Please contact John Lippmann at johnl@adsf.org.au for more information. ADSF has also kindly sponsored SPUMS membership for a year for course participants.

Just prior to the 2025 AGM, nominations for the position of SPUMS President-elect will be sought, with the position being decided at the Bali AGM. The incoming President-elect will have a year to "*learn the ropes*" prior to the completion of my second 3-year term as President at the 2026 AGM. Please consider yourself for this.

Dr Neil Banham
SPUMS President

Reference

1 Smart D, Mitchell S, Wilmshurst P, Turner M, Banham N. Joint position statement on persistent foramen ovale (PFO) and diving. South Pacific Underwater Medicine Society (SPUMS) and the United Kingdom Sports Diving Medical Committee (UKSDMC). Diving Hyperb Med. 2015;45:129-31. PMID: 26165538.

The Australian and New Zealand Hyperbaric Medicine Group

Introductory Course in Diving and Hyperbaric Medicine

Dates: 17–28 February 2025
Venue: Hougoumont Hotel, Fremantle, Western Australia
Cost: AUD$3,200.00 (inclusive of GST) for two weeks

Successful completion of this course will allow the doctor to perform Recreational and Occupational (as per AS/ NZS 2299.1) fitness for diving medicals and be listed for such on the SPUMS Diving Doctors List (provided that they continue to be a financial SPUMS member).

The course content includes:

- History of diving medicine and hyperbaric oxygen treatment
- Physics and physiology of diving and compressed gases
- Presentation, diagnosis and management of diving injuries
- Assessment of fitness to dive
- Visit to RFDS base for flying and diving workshop
- Accepted indications for hyperbaric oxygen treatment
- Hyperbaric oxygen evidence based medicine
- Wound management and transcutaneous oximetry
- In water rescue and management of a seriously ill diver
- Visit to HMAS Stirling
- Practical workshops
- Marine Envenomation

Contact for information:

Sam Swale, Course Administrator
Phone:*+61 (0)8-6152-5222*
Fax:*+61 (0)8-6152-4943*
Email: *fsh.hyperbaric@health.wa.gov.au*
Accommodation information can be provided on request.

Royal Australian Navy Medical Officers' Underwater Medicine Course

Dates: 14–25 October 2024 and 17–28 March 2025

Venue: HMAS Penguin, Sydney

The MOUM course seeks to provide the medical practitioner with an understanding of the range of potential medical problems faced by divers. Emphasis is placed on the contraindications to diving and the diving medical assessment, together with the pathophysiology, diagnosis and management of common diving-related illnesses. The course includes scenario-based simulation focusing on the management of diving emergencies and workshops covering the key components of the diving medical.

Cost: The course cost remains at AUD$1,355 (excl GST) but is subject to change.

Successful completion of this course will allow the doctor to perform Recreational and Occupational (as per AS/ NZS 2299.1) fitness for diving medicals and be listed for such on the SPUMS Diving Doctors List (provided that they continue to be a financial SPUMS member).

For information and application forms contact:

Rajeev Karekar, for Officer in Charge
Submarine and Underwater Medicine Unit
HMAS Penguin
Middle Head Rd, Mosman
NSW 2088, Australia
Phone: *+61 (0)2-9647-5572*
Fax: *+61 (0)2-9647-511*
Email: *rajeev.karekar@defence.gov.au*

The SPUMS South Pacific Underwater Medicine Society

website is at
https://spums.org.au/

Members are encouraged to login and check it out! Keep your personal details up-to-date.

The latest issues of *Diving and Hyperbaric Medicine* are via your society website login.

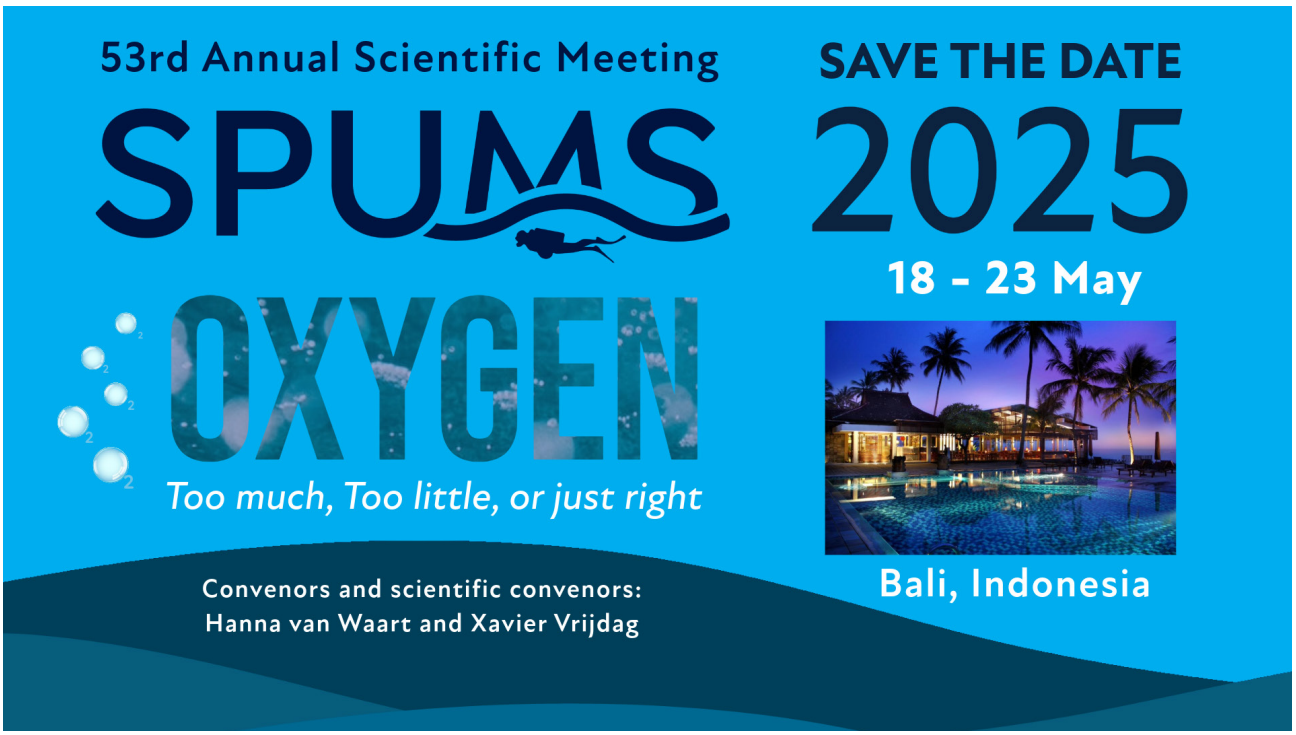
SPUMS Facebook page
Find us at:
SPUMS on Facebook

HBOE HBOEvidence

HBOEvidence

HBO Evidence is seeking an interested person/group to continue the HBOEvidence site. The database of randomised controlled trials in diving and hyperbaric medicine: hboevidence wikis.unsw.edu.au. The HBOEvidence site is planned to be integrated into the SPUMS website in the near future.

Those interested in participating in this project can contact Neil Banham president@spums.org.au



SPUMS Diploma in Diving and Hyperbaric Medicine

Requirements for candidates (May 2014)

In order for the Diploma of Diving and Hyperbaric Medicine to be awarded by the Society, the candidate must comply with the following conditions: They must

1 be medically qualified, and remain a current financial member of the Society at least until they have completed all requirements of the Diploma;
2 supply evidence of satisfactory completion of an examined two-week full-time course in diving and hyperbaric medicine at an approved facility. The list of such approved facilities may be found on the SPUMS website;
3 have completed the equivalent (as determined by the Education Officer) of at least six months' full-time clinical training in an approved Hyperbaric Medicine Unit;
4 submit a written proposal for research in a relevant area of underwater or hyperbaric medicine, in a standard format, for approval before commencing the research project;
5 produce, to the satisfaction of the Academic Board, a written report on the approved research project, in the form of a scientific paper suitable for publication. Accompanying this report should be a request to be considered for the SPUMS Diploma and supporting documentation for 1–4 above.

In the absence of other documentation, it will be assumed that the paper is to be submitted for publication in *Diving and Hyperbaric Medicine*. As such, the structure of the paper needs to broadly comply with the 'Instructions for authors' available on the SPUMS website https://spums.org.au/ or at https://www.dhmjournal.com/.

The paper may be submitted to journals other than *Diving and Hyperbaric Medicine*; however, even if published in another journal, the completed paper must be submitted to the Education Officer (EO) for assessment as a diploma paper. If the paper has been accepted for publication or published in another journal, then evidence of this should be provided.

The diploma paper will be assessed, and changes may be requested, before it is regarded to be of the standard required for award of the Diploma. Once completed to the reviewers' satisfaction, papers not already submitted to, or accepted by, other journals should be forwarded to the Editor of *Diving and Hyperbaric Medicine* for consideration. At this point the Diploma will be awarded, provided all other requirements are satisfied. Diploma projects submitted to *Diving and Hyperbaric Medicine* for consideration of publication will be subject to the Journal's own peer review process.

Additional information – prospective approval of projects is required

The candidate must contact the EO in writing (or email) to advise of their intended candidacy and to discuss the proposed topic of their research. A written research proposal must be submitted before commencement of the research project.

All research reports must clearly test a hypothesis. Original basic and clinical research are acceptable. Case series reports may be acceptable if thoroughly documented, subject to quantitative analysis and if the subject is extensively researched in detail. Reports of a single case are insufficient. Review articles may be acceptable if the world literature is thoroughly analysed and discussed and the subject has not recently been similarly reviewed. Previously published material will not be considered. It is expected that the research project and the written report will be primarily the work of the candidate, and that the candidate is the first author where there are more than one.

It is expected that all research will be conducted in accordance with the joint NHMRC/AVCC statement and guidelines on research practice, available at: https://www.nhmrc.gov.au/about-us/publications/australian-code-responsible-conduct-research-2018, or the equivalent requirement of the country in which the research is conducted. All research involving humans, including case series, or animals must be accompanied by documentary evidence of approval by an appropriate research ethics committee. Human studies must comply with the Declaration of Helsinki (1975, revised 2013). Clinical trials commenced after 2011 must have been registered at a recognised trial registry site such as the Australia and New Zealand Clinical Trials Registry http://www.anzctr.org.au/ and details of the registration provided in the accompanying letter. Studies using animals must comply with National Health and Medical Research Council Guidelines or their equivalent in the country in which the work was conducted.

The SPUMS Diploma will not be awarded until all requirements are completed. The individual components do not necessarily need to be completed in the order outlined above. However, it is mandatory that the research proposal is approved prior to commencing research.

Projects will be deemed to have lapsed if:

- the project is inactive for a period of three years, or
- the candidate fails to renew SPUMS Membership in any year after their Diploma project is registered (but not completed).

For unforeseen delays where the project will exceed three years, candidates must explain to the EO by email why they wish their diploma project to remain active, and a three-year extension may be approved. If there are extenuating circumstances why a candidate is unable to maintain financial membership, then these must be advised by email to the EO for consideration by the SPUMS Executive. If a project has lapsed, and the candidate wishes to continue with their DipDHM, then they must submit a new application as per these guidelines.

The Academic Board reserves the right to modify any of these requirements from time to time. As of October 2020, the SPUMS Academic Board consists of:

Associate Professor David Cooper, Education Officer, Hobart
Professor Simon Mitchell, Auckland

All enquiries and applications should be addressed to:
Associate Professor David Cooper
education@spums.org.au

Keywords
Qualifications; Underwater medicine; Hyperbaric oxygen; Research; Medical society

Courses and meetings

Publications database of the German Diving and Hyperbaric Medical Society (GTÜM)

EUBS and SPUMS members are able to access the German Society's large database of publications in diving and hyperbaric medicine. EUBS members have had this access for many years. SPUMS members should log into the SPUMS website, click on 'Resources' then on 'GTÜM database' in the pull-down menu. In the new window, click on the link provided and enter the user name and password listed on the page that appears in order to access the database.

The Science of Diving

Support EUBS by buying the PHYPODE book '*The science of diving*'. Written for anyone with an interest in the latest research in diving physiology and pathology. The royalties from this book are being donated to the EUBS.

Available from:
Morebooks
https://www.morebooks.de/store/gb/book/the-science-of-diving/isbn/978-3-659-66233-1

Advertising in DHM

Commercial advertising is welcomed within the pages of *Diving and Hyperbaric Medicine*. Companies and organisations within the diving, hyperbaric medicine and wound-care communities who might wish to advertise their equipment and services are welcome. The advertising policy of the parent societies – EUBS and SPUMS is available for download on Diving and Hyperbaric Medicine website. Scan the QR code above for more information.

Further information can be obtained by contacting our Editorial Manager, Nicky Telles.
Email: editorialassist@dhmjournal.com

Scott Haldane Foundation

As an institute dedicated to education in diving medicine, the Scott Haldane Foundation has organized more than 300 courses all over the world, over the past 32 years. SHF is targeting on an international audience with courses world wide.

Below the schedule of upcoming SHF-courses in the second half of 2024.

The courses Medical Examiner of Divers (part 1 and 2) and SHF in-depth courses, as modules of the level 2d Diving Medicine Physician course, fully comply with the ECHM/EDTC curriculum for Level 1 and 2d respectively and are accredited by the European College of Baromedicine (ECB).

2024

09–16 November	Medical Examiner of Divers part 1 (level 1) Tropical location
16–23 November	31st in-depth course Diving Medicine (level 2d) Tropical location
23–30 November	31st in-depth course Diving Medicine (level 2d) Tropical location
On request	Internship HBOt (level 2d) NL/Belgium

The course calendar will be supplemented regularly. For the latest information see: www.scotthaldane.org.

Historical Diving Society Australia - Pacific

P O Box 347, Dingley Village Victoria, 3172, Australia
Email: info@historicaldivingsociety.com.au
Website: https://www.historicaldivingsociety.com.au/

DHM Journal Facebook

Find us at:
https://www.facebook.com/divingandhyperbaricmedicine

Diving and Hyperbaric Medicine: Instructions for authors

(Full version – updated June 2024)

Diving and Hyperbaric Medicine (DHM) is the combined journal of the South Pacific Underwater Medicine Society (SPUMS) and the European Underwater and Baromedical Society (EUBS). It seeks to publish papers of high quality on all aspects of diving and hyperbaric medicine of interest to diving medical professionals, physicians of all specialties, scientists, members of the diving and hyperbaric industries, and divers. Manuscripts must be offered exclusively to *Diving and Hyperbaric Medicine* unless clearly authenticated copyright exemption accompaniesthe manuscript. All manuscripts will be subject to peer review. Accepted contributions will also be subject to editing.

***Address*:** The Editor, Diving and Hyperbaric Medicine, Department of Anaesthesiology, University of Auckland, Private Bag 92019, Auckland 1142, New Zealand
***Email*:** editor@dhmjournal.com
***Phone: (mobile)*:** +64 (0)27 4141 212
***European Editor*:** euroeditor@dhmjournal.com
***Editorial Manager*:** editorialassist@dhmjournal.com
***Journal information*:** info@dhmjournal.com

Contributions should be submitted electronically by following the link:
http://www.manuscriptmanager.net/dhm

There is on-screen help on the platform to assist authors as they assemble their submission. In order to submit, the corresponding author needs to create an 'account' with a username and password (keep a record of these for subsequent use). The process of uploading the files related to the submission is simple and well described in the on-screen help provided the instructions are followed carefully. The submitting author must remain the same throughout the peer review process.

Types of articles

DHM welcomes contributions of the following types:

Original articles, Technical reports and Case series: up to 3,000 words is preferred, and no more than 30 references (excluded from word count). Longer articles may be considered at the editor's discretion. These articles should be subdivided into the following sections: an **Abstract** (subdivided into Introduction, Methods, Results and Conclusions) of no more than 250 words (excluded from word count), **Introduction, Methods, Results, Discussion, Conclusions, References, Acknowledgements**, **Funding** sources and any **Conflicts of interest**. **Legends/captions** for illustrations, figures and tables should be placed at the end of the text file.

Review articles: up to 5,000 words is preferred and a maximum of 50 references (excluded from the word count); include an informative **Abstract** of no more than 300 words (excluded from the total word count); structure of the article and abstract is at the author(s)' discretion.

Case reports, Short communications and **Work in progress** reports: maximum 1,500 words, and 20 references (excluded from the word count); include an informative **Abstract** (structure at author's discretion) of no more than 200 words (excluded from the word count).

Educational articles, Commentaries and **Consensus reports** for occasional sections may vary in format and length but should generally be a maximum of 2,000 words and 15 references (excluded from word count); include an informative **Abstract** of no more than 200 words (excluded from word count).

Letters to the Editor: maximum 600 words, plus one figure or table and five references.

The journal occasionally runs **'World as it is'** articles; a category into which articles of general interest, perhaps to divers rather than (or in addition to) physicians or scientists, may fall. This is particularly so if the article reports an investigation that is semi-scientific; that is, based on methodology that would not necessarily justify publication as an original study. Such articles should follow the length and reference count recommendations for an original article. The structure of such articles is flexible. The submission of an abstract is encouraged.

Supplements to a particular issue are occasionally published for purposes deemed appropriate by the editor. These may accommodate articles / treatises that are too long for the main journal or collections of articles on thematic areas. There is no open portal for submission of such material and any plans or suggestions for supplements should be discussed with the editor before writing.

Formatting of manuscripts

All submissions must comply with the following requirements. **Manuscripts not complying with these instructions will be suspended** and returned to the author for correction before consideration. Guidance on structure for the different types of articles is given above.

Title page: Irrespective of article type, it must have a title page that lists the title of the paper, all authors' names in full and their affiliations and provide full contact details for the first (and corresponding, if different) author(s).

ORCiD requirements: ORCiD An ORCiD is now required for all corresponding authors when submitting to *Diving and Hyperbaric* Medicine. The ORCiD must be entered into Manuscript Manager when submitting (the site will prompt you to create one if you do not have one). Please add your ORCiD to the title page of your manuscript.

What is an ORCiD? ORCiD provides a persistent digital identifier (an ORCiD iD) that you own and control, and that distinguishes you from every other researcher. You can connect your iD with your professional information – affiliations, grants, publications, peer review, and more. You can use your iD to share your information with other systems, ensuring you get recognition for all your contributions, saving you time and hassle, and reducing the risk of errors. For more information see https://orcid.org/.

Keywords: The title page must also list a maximum of seven keywords best describing the paper. These should be chosen from the list on the journal website DHM Key words 2023 or on the Manuscript Manager website. New keywords, complementary with the US National Library of Medicine NML MeSH, https://www.nlm.nih.gov/mesh/meshhome.html/ may be used but are at the discretion of the Editor. Do not use keyword terms that already appear in the title of your article.

Text format: The preferred format is Microsoft Office Word or rich text format (RTF), with 1.5 line spacing, using both upper and lower case throughout. The preferred font is Times New Roman, font size 11 or 12. Please avoid using auto-formatting tools such as automatic spaces before and after paragraphs. **Lines must** be numbered **continuously** throughout the manuscript to facilitate the review process.

Section Headings should conform to the current format in DHM
This is:
Section heading (for Introduction, Methods, etc.)
SUBSECTION HEADING 1
Subsection heading 2

Numbering: All pages must be numbered, but no other text should appear in the header and footer space of the document. Do not use underlining. No running title is required.

English spelling will be in accordance with the Concise Oxford Dictionary, 11th edition revised (or later). Oxford: Oxford University Press; 2006.

Measurements will be in SI units (mmHg are acceptable for blood pressure measurements) and normal ranges should be included where appropriate. Authors are referred to the online BIPM brochure, International Bureau of Weights and Measures (2006), The International System of Units (SI), 8th ed, available as a pdf at https://www.bipm.org/en/publications/si-brochure/. Atmospheric and gas partial pressures and blood gas values should be presented in kPa (atmospheres absolute [abbreviated as atm abs]/bar/mmHg may be provided in parenthesis). The ambient pressure should always be given in absolute not gauge values unless there is a particular reason to use gauge pressure and the distinction is made clear. Water depths should be presented in metres of sea (or fresh) water (msw or mfw). Cylinder pressures may be presented as 'bar' or megapascals.

Equations: Authors are responsible for the correct formatting of each equation, and, because of potential conversion problems, they must be submitted using the Times New Roman font in a TIFF file. Equations should be camera-ready when they are submitted.

Abbreviations may be used once they have been shown in parenthesis after the complete expression. For example, decompression illness (DCI) can thereafter be referred to as DCI. This applies separately to the abstract and main text. Use generally accepted abbreviations that readers are likely to be familiar with rather than neologisms of your own invention. The overuse of abbreviations is strongly discouraged.

References: References should be numbered consecutively in the order in which they are first mentioned in the text, tables or figures where they should appear as superscript numbers, either following the statement referenced,[1] or at the end of the sentence, **after the full stop**.[1,2] Do not use references in the Abstract. References appearing in tables or figures or their legends should continue the sequence of reference numbering in the main text of the article in accordance with the position of first citing the table/figure in the text. Use MEDLINE abbreviations for journal names. Journals not indexed in MEDLINE should have the journal name written in full. Please ensure you include **doi/PMID/PMCID** numbers where available (see example below). Failure to do so will result in your references being sent to the corresponding author to format correctly and hold up the review process.

The Journal reference style is based exactly on that of the International Committee of Medical Journal Editors (ICMJE) *Recommendations for the Conduct, Reporting, Editing and Publication of Scholarly Work in Medical Journals: Sample References* (updated June 2024) https://www.nlm.nih.gov/bsd/uniform_requirements.html. Examples of the formats for different types of references (journal articles, books, monographs, electronic material, etc.) are given in detail on this website. Authors MUST consult this in preparing their reference list.

An example of a journal reference in the ICMJE format is:

Wilson CM, Sayer MDJ. Transportation of divers with decompression illness on the west coast of Scotland. Diving Hyperb Med. 2011;41(2):64–69.

If a journal uses continuous pagination throughout a volume (as many do) then the issue number should be omitted and the pagination reduced. Therefore, the shortened ICMJE version used in DHM is:

Wilson CM, Sayer MDJ. Transportation of divers with decompression illness on the west coast of Scotland. Diving Hyperb Med. 2011;41:64–9.

If an article has a unique identifier for the citation (e.g., doi number, PubMed PMID, PubMed Central PMCID) then this must be included at the end of the reference. The format and order for this is:
doi: number. PMID: number. PMCID: number.

For example:

Doolette DJ, Mitchell SJ. In-water recompression. Diving Hyperb Med. 2018;48:84–95. doi: 10.28920/dhm48.2.84-95. PMID: 29888380. PMCID: PMC6156824.

An example book reference is:

Kindwall EP, Whelan HT, editors. Hyperbaric medicine practice, 3rd ed. Flagstaff (AZ): Best Publishing Company; 2008.

A chapter in a book is referenced similarly, for example:

Moon RE, Gorman DF. Treatment of decompression disorders. In: Brubakk AO, Neuman TS, editors. Bennett and Elliott's physiology and medicine of diving. Edinburgh: Saunders; 2003. p. 600–50.

Examples of many other types of references are to be found on the National Library of Medicine site (see https://www.nlm.nih.gov/bsd/uniform_requirements.html).

When citing workshop/conference proceedings or technical reports, authors are requested to investigate their availability online and provide an online source for the reference if available. The date that the reference was cited (year/month/day) from the source should be noted. For example:

Mitchell SJ, Doolette DJ, Wacholz CJ, Vann R, editors. Management of mild or marginal decompression illness in remote locations workshop proceedings. Durham (NC): Divers Alert Network; 2005. [cited 2022 May 5]. Available from: https://world.dan.org/wp-content/uploads/2021/06/remotewrkshpfinal05-1.pdf.

Additional notes regarding referencing in DHM are:

- If using **EndNote** or another reference manager to prepare the references in the document see EndNote website for advice. Once accepted, the final version of the submitted text should have all field codes removed.
- Verifying the accuracy of references against the original documents is the responsibility of the authors.
- Personal communications should appear as such in the text and not be included in the reference list (e.g., Smith AN, personal communication, year).
- Abstracts from meeting proceedings should not be used as references unless absolutely essential, as these are generally not peer-reviewed material.
- Please avoid using auto-formatting functions like numbering, indentations, and spaces before and after paragraphs in compiling your reference list.
- Please list six authors if using et al. not three – this is our preference.

Tables must **not be** embedded in the main manuscript document. They are to be uploaded as separate Word documents (one document per table) in Manuscript Manager (use the 'Table' category when asked to select a description of the document being uploaded). Name the document with the first author's name and table number as appropriate. Tables need to be labelled at the top of the page with **first** author name and the Table number.

Tables should be presented using MS Word table format with cells framed. Please do not use bolded lines or shading in the table. The editorial team will format the table in the journal style provided the preceding simple instructions are followed. Please avoid complicated, large tables whenever possible. Very large tables (full page or more) may not be incorporated into the final article but, rather, displayed on the journal website as additional material at the Editor's discretion.

The title of the table and caption are not to be included in the table. These appear in the 'legends and captions' section at the end of the manuscript document. Captions should generally contain fewer than 40 words and should be thorough enough to be understood independently of the main text. Any abbreviations or acronyms used in the table should be defined (in alphabetical order) at the end of the caption.

The table must be mentioned within the text of the article, e.g., "*Differences in rates of decompression illness were not significant (Table 1)*", etc. The approximate positions of tables and figures should also be identified in the manuscript text.

Figures (including photos, graphs, diagrams, illustrations and radiographs) must **not be** embedded in the main manuscript document. They are to be uploaded as separate electronic files in high resolution preferably TIF but DHM accepts JPG format in Manuscript Manager. Name the document with the first author's name and figure number as appropriate. *Figures should be uploaded to Manuscript Manager in their numbered order, which results in them being compiled in the review document in the correct order.*

The title of the figure and caption are not to be included in the figure. These appear in the 'legends and captions'

section at the end of the manuscript document. Captions should generally contain fewer than 40 words and should be thorough enough to be understood independently of the main text. Any abbreviations or acronyms used in the figure should be defined (in alphabetical order) at the end of the caption. Magnification should be indicated in the captions for photomicrographs, and consideration given to the positioning of labels on diagnostic material as this can greatly influence the size of reproduction that can be achieved in the published article.

Graphs may be submitted either in colour or grey scale, with no unnecessary shading, grid lines or box lines. Please choose the simplest graphical format that displays the data effectively. 3-D graphs are discouraged unless they are necessary to display 3-D data. Both markers and lines should be unique to facilitate easy discrimination of the data being presented. Special attention should be given to ensuring that font sizes within a diagram are sufficiently large to be legible should the diagram be sized for single-column presentation. The preferred font in diagrams and graphs is Times New Roman. Graph symbol keys should appear within the white space of the figure (not outside the axes) if possible or be included in the caption. Please ensure that axes are labelled using sentence case and the same data formatting conventions presented below.

Any graphs or histograms created in Excel should be sent within their original Excel file, including the data table(s) from which they were produced. This allows the journal office to edit figures for maximum legibility when printed. Upload the spreadsheet to Manuscript Manager with the other manuscript documents and select the designator 'other' and the option 'hide from reviewers' so that the spreadsheet is not incorporated in the review document.

Any photograph or radiograph of a patient must be de-identified. Patient details must be removed, and photographs made unrecognisable. Colour photos are acceptable.

If any figures, images or tables are to be reproduced from previous publications, it is the responsibility of the author(s) to obtain the necessary permissions. This permission should be acknowledged in the figure caption using the format "*Reproduced with permission of .....*" or, if necessary, another format specified by the copyright holder granting permission.

The figure must be mentioned within the text of the article. The approximate positions of tables and figures should also be identified in the manuscript text.

Miscellaneous data formatting conventions: Please follow the following recommendations when presenting data in text, figures or graphs.
Standard deviations and standard errors should be expressed as mean (SD), not mean ± SD.
Composite units of measurement should be expressed as (for example) $g{\cdot}L^{-1}$ or $mL{\cdot}kg^{-1}{\cdot}min^{1}$, not g/L or mL/kg/min
Please use a space between symbols like <, >, ≤, ≥. Thus (for example) > 25, not >25.
Please use decimal points and not commas in decimals. For example: 2.5, not 2,5.
Numbers greater than 999 should contain commas. For example: 1,000 or 25,300,000.
Please leave a space between a number and unit of measurement. For example: 25 msw
Please italicise *n* when used to indicate number and *P* when used to indicate P-values
Please leave spaces in expressions like $n = 25$ or $P < 0.05$ (not n=25 or P<0.05).
For number ranges please use an en-dash without spaces. For example: 17–420. This also applies to page ranges when citing references.
Percent signs should immediately follow a number without a space. For example: 51% not 51 %.

Appendices and Supplementary material (these are placed on DHM's website and linked in the text): These are submitted as per our Table or Figure formatting e.g., if you are submitting a figure as a supplement/appendix, please submit as a JPG formatted image. If you are submitting a table, please use a Word document format. We also accept PDFs as appendices or supplementary material, these can be uploaded with your submission documents and labelled clearly Appendix 1, 2 or Supplement 1, 2, etc. Ensure that they have a caption at the top of the document and highlighted where in the manuscript text your Appendix is referenced.

Diving and Hyperbaric Medicine (DHM) policy re: use of Generative Artificial Intelligence: Artificial Intelligence Generated Content (AIGC) tools—such as ChatGPT and other similar platforms cannot be used for articles published in DHM without explicit approval from the Editor of DHM, and such use must be acknowledged in detail in the **Methods** and/ or **Acknowledgements** section(s) of the manuscript.

DHM is in agreement with COPE's (Committee on Publication Ethics) position statement regarding this: https://publicationethics.org/cope-position-statements/ai-author.

Other manuscript requirements and guidelines

DHM follows as much as possible the ***Recommendations for the conduct, reporting, editing and publication of scholarly work in medical journals***. International Committee of Medical Journal Editors; December 2015.

Available from: https://www.icmje.org/recommendations/. Authors are strongly encouraged to read this and other documents on the ICMJE website in preparing their submission. Authors should also consult guidelines for

specific types of study (e.g., the CONSORT guidelines for the reporting of randomised controlled trials); see https://www.equator-network.org/.

Trial design, analysis and presentation: Before preparing their manuscript, authors must read the summary advice on the journal website on the reporting of trial design, sample size calculation, statistical methods and results. https://www.dhmjournal.com/images/Docs/Trial-design-analysis-and-presentation.pdf.

Consent and ethical approval: Studies on human subjects must comply with the Helsinki Declaration of 1975, revised October 2013 (see https://www.dhmjournal.com/index.php/author-instructions for a copy).

Studies using animals must comply with National Health and Medical Research Council Guidelines or their equivalent in the country in which the work was conducted. It is insufficient to refer to previous publications for details of animal welfare and procedural care. The Physiological Society provides detailed advice regarding animal experimentation and its reporting in research publications and this link is provided with their kind permission: https://physoc.onlinelibrary.wiley.com/doi/full/10.1113/jphysiol.2010.192278.

A statement affirming Ethics Committee (Institutional Review Board) approval (and the approval number) should be included in the text at the beginning of the methods section. A copy of that approval should be uploaded with the submission. Similarly, a statement affirming the securing of written informed consent from subjects should be included in the methods where this was part of the methodology.

Clinical trials commenced after 2011 must have been registered at a recognised trial registry site such as the Australia and New Zealand Clinical Trials Registry https://www.anzctr.org.au/ or EudraCT in Europe https://eudract.ema.europa.eu/. Details of the registration must be provided in the accompanying MSF, and should also be mentioned in the methods section.

For individual case reports, evidence of informed patient consent to anonymous publication of their clinical details and/or images, etc. must be provided. Case series, where only limited anonymous summary data are reported do not require patient consent but must have been assessed by an ethics committee and, if indicated, have ethics approval. Consult your local ethics committee if you are unsure.

Authorship: Authors must have contributed significantly to the study (see guideline to authorship at: https://www.dhmjournal.com/images/Docs/Guideline_to_authorship_in_DHM_journal-2015.pdf.

Inclusion of more than six authors in any one manuscript requires strong justification. Other contributors may be listed in the **Acknowledgements** section.

Mandatory submission form (MSF): A fully completed MSF must be signed by the first author and the corresponding author (if different) and must be uploaded with other manuscript documents in Manuscript Manager with all submissions, irrespective of type. Authors should be listed with the principal author first. Authors should be listed on the MSF in the order intended for the published paper. The form requires the full postal address, phone number and e-mail address supplied for the first author; if the corresponding author is not the first author, then full contact details for both are required. The MSF is available for download on the DHM website.
https://www.dhmjournal.com/index.php/author-instructions

Conflict of interest form: All conflicts of interest by any author must be reported in summary in the Mandatory Submission Form. If your paper is accepted and any conflicts have been listed here, then more detailed information will be required using the ICMJE form available on the ICMJE website at: https://www.icmje.org/disclosure-of-interest/. A form for each author for whom a potential conflict was listed must be submitted.

All potential conflicts of interest, financial or otherwise (e.g., consultancies, equity interests, patent-licensing arrangements, lack of access to data, or lack of control of the decision to publish) by any author must be declared. DHM reserves the right to seek further clarification as necessary. All conflicts or a declaration of no conflicts will appear at the end of the published article. Failure to report potential conflicts of interest prior to peer review may result in publication delays or rejection of the manuscript.

Authors should consult the WAME website https://www.wame.org/about/conflict-of-interest-in-peer-reviewed-medical if they need further clarification.

Peer review and publication process: All submitted manuscripts will be subject to open peer review usually by a member of the Editorial Board and/or external reviewers. Reviewer comments will be provided to authors with any recommendations for improvement before acceptance for publication, or if the article is rejected. DHM believes that a transparent review process is indicated in such a small specialty; reviewers are often able to identify the origin of manuscripts and, in the interests of fairness, the authors are, therefore, generally provided the names of their reviewers. The review process typically takes about eight weeks but can be longer. If additional reviews are needed, this will prolong the process. Papers are generally scheduled for publication in order of final acceptance. The Editor retains the right to delay or expedite publication in the interests of the Journal.

If the submission requires revision and resubmission before it can be accepted for publication (and the majority of papers do), then the revised files must be submitted by logging on again at https://www.manuscriptmanager.net/dhm with the same user name and password created for the original

submission, then the article can be **resubmitted** by clicking the **resubmit** link NOT the new submission link. Do NOT create a new account.

Proofs of articles to be published will be sent to corresponding authors in pdf format by email close to the time of publication. You will require Adobe Reader to access this, which may be downloaded from https://get.adobe.com/reader/. Authors are expected to read the proof carefully and inform the editorial office within the time specified of any minor corrections they require. Corrections should be listed in an email sent to the journal address editorialassist@dhmjournal.com, or annotated electronically within the pdf file and returned to the same address. It is expected that the corresponding author will have obtained the approval of all authors for this final version.

English as a second language: Adequate English usage and grammar are prerequisites for acceptance of a paper. However, some editorial assistance may be provided to authors for whom English is not their native language. English language services can be accessed through the European Association of Science Editors (EASE) website https://www.ease.org.uk/. Alternatively, the journal office may be able to put you in touch with a commercial scientific writer.

Copyright: Manuscripts must be offered exclusively to *Diving and Hyperbaric Medicine*, unless a clearly authenticated copyright exemption accompanies the manuscript. Authors must agree to accept the standard conditions of publication. These grant DHM a non-exclusive license to publish the article in digital (electronic) form in *Diving and Hyperbaric Medicine*; also granting the right to sublicense third parties to exercise all or any of these rights. *Diving and Hyperbaric Medicine* agrees that in publishing the article(s) and exercising this non-exclusive publishing sub-license, the author(s) will always be acknowledged as the copyright owner(s) of the article.

Articles are embargoed for one year from the date of publication, after which they will be free to access on the DHM website. If authors wish their article to be free to access immediately upon publication, then a fee (determined by the publishers, EUBS and SPUMS) will be charged for its release. Authors may place their publication on their own institutional website using the 'restricted distribution', password protected pdf provided but not elsewhere during the first year following publication. Thereafter, the non-protected pdf may be used ad-lib.

Author fees: No fees are charged for publication in DHM. However, articles for publication in DHM are embargoed for 12 months. If immediate release is requested by authors, then there is a charge for this, set by the publishers.

PDF: Following publication, two electronic PDFs of articles will be forwarded to the corresponding author. One of these, password protected 'restricted use' may be placed on the author's institutional website during the one-year embargo following publication. Thereafter, the non-protected pdf may be used ad-lib.

These *Instructions for authors* are available as a pdf file on the DHM website at:
https://www.dhmjournal.com/index.php/author-instructions
and on the web platform https://www.manuscriptmanager.net/dhm. They are also available on the EUBS and SPUMS websites.

Summary of files to be uploaded in Manuscript Manager when submitting an article

1. Mandatory submission form
2. Ethics approval letter where relevant, and/or signed patient consent
3. Manuscript document
4. Tables where relevant (each table as a separate Word document)
5. Figures where relevant, uploaded in the order in which they should appear in the manuscript (each Figure as a separate high-resolution TIFF or JPEG file)
6. Any Appendix or Supplementary material.
7. Excel spreadsheet with data and graphs if graphs have been generated in Excel.
8. Submission letter; authors can use this to communicate any particular considerations or issues they wish the editor to be aware of in relation to their manuscript. The letter should state that the paper is being submitted exclusively to DHM.

Documents on DHM website https://www.dhmjournal.com/index.php/author-instructions

The following pdf files are available on the DHM website to assist authors in preparing their submission:

Instructions for authors 2024 (this document)
DHM Keywords 2023
DHM Mandatory submission form 2024
Trial design analysis and presentation
Conflict of interest statement
English as a second language
Guideline to authorship in DHM 2015
Samples of formatted references for authors of journal articles (last reviewed 2024)
Recommendations for the conduct, reporting, editing, and publication of scholarly work in medical journals 2024
Helsinki Declaration revised 2013
Is ethics approval needed?

DIVER EMERGENCY SERVICES PHONE NUMBERS

AUSTRALIA – DAN
1800-088200 (in Australia toll free)
+61-8-8212-9242 User pays
(outside Australia)

NEW ZEALAND – DAN Emergency Service
0800-4DES-111 (in New Zealand toll free)
+64-9-445-8454 (International)

ASIA, PACIFIC ISLANDS – DAN World
+618-8212-9242

EUROPE – DAN
+39-06-4211-8685 (24-hour hotline)

SOUTHERN AFRICA – DAN
+27-10-209-8112 (International call collect)

USA – DAN
+1-919-684-9111

JAPAN – DAN
+81-3-3812-4999 (Japan)

ADSF
AUSTRALASIAN DIVING SAFETY FOUNDATION

Scholarships for Diving Medical Training for Doctors

The Australasian Diving Safety Foundation is proud to offer a series of annual Diving Medical Training scholarships. We are offering these scholarships to qualified medical doctors to increase their knowledge of diving medicine by participating in an approved diving medicine training programme. These scholarships are mainly available to doctors who reside in Australia. However, exceptions may be considered for regional overseas residents, especially in places frequented by Australian divers. The awarding of such a scholarship will be at the sole discretion of the ADSF. It will be based on a variety of criteria such as the location of the applicant, their working environment, financial need and the perception of where and how the training would likely be utilised to reduce diving morbidity and mortality. Each scholarship is to the value of AUD5,000.00.

There are two categories of scholarships:

1. ADSF scholarships for any approved diving medical training program such as the annual ANZHMG course at Fiona Stanley Hospital in Perth, Western Australia.
2. The Carl Edmonds Memorial Diving Medicine Scholarship specifically for training at the Royal Australian Navy Medical Officers' Underwater Medicine Course, HMAS Penguin, Sydney, Australia.

Interested persons should first enrol in the chosen course, then complete the relevant ADSF Scholarship application form available at: https://www.adsf.org.au/r/diving-medical-training-scholarships and send it by email to John Lippmann at johnl@adsf.org.au.
