Diving and Hyperbaric Medicine

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

SPUMS

Volume 55 No. 2 June 2025

EUBS

Randomised controlled trial of HBOT for Long COVID

Outcomes for necrotising fasciitis research

First aid and retrieval of divers in Queensland, Australia

Diving practices among technical divers

HBOT for hearing loss after acoustic trauma

Effect of prior hypoxia exposure on recognition of hypoxia

Planning and challenges in extreme depth bounce dives

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Safety of continuous glucose monitoring devices in HBOT

Psychosis and diving

Shared decision making in HBOT

Cardiopulmonary resuscitation in diving bells

E-ISSN 2209-1491

ABN 29 299 823 713

THE JOURNAL OF DIVING AND HYPERBARIC MEDICINE
***Diving and Hyperbaric Medicine* is published online jointly by the South Pacific Underwater Medicine Society and the European Underwater and Baromedical Society**
https://www.dhmjournal.com/

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To publish a journal and to convene members of each Society annually at a scientific conference

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E-ISSN 2209-1491; ABN 29 299 823 713

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

The Editor's offering

The June 2025 iteration of the journal is a large issue with many fascinating papers on a variety of topics across the diving and hyperbaric medicine spectrum.

Most notably, we report the randomised, double-blind study by Leen D'hoore and colleagues who investigated the efficacy of hyperbaric oxygen treatment (HBOT) for patients suffering Long COVID symptoms. The authors cite three previous uncontrolled open-label studies that reported improvement in Long COVID symptoms such as fatigue, cognitive function and physical performance after 10 HBOT treatments. The use of uncontrolled, open label approaches to evaluating efficacy of HBOT in conditions that may be subject to a placebo or participation effect is flawed. D'hoore et al. have addressed this in a study of four groups of 20 Long COVID patients; one exposed to hyperbaric oxygen (100% oxygen at 253 kPa), one exposed to 100% oxygen at surface pressure, one exposed to the same oxygen dose as the latter group but at hyperbaric pressure (40% oxygen at 253 kPa), and one exposed to 21% oxygen at surface pressure. The protocol which involved pressure shifts in a hyperbaric chamber for all patients ensured successful blinding. To be consistent with the earlier uncontrolled studies citing benefit there were 10 exposures. The outcome measures addressed cognitive function, quality of life, and physical performance. Although there was variability in outcomes among patients across all groups (including patients who perceived benefit) there was no difference between the groups. A similar result was reported two months ago in another randomised double blind controlled trial of 10 HBOT sessions for Long COVID; patients in both treatment and placebo groups improved but there was no difference between the groups.[1] These results illustrate the importance of properly designed controlled and blinded trials of HBOT in conditions where there is potential for placebo-induced cognitive overlay to influence results. The potential placebo effect of the ritual of care associated with HBOT has been previously discussed in this journal.[2]

Also in this issue are two papers pertaining to technical diving from our French colleagues. In the first they describe the results of a survey of diving practices and responses to adverse symptoms. As recently reported by the group from Finland,[3] technical divers often self-treat mild symptoms suggestive of decompression sickness without medical assessment. In the second they provide a fascinating insight into the practices of technical divers performing deep dives beyond 200 m.

Elsewhere among the original research papers, Denise Blake and colleagues describe first aid and retrievals for divers in the enormous 'catchment' of the Townsville Hyperbaric Unit, Queensland, Australia. Bridget Devaney and colleagues report on a Delphi process to derive a core outcome set for research into interventions for necrotising soft tissue infections. Maayan Manheim and colleagues report the outcomes for patients with acute acoustic trauma treated with hyperbaric oxygen. Our own group (Allocco et al.) report a randomised, blinded, controlled trial to determine whether a prior open label exposure to hypoxia can enhance ability to recognise the symptoms in a subsequent blinded hypoxic exposure. Gerald Schmitz provides a high quality assessment of infusion pump performance during use with monoplace chambers.

There are five reviews in this issue. Lachlan Barnes summarises previous descriptions of electroencephalographic changes during hyperoxia as a prelude to his work attempting to develop a real time EEG monitor to warn of impending hyperoxic seizures. Glen Katznelson and colleagues review the use of continuous glucose monitoring devices in hyperbaric chambers. Bram Querido and Thijs Wingelaar provide a very useful review of the issues for consideration around psychotic disorders and diving. Joost Meigering and colleagues discuss the principles of shared decision making around HBOT; an issue that has received almost no attention in our literature. Graham Johnson and colleagues summarise recent literature around the delivery of cardiopulmonary resuscitation in a diving bell. There are also three very interesting case reports.

I offer my congratulations to Xavier Vrijdag and Hanna van Waart on a fabulous SPUMS meeting in Bali in May. I also enjoyed the UHMS meeting in Atlanta where a highlight was joining several members of the executive team for dinner with Chris Lemmons, the involuntary star of "*The Last Breath*", and hearing his story first hand. I am looking forward to the EUBS meeting in Helsinki and diving the local flooded mines just prior to the meeting!

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Professor Simon J Mitchell
Editor, Diving and Hyperbaric Medicine

Cover photo: Green sea turtle at St Lucia, DAN/UHMS diving medicine course, May 2025. Simon Mitchell.

Original articles

Oxygen treatment and retrieval pathways of divers with diving-related conditions in Townsville, Australia: a 15-year retrospective review

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Keywords
Arterial gas embolism; Decompression sickness; First aid; Oxygen toxicity; Retrieval platform; Scuba diving; Treatment

Abstract
(Blake DF, Crowe M, Lindsay D, Turk R, Mitchell SJ, Pollock NW. Oxygen treatment and retrieval pathways of divers with diving-related conditions in Townsville, Australia: a 15-year retrospective review. Diving and Hyperbaric Medicine. 2025 30 June;55(2):79–90. doi: 10.28920/dhm55.2.79-90. PMID: 40544136.)
Introduction: First aid for injured divers includes oxygen delivery prior to definitive care. Delay to specialist assessment and/or hyperbaric oxygen treatment (HBOT) may be due to dive site remoteness and limited access to facilities. Townsville has the only hyperbaric facility along the Great Barrier Reef. Analysis of oxygen therapy and retrieval pathways of divers treated in Townsville may assist with establishing future education strategies and resource allocation.
Methods: Data were retrospectively collected on divers assessed at the Townsville hyperbaric medicine unit from November 2003 through December 2018. Demographics, dive incident location, oxygen treatment, retrieval platform and pathway, and initial disease grade were reviewed. Data are presented as frequencies and percentages.
Results: A total of 306 cases were included (184 males). Divers typically received oxygen therapy (87%, 267/305 known) prior to specialist review. The non-rebreather mask was the most frequently used (44%, 28/63) followed by in-water recompression (24%, 15/63). While 34% of the divers were retrieved from the scene (n = 104), only 11 (11%, 11/104) were retrieved directly to Townsville. Most divers initially classified as severe were retrieved from the scene (82%, 27/33), only two directly to Townsville. Fifteen cases had three retrieval legs (5%, 15/306).
Conclusions: Most injured divers received oxygen first aid and were transported to Townsville for definitive care with a variable number of retrieval stages. Continuing education of retrieval physicians should address knowledge of diving related injuries and highlight cases that may benefit from expedited transfer.

Introduction

The Great Barrier Reef (GBR) is the world's most extensive coral reef ecosystem, extending from the northern tip of Queensland, Australia to just north of Bundaberg. As one of the best-known reef systems in the world, over two million visits are made to the reef each year.[1] Midway along the coastline parallel to the reef system is located the city of Townsville. The Townsville University Hospital houses the only hyperbaric facility along the GBR, providing specialist advice and recompression/hyperbaric oxygen treatment (HBOT) for divers with decompression sickness (DCS) or arterial gas embolism (AGE) (collectively referred to as decompression illness [DCI]) on the GBR and neighbouring Pacific Islands. The next nearest hyperbaric facility is located 1,400 km south of Townsville in Brisbane. For the

purpose of this study, the term 'injured divers' refers to those with suspected DCI or another malady after a dive such as immersion pulmonary oedema thought to require review by a diving specialist. A centralised Queensland retrieval service assists with the transport of injured divers to definitive treatment, with the northern zone co-ordination centre located in Townsville. Rotary and fixed wing assets are located along the Queensland coast, including a jet in Townsville for international and long-haul retrievals (Figure 1). Referrals to the coordination centre may come directly from dive boats (skippers), the Queensland Ambulance Service (supervisors), health care facilities (nurses or doctors) or diving physicians (emergency hotlines or hyperbaric facilities). It is the job of the clinical coordinator to provide medical advice and determine the urgency, retrieval platform, and appropriate destination for injured divers.

First aid treatment for divers may include oxygen delivery while obtaining specialist advice and preparing for evacuation.[2] In relevant scenarios, surface oxygen may reduce or resolve symptoms, and hasten recovery,[3] and therefore should be initiated as soon as possible when symptoms develop, and maintained until definitive treatment can be delivered. Many dive sites are remote, requiring a variety of retrieval platforms and stages to be used in transferring injured divers to a facility capable of providing HBOT. Organising transport to a hyperbaric facility can be challenging and early advice from a diving physician can assist in appropriate patient selection, treatment options, level of urgency and destination decisions.

The aim of this retrospective review was to analyse oxygen therapy and the retrieval platform and pathways of injured divers presenting to the Townsville hyperbaric medicine unit. Mapping of the retrieval pathway will provide insight into the appropriateness of aircraft base locations and destination decisions. Analysis of pre-hospital care and retrieval pathways of these injured divers could assist with establishing future education strategies and resource allocation.

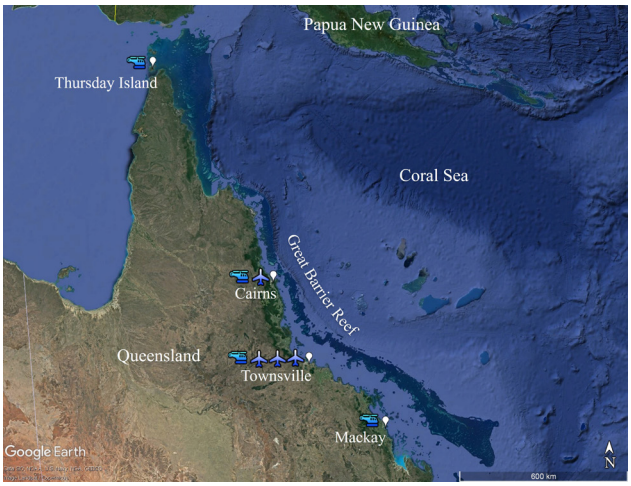
Methods

Ethics approval was granted from the Townsville Hospital and Health Service (LNR/2019/QTHS/51229) and James Cook University (H7767). This retrospective review includes all injured divers assessed and treated at the Townsville hyperbaric medicine unit (THMU) after a previous report,[4] from 4 November 2003 through 31 December 2018. Cases were identified for inclusion by reviewing yearly HMU patient logs and electronic discharge summaries.

Retrieval Services Queensland databases (Queensland neonatal emergency transport service, clinical coordination retrieval information system, and Brolga [retrieval information system]) were searched using keywords and relevant diagnoses (cerebral arterial gas embolism, decompression [including illness and sickness], drown*, snorkel*, and scuba), hyperbaric med, and offshore retrievals by rotary wing asset to identify cases. Identifying data (name, date of birth, and date of incident) were recorded so that cases could be correlated with THMU data, looking for any missed cases and ensuring no cases were duplicated.

Figure 1

Map of Queensland with northern coastal aeromedical retrieval bases and assets. The vehicle symbol (helicopter or plane) indicates the number of aeromedical assets at each base; Thursday Island to Townsville 1,000 km; Cairns to Townsville 350 km, approximately 60 min rotary flying time; Mackay to Townsville 389 km, approximately 60 min rotary flying time



Individual charts were reviewed, and data extracted to pre-formatted templates. The divers' ages in years and sex were recorded. Time of symptom onset was defined in two ways. Firstly, whether symptom onset occurred underwater during the dive or post-dive after arriving at the surface. Secondly, an actual time duration from arrival at the surface to symptom onset. Due to the unavailability of details on time to symptom onset underwater, the time of arrival at the surface was used as the starting time point for these cases. Initial disease grade was classified using a previously published scale (Table 1).[4] Treatment details were recorded including time to oxygen commencement post-symptom onset, oxygen delivery method, and change of symptoms with oxygen. Oxygen therapy duration was calculated and documentation of any symptom(s) of oxygen toxicity collected.

Retrieval details were collected including platform (boat, rotary wing, fixed wing, or road), oxygen delivery, retrieval origin and destination, and type of retrieval (primary, secondary, or tertiary). Primary retrievals were classified as retrievals from the scene of the dive incident or other prehospital location.[5] If a dive boat called for medical advice and was directed to return to shore, this was classified as a primary retrieval by boat. If a dive boat returned to shore without any urgency after completing their trip, this was not considered a retrieval. Secondary retrieval was defined as a transfer between health care facilities. This may be a second

Table 1
Initial disease severity grade using the established Townsville Hospital categories;[4] mild and moderate symptoms are invariably decompression sickness (DCS) while arterial gas embolism events would be classified as severe. It is acknowledged that these classifications do not correspond exactly with the final definition of mild DCS arising from the workshop where Reference 4 was presented, but they were historically applied to the Townsville data and so are used here

Severity	Definition
Mild	Symptomatic with no objective signs except: Minor skin rash Lymphatic DCS Sharpened Romberg test < 30 seconds
Moderate	Symptomatic with subtle signs: Impaired higher function Impaired Romberg test Subjective sensory changes Minor weakness due to pain Cutis marmorata
Severe	Symptoms threatening life or mobility: Loss of consciousness Cardiopulmonary DCS Spinal DCS

retrieval leg after a primary retrieval or the transfer between two health care facilities after self-presentation. Tertiary retrieval was defined as a third retrieval leg transfer between health care facilities. Road retrievals included ambulance, bus, or car. Assessment by a health care professional and oxygen use prior to review in the THMU were collected. In relevant cases, time to start of HBOT following symptom onset was determined. All treatments were completed in a multi-place rectangular hyperbaric chamber (Fink Engineering Pty Inc., Warana, Queensland, Australia). Clinical outcome at the end of HBOT was classified as no residual symptoms, minor residual symptoms, or moderate/major residual symptoms.[6,7]

Two researchers (DB and RT) performed the data extraction. Forms were compared and consensus reached. Individual Retrieval Services Queensland records were accessed to clarify retrieval information not apparent in the hospital medical records. All collected data were de-identified and entered into a pre-formatted Excel (Microsoft Office 365, Redmond, Washington, USA) worksheet.

ANALYSIS

Data are presented using frequencies and percentages for categorical variables, and medians and interquartile range [IQR] for continuous variables as all data were non-normally distributed as assessed using Shapiro-Wilk tests. The Mann-Whitney U test was used for analysis comparing times for oxygen commencement between divers with symptom onset during versus symptom onset after the dive and for oxygen duration in divers with and without symptoms of oxygen toxicity. The Kruskal-Wallis test was used for analysis comparing times for oxygen commencement for divers treated at the scene by initial disease grade. Spearman rank-order correlations were computed to examine the relationship between time to symptom onset and time to oxygen commencement. Pairwise two-tailed z tests were used for *post hoc* analysis with Bonferroni correction. Significance was accepted as $P < 0.05$. The Statistical Package for the Social Sciences version 28.0.0 (SPSS®, IBM® Corporation, Armonk, New York, USA) was used for analysis.

Retrieval data including mode of retrieval, and primary, secondary, or tertiary retrieval destinations were collected. Geospatial mapping of the retrieval pathway was completed by entering latitudes and longitudes or names of dive sites and retrieval destinations into Google Earth Pro (NOAA, 2015). Sites and destination placemarks were visually verified (zooming in) on the map and adjustments made to coordinates to ensure appropriate positioning. Retrieval destination appropriateness for divers with severe initial disease grade and primary retrievals was examined. Retrieval pathways of divers with three retrieval legs were evaluated for appropriateness. Initial disease severity, diagnosis, need for HBOT, and distance from Townsville were used to assess appropriateness of primary destination and staging. Identified cases were reviewed by two diving medicine and retrieval experts with extensive knowledge of the geographic area and capabilities of retrieval assets and facilities. As data were missing from some medical records, the *n* presented throughout the results denotes the number of records for which the information was documented.

Results

A total of 310 injured divers were identified during the study period with retrieval pathways as long as 3,200 km. Four divers were excluded as their paper medical records had been destroyed following national medical record guidelines, leaving 306 divers for the analysis. The median age of the divers was 29 [interquartile range 24, 35] years and 60% were male. Most were recreational divers (72%, 187/260) performing no-decompression diving. Other diver demographics and dive incident details for this cohort have been published elsewhere.[7]

Most symptoms started after the incident dive (90%, 275/306). Median time to symptom onset was 60 [10, 360] min in the divers whose symptoms commenced after surfacing and shorter for divers receiving oxygen at the scene (20 [5, 90] min), and for those primarily retrieved (15 [2, 90] min). Time to symptom onset was shorter in divers with severe initial disease grade (details previously published).[7]

Most of the injured divers received oxygen therapy (87%, 267/305) prior to assessment by a diving physician. Of the divers with a final diagnosis of DCI, 89% (245/274) received oxygen therapy. A high percentage of divers treated at the scene were given oxygen (Table 2). Other treatments included analgesia, antiemetics, and fluid administration. There was poor documentation of the type of oxygen delivery system used, but of those with documentation the non-rebreather mask was most often used with demand valve systems being less common. Most divers had partial or full relief of their symptoms with oxygen treatment (Table 2). In cases where the oxygen delivery method and change in symptoms were documented, symptom improvement was seen in 81% (35/43) of divers breathing surface oxygen and in 78% (7/9) divers receiving in-water recompression (IWR) on oxygen. Further evaluation comparing oxygen delivery device and change of symptoms could not be completed due to incomplete data.

The vast majority (14/15) of divers who received IWR were conducting occupational dives. The majority conducted their dives using a surface-supplied breathing system (9/15). Two were using open-circuit scuba and four had no documentation of the breathing system used. All IWR was done using surface-supplied systems (Table 2). Most divers undertaking IWR (9/15) were in remote locations 500 to 1,000 km from Townsville, three were diving 350 km from Townsville, one was diving 200 km from Townsville and two dive sites were unknown.

Of the divers who had symptom onset during the dive, most (71%, 22/31) received oxygen at the scene. Divers with symptom onset during the incident dive had significantly shorter times to oxygen commencement than divers with symptom onset post-dive (Table 3). Those who had severe initial disease grade and received oxygen at the scene had shorter times to oxygen onset than those with mild initial disease grade (Table 3). The Spearman rho showed a significant positive correlation between time of symptom onset and time of oxygen start ($r_s = 0.4$, $n = 225$, $P < 0.001$). Duration of oxygen delivery for the group of injured divers is presented in Table 3. Divers with symptom onset during dives did not have significantly longer oxygen treatment durations than those with symptom onset post-dive ($P = 0.85$). Divers with oxygen treatment started at the scene had significantly longer oxygen duration than those who did not have oxygen started at the scene (Table 3). Only 35% (46/132) of the injured divers received continuous oxygen.

The presence or absence of oxygen toxicity was infrequently documented. Of those cases with documentation ($n = 41$), 88% described oxygen toxicity. Most of the cases were mild pulmonary oxygen toxicity (92%) with only three cases of possible central nervous system (CNS) toxicity (one nausea, one lip tingling, and one metallic taste). Pulmonary oxygen toxicity was documented in seven cases while breathing normobaric oxygen (two during fixed wing retrievals), in 15 cases while during HBOT and in 11 cases the timing was undetermined. The three cases of possible central nervous system oxygen toxicity were all during HBOT. The cases of oxygen toxicity during HBOT were all given air breaks and treatments continued. Pre-HBOT oxygen delivery duration was significantly longer in the oxygen toxicity group (Table 3). Three divers with oxygen toxicity were international retrievals, one had received HBOT on a Pacific Island prior to the transfer to Townsville. The removal of the oxygen mask by the diver was not recognised as oxygen toxicity by the retrieval team and the diver was sedated to enforce the wearing of the mask. Only one diver who had received IWR on oxygen had possible CNS oxygen toxicity (nausea). Of the divers who received continuous oxygen ($n = 46$), six had documented symptoms of pulmonary oxygen toxicity and two had documentation of no symptoms of oxygen toxicity. The median duration of oxygen delivery in the group who had continuous oxygen and symptoms of oxygen toxicity was 7:20 [3:56, 10:29] h:min.

Of the injured divers primarily retrieved, the majority had oxygen delivered during the retrieval (Table 4). Of the divers who had a secondary retrieval, most had oxygen delivered during the aeromedical retrieval (rotary wing = 93%, 14/15, fixed wing = 91%, 84/92 [eight cases missing data]) (Table 5). The rotary wing secondary retrieval where the

Table 2

Pre-hospital treatment of injured divers; [a]treatment included fluids, medications, and oxygen; [b]*n* = number of divers for which the information was documented; CPR – cardiopulmonary resuscitation; ROSC – return of spontaneous circulation

Parameter	*n* (%)
Treatment[a] at scene *n* = 304[b]	155 (51)
Oxygen at scene *n* = 155[b]	143 (92)
Other (CPR, ROSC then oxygen)	1 (< 1)
Initial disease grade mild *n* = 216[b]	82 (38)
Initial disease grade moderate *n* = 57[b]	37 (65)
Initial disease grade severe *n* = 33[b]	24 (73)
Oxygen delivery method *n* = 63[b]	
Non-rebreather mask	28 (44)
In-water recompression (IWR)	15 (24)
IWR oxygen	12 (19)
IWR air	3 (5)
Demand valve	13 (21)
Bag valve mask	4 (6)
Simple face mask	3 (5)
Change of symptoms with oxygen *n* = 124[b]	
Partial relief	86 (69)
Full relief	15 (12)
No relief	17 (14)
Worse	3 (2)
Relapsing	2 (2)

Table 3

Time to and total duration of oxygen delivery pre-hyperbaric oxygen therapy post incident dive; *$P < 0.001$ Mann-Whitney U test; †$P = 0.006$ Mann-Whitney U test; ¥$P = 0.017$ Kruskal-Wallis test

Parameter	Median [IQR] h:min
Time to oxygen start post-symptom onset, *n* = 254	4:00 [0:30, 24:27]
Time to oxygen start where symptom onset was post-dive, *n* = 227	5:00 [0:30, 26:30]*
Time to oxygen start where symptom onset was during dive, *n* = 27	00:15 [0:10, 2:30]*
Time to oxygen start post-symptom onset where treated at scene, *n* = 132/143	00:30 [0:10, 2:00]
Mild initial disease grade, *n* = 74/82	00:30 [0:15, 2:30]¥
Moderate initial disease grade, *n* = 35/37	00:20 [0:10, 1:58]
Severe initial disease grade, *n* = 23/24	00:10 [0:05, 00:30]¥
Duration of oxygen delivery, *n* = 256	10:00 [6:00, 16:14]
Duration of oxygen delivery where symptom onset was during dive *n* = 27	9:05 [7:30, 12:05]
Duration of oxygen delivery where oxygen was started at scene *n* = 145	11:25 [6:55, 18:11]*
Duration of oxygen delivery where oxygen was NOT started at scene *n* = 109	8:00 [4:07, 13:17]*
Duration of oxygen delivery in divers with no oxygen toxicity or no documentation of oxygen toxicity *n* = 221	9:03 [5:07, 15:35]†
Duration of oxygen delivery in divers with documentation of oxygen toxicity *n* = 35	14:16 [9:06, 18:05]†

Table 4

Primary retrieval details; QAS – Queensland ambulance service; [a]*n* = number of divers for which the information was documented; [b]World Health Organization definition

Parameter	*n* (%)
Primary retrieval, *n* = 306	104 (34)
Oxygen during primary retrieval *n* = 81[a]	77 (95)
Primary retrieval initial disease grade *n* = 104	
Mild	42 (40)
Moderate	35 (34)
Severe	27 (26)
Primary retrieval platform *n* = 104	
Boat	52 (50)
Rotary wing	26 (25)
Road (QAS = 19, self = 2)	21 (20)
Fixed wing	5 (5)
Primary retrieval destination *n* = 104	
Cairns	37 (35)
Townsville	11 (10)
Torres Strait and Pacific Is[b]	10 (9)
Lizard Island	9 (9)
Cooktown	8 (8)
Alva Beach/Ayr	7 (7)
Whitsunday islands/Proserpine	7 (7)
Lockhart River	4 (4)
Mossman/Port Douglas	4 (4)
Gladstone	2 (2)
Mackay	1 (1)
Other	4 (4)

Table 5

Secondary retrieval details; QAS-Queensland ambulance service; [a]*n* = number of divers for which the information was documented; [b]World Health Organization definition

Parameter	*n* (%)
Secondary retrieval *n* = 306	236 (77)
Oxygen during secondary retrieval *n* = 115[a]	111 (97)
Secondary retrieval platform *n* = 235	
Road (QAS = 20, bus = 38, self = 53)	127 (54)
Fixed wing	92 (39)
Rotary wing	15 (6)
Boat	1 (< 1)
Secondary retrieval destination *n* = 236	
Townsville	211 (89)
Cairns	19 (4)
Torres strait and Pacific islands[b]	8 (3)
Whitsunday islands/Proserpine	2 (1)
Alva beach/Ayr	1 (< 1)
Mackay	1 (< 1)
Mossman/Port Douglas	1 (< 1)
Other	3 (1)

Table 6
Tertiary retrieval details; [a]*n* = number of divers for which the information was documented

Parameter	*n* (%)
Tertiary retrieval *n* = 306	24 (8)
Oxygen during tertiary retrieval *n* = 20[a]	18 (90)
Tertiary retrieval platform *n* = 24	
Fixed wing	18 (75)
Rotary wing	4 (17)
Road (bus = 2)	2 (8)
Tertiary retrieval destination *n* = 24	
Townsville	24 (100)

diver did not receive oxygen was completed using an Australian military helicopter. The pattern was similar for tertiary retrievals with 90% of the divers retrieved aeromedically receiving oxygen (Table 6).

Most of the injured divers were assessed by a health care professional prior to arrival at the THMU (95%, 290/306). This included physicians diving on the dive boat, primary retrieval physicians, nurses in primary health care centres, general practitioners, and emergency physicians. Just under half (49%, 151/306) of the injured divers had at least two medical assessments prior to review by a hyperbaric physician, 14% (42/306) had three medical assessments and 2% (7/306) had four medical assessments. A high percentage of the divers received oxygen at these visits (78% [199/256], 86% [123/143], 80% [32/40] and 50% [3/6] respectively).

The most common primary retrieval destination was Cairns (Figure 1), and the most common retrieval platform was a boat (Table 4). The 'other' destination category consisted of different ports along the Queensland coast (Magnetic Island, Bowen and Gympie) as well as an international site (Indonesia) (Table 4). More than three-quarters of the injured divers required a secondary retrieval. Road transfer was the most common modality with Townsville the most frequent destination (Table 5). The 'other' destination category included Brisbane, Magnetic Island, and Julia Creek (Table 5). Only 24 injured divers had a tertiary retrieval, all to Townsville (Table 6).

The majority of the injured divers initially classified as severe (82%, 27/33) were retrieved from the scene (Table 4). The six divers not retrieved from the scene had a variety of reasons for not being primarily retrieved. Two had symptom onset during flights post diving, one went back to their accommodation and symptoms worsened, one presented to a general practitioner after returning from the dive trip, one self-transported to a hospital in Papua New Guinea, and for one diver there were two doctors on the dive boat who provided care while the boat steamed back to shore. Eighteen (18/27) of these severe cases were within a radius where they could have been primarily retrieved directly to Townsville. Only two were retrieved directly to

Figure 2
Retrieval pathways, assets, and destinations of injured divers with severe initial disease grade in the Cairns area. The vehicle symbol describes the asset used (helicopter, boat, ambulance, or plane), and the number of symbols represents the number of divers transported using that asset

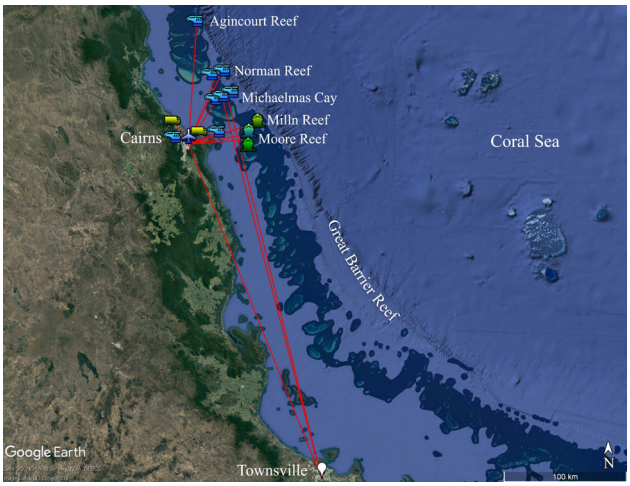


Figure 3
Retrieval pathways, assets, and destinations of injured divers with severe initial disease grade in the Townsville area. The vehicle symbol describes the asset used (helicopter, boat, or ambulance), and the number of symbols represents the number of divers transported using that asset

Townsville (Figure 2). Three went to Ayr hospital (nearest facility) initially and then were transferred to Townsville (Figure 3). Three in the Whitsunday area went by boat to a nearby island, one was then transferred to Mackay hospital (nearest facility) and then onto Townsville, and two were transferred directly to Townville (Figure 4). Ten cases were primarily retrieved to Cairns and then transferred to Townsville, eight by fixed wing and two by rotary wing (Figure 2). Of these 18 severe cases, 14 had a final diagnosis of cerebral AGE, three immersion pulmonary oedema, and one central neurological DCS.

There were 11 primary retrievals direct to Townsville (Figure 5), three were international retrievals direct from

Figure 4
Retrieval pathways, assets, and destinations of injured divers with severe initial disease grade in the Whitsunday area. The vehicle symbol describes the asset used (helicopter, boat, or plane), and the number of symbols represents the number of divers transported using that asset

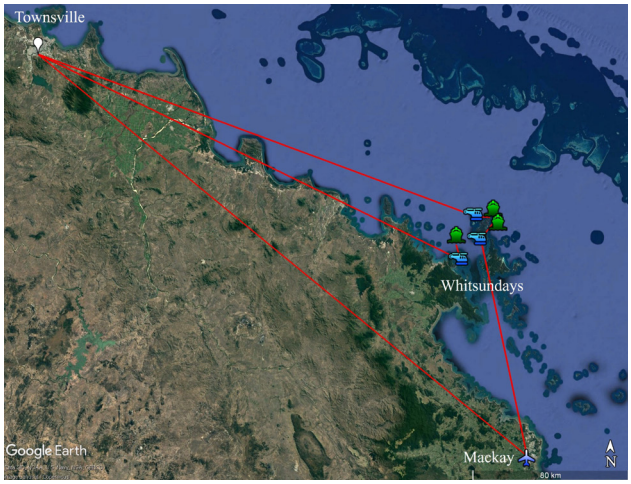
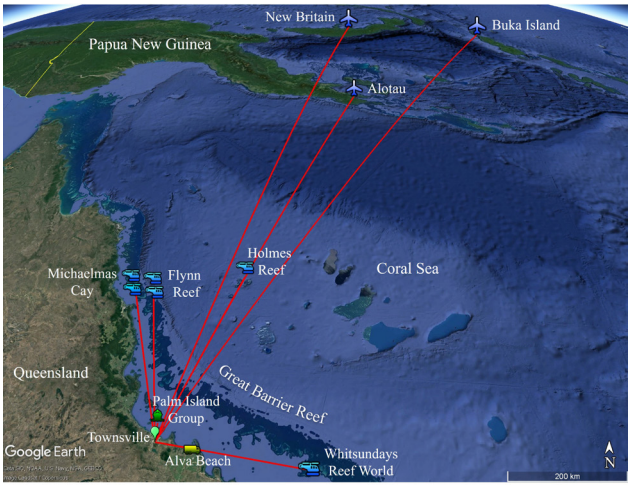


Figure 5
Retrieval pathways and assets of injured divers primarily retrieved to Townsville. The vehicle symbol describes the asset used (helicopter, boat, ambulance, or plane), and the number of symbols represents the number of divers transported using that asset



Papua New Guinea. The other local cases included seven divers with severe neurological symptoms and one diver with severe respiratory distress. Three of the divers did not receive HBOT. Their final diagnoses were cerebrovascular accident, migraine, and immersion pulmonary oedema. Three divers had a final diagnosis of cerebral AGE, one peripheral neurological DCS, and one vestibular DCS. Of the 93 additional primary retrievals, four of the divers had moderate to severe initial disease grades, were transported during daylight, and were within a radius where they could have been transferred directly to Townsville. All the other cases required an initial destination other than Townsville due to severity or distance, needing staging, stabilisation, or treatment at the closest medical facility. Time to start of HBOT was shorter for divers that were primarily retrieved (Table 7).

There were 15 cases with three retrieval legs (Figure 6). Four cases were international retrievals. Two of these cases were treated on a Pacific Island and then transferred to Townsville for further treatment. The 11 Australian cases were retrieved from the dive site by boat, then onward travel for medical review and then onto Townsville for HBOT. Six of these 11 cases were identified as inappropriately staged during the retrieval process. Three of these cases were cerebral AGE, one spinal DCS and two divers were doing decompression diving and had moderate symptoms of DCS.

Most divers had a good clinical outcome and no treated diver died.[7] A higher percentage of divers with moderate (98%, 56/57) or severe (97%, 32/33) initial disease grade received oxygen therapy prior to HBOT than those with mild initial disease grade (83%, 179/216). Divers with moderate or severe initial disease more often had oxygen treatment commenced at the scene of the incident (Table 2). All divers with severe initial disease were retrieved ($n = 33$) and more frequently primarily retrieved (82%, 27/33) than those with mild (19%, 42/216) or moderate (61%, 35/57) initial disease (Table 4).

Discussion

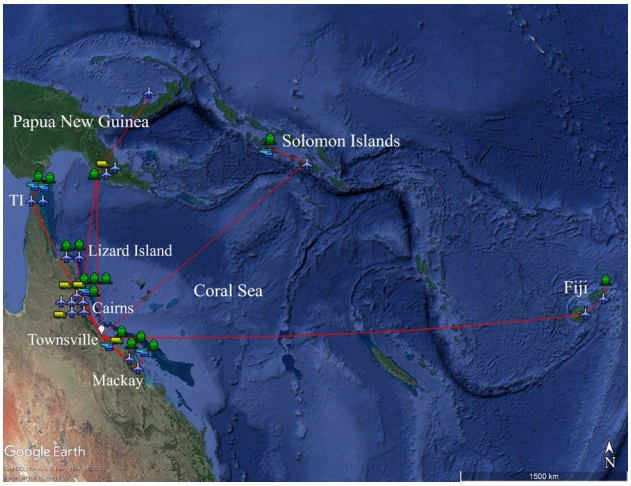
Townsville is strategically located on the east coast of Queensland, providing hyperbaric services to divers on the GBR and neighbouring Pacific Islands. Covering such a large area, there is often a necessity to transport injured divers a great distance to receive HBOT. Most divers in this study received oxygen treatment while awaiting transport and were appropriately staged or primarily transported to Townsville for definitive care.

A large percentage of the injured divers treated in Townsville received oxygen either at the scene, during transport, or at a health care professional visit. Oxygen delivery has long been recommended as a first aid measure for injured divers.[8] Divers Alert Network (DAN) created an oxygen first aid training program in 1991 focusing on the delivery of oxygen in the event of a diving emergency.[9] This program was modified to meet Australian guidelines and introduced in Australia in 1994.[10] Unfortunately, data from calls to DAN Asia-Pacific in 2018 showed only 24% of injured divers received oxygen first aid.[11] This low level of oxygen administration reported by DAN is consistent with other published international studies,[12–17] but unexpected since our incidence of oxygen treatment in North Queensland was much higher. The higher incidence of oxygen delivery in our study may be due to Queensland workplace health and safety code of practice for oxygen use in recreational diving originally published in 1992 (Workplace health and safety Queensland, personal communication, 2023) requiring diving first aid qualifications for all dive masters and instructors and the availability of oxygen at all dive sites.

Table 7
Time to hyperbaric oxygen therapy (HBOT) from time of symptom onset

Parameter	Median [IQR] h:min
Time to HBOT for all injured divers *n* = 283	38:51 [22:11, 69:15]
Time to HBOT for all divers primarily retrieved *n* = 97	21:40 [10:30, 38:10]
Time to HBOT for divers NOT primarily retrieved to Townsville *n* = 89	21:11 [10:43, 35:24]
Time to HBOT for divers primarily retrieved to Townsville *n* = 8	27:05 [5:43, 48:45]

Figure 6
Retrieval pathways and assets of injured divers having three retrieval legs. The vehicle symbol describes the asset used (helicopter, boat, ambulance, or plane), and the number of symbols represents the number of divers transported using that asset; TI – Thursday Island



Although the incidence of oxygen treatment in our study was high, documentation of oxygen delivery device and flow rate was often missing. This appears to be consistent with other studies. One study examining the self-treatment of technical divers experiencing mild symptoms of DCI found a high percentage of divers hydrated orally (74%) and rested (70%) but only a small percentage breathed oxygen (21%) with no documentation of the delivery device used.[18] One paper stated that no divers received oxygen prior to HBOT[19] and one did not mention oxygen in their description of pre-hospital treatment, though they commented on fluids and acetylsalicylic acid administration.[20] One study stated that oxygen was "*routinely administered*"[21] and two others that oxygen was administered during transport[22,23] but details on delivery device and flow rate was not provided.[22] One small study only mentioned in the limitations that most divers received oxygen, stating that there were no data available on the inspired fraction or duration of therapy.[24] In fact, only one of these studies commented on the type of oxygen delivery device used.[23] The current recommendation is to provide the highest possible concentration of oxygen.[2,8]

Similar to previous reports,[3,23] the non-rebreather mask was the most frequently used device in our cohort although the oxygen flow rate was infrequently documented. To provide a high level of oxygen to the tissues, a non-rebreather mask may require a flow rate of 15 L·min^{-1}.[25] However, a high flow rate will compromise the duration of available oxygen which is of relevance when treatment occurs at remote dive sites.

After the non-rebreather mask, IWR (breathing air or oxygen) was the second most frequently documented form of oxygen treatment at the scene. IWR breathing oxygen is an established, albeit not universally accepted, strategy for treating DCI,[26] especially at remote dive sites when access to a recompression chamber is not readily available.[27] This procedure is not without risks and requires special equipment and training, with a clear protocol in place prior to use.[28] Indeed, all the divers in our study who performed IWR used surface-supplied breathing systems and all but one had been performing occupational dives. The use of a surface-supplied breathing system suggests that the expertise, equipment, and processes were in place to perform IWR, however, some of the IWR procedures were conducted using air which is not recommended.[27] Despite this, the indication for performing IWR or the protocol used was not documented in the medical chart. Most of the dives were conducted in remote areas but four were conducted in areas reasonably close to Townsville (< 400 km). Given the limited details recorded, further comment on the use of IWR in these cases cannot be made.

Our cohort of injured divers received oxygen for a considerably longer time than previously reported data,[3] but the administration was not necessarily continuous. Oxygen delivery duration is often not stipulated in recommendations.[2] When reported, the recommended durations are often vaguely written and vary from several hours,[29] even if relief of symptoms, to until arrival at a recompression facility.[30,31] Other recommendations include giving oxygen for four to five hours without breaks depending on the time to the chamber,[32] or giving five min air breaks every 30 min if time to recompression is likely to be greater than four hours.[33] A more concrete recommendation is the administration of as close to 100% oxygen as possible for 12 hours with 15 min breaks every four hours.[34] This recommendation is based

on the risk of pulmonary oxygen toxicity as an estimate of the maximum amount of time oxygen can be safely breathed rather than the dose of oxygen an injured diver requires.

Oxygen toxicity is a risk for injured divers breathing oxygen. Though poorly documented, 36 divers in our study appeared to demonstrate some level of oxygen toxicity, all but three being pulmonary toxicity, and all with long exposures. Divers with oxygen toxicity had a median oxygen duration (Table 3) greater than the recommended 12 hours.[34,35] Only a small number of the divers in this work received continuous oxygen delivery, with the majority suffering from oxygen toxicity not having had continuous oxygen. Pulmonary oxygen toxicity is a concern from a patient comfort perspective, reversible in its early stages and extremely unlikely to cause harm in this group of patients. If symptoms of pulmonary oxygen toxicity occur, discussing the benefits and risks of ongoing oxygen therapy with an experienced diving physician is warranted. Future guidelines on pre-hospital management of DCI should provide recommendations on the duration of oxygen delivery and address the possible occurrence of pulmonary oxygen toxicity especially during long retrievals or onward transfer after receiving HBOT at another facility.

Air breaks in oxygen breathing during treatment at the scene or during retrievals were for logistical reasons rather than for scheduled air breaks or limited oxygen supplies. Air breaks (15 min off oxygen every four hours) are commonly recommended for injured divers receiving oxygen overnight awaiting HBOT, though this was infrequently documented. Air breaks have been recommended for divers receiving oxygen for longer than 12 hours.[34] This recommendation is thought to reduce the risk of pulmonary oxygen toxicity as well as giving the diver a break from wearing a mask, allowing them to eat and drink. It is interesting that the research supporting the recommendation of only providing oxygen for 12 hours also showed that a 15 min air break every four hours did not decrease the risk of pulmonary oxygen toxicity even though it did decrease its severity.[35] In our experience of long evacuations, clinically significant pulmonary oxygen toxicity seems extremely rare and it is not clear whether potential compromise of DCI treatment by imposing air breaks is justified, or at what time point in a long evacuation this should occur. Further research would be necessary to establish answers to these questions which seem relevant to only a small minority of cases.

Aeromedical assets are frequently used to transfer injured divers as dive sites can be remote and hyperbaric centres few and far between.[20] In our study, rotary wing assets were more often used for the primary versus other retrieval legs and for at least one retrieval leg in 55% (18/33) of divers classified as having severe initial disease. Other studies reported 16%[36] and 39%[6] of divers retrieved by helicopter. Comparable with our results, asset choice can be for geographical considerations[14] or for severity.[6] Helicopters often provide the most timely and efficient means of transfer[14] and may be chosen independent of illness severity.[37] Routes chosen for helicopter retrievals were at the lowest altitude possible. It has been suggested that the vibration generated from rotary aircraft may worsen symptoms of DCS, but there is no published research to support this premise.[38] Even though in our study rotary wing assets were more often used for the primary retrieval leg than for other retrieval legs, due to the location of the dive sites, boat retrieval predominated as the choice for primary retrieval platform.

Logistic difficulties often result in a variety of assets being tasked to transport injured divers to definitive care.[14,39] Previous examination of divers with mild or moderate DCI treated at our facility found that divers transported by surface transport, without oxygen or fluids, had a similar outcome following HBOT to those retrieved using an aeromedical asset.[4] Road retrieval predominated for the secondary retrieval leg in the current study, as it has been the continued practice to have divers with mild symptoms travel to Townsville either by bus or private vehicle. This leaves aeromedical assets available for the transfer of acutely injured patients. Most of these divers had been assessed by a healthcare practitioner (n = 88/91, 97%) and discussed with the hyperbaric medicine physician on-call prior to the decision of suitability for road transfer.

The THMU provides care and support to injured divers along the Queensland coast from Rockhampton north to the Torres Strait Islands as well for some Pacific Islands. Providing coverage for this large area often leads to the need for staging of injured divers at various sites during their retrieval to Townsville. Retrieval destination and asset choice are determined at the time of referral based on the diver's clinical condition, location, asset and staff availability, time of day, weather conditions, and competing tasks. Perhaps not surprisingly, some of our divers required three retrieval legs using different assets. The majority of the current cases that required three retrieval legs were due to these geographical constraints. However, four divers likely should have come to Townsville on their second retrieval leg and two remained at their secondary destination overnight and likely should have been transferred earlier. Similar studies described one asset per retrieval[6,14,36] or only focused on one type of retrieval asset.[23]

Despite the multiple factors playing a role in retrieval decisions, few cases were identified as being inappropriately transported. Of the severe cases, one diver with immersion pulmonary oedema did not require further transfer to Townsville, and one diver with a final diagnosis of cerebral AGE should have primarily gone to Townsville. Four primarily retrieved cases were identified that could have been directly retrieved to Townsville. As described above, six cases with three retrieval legs were inappropriately staged. Decisions on the timeliness of retrieval to Townsville for assessment and possible HBOT is often jointly made by the hyperbaric physician and the clinical coordinator. Documentation of this decision-making process could allow

for future analysis and the development of a clinical decision support tool for determining the urgency of the retrieval and the appropriate destination.[37]

LIMITATIONS

This study was retrospective and limited by incomplete records and missing data. Poor documentation of type of oxygen mask used, gas flow rates, starting and stopping times, air breaks, and change in symptoms limited the ability to assess the efficacy of these devices. Documentation of the referral to the THMU and the decision-making process about the retrieval was poor. There was no documentation on tasking deliberations or resource availability. With this decision-making information unavailable, determination of the appropriateness of destination and retrieval timeliness was decided based on the available medical and retrieval notes.

RECOMMENDATIONS

Improved documentation by all persons involved in the care of injured divers, from those providing first aid to diving physicians, in the area of oxygen therapy would allow for a more comprehensive assessment of the effectiveness of the treatment, problems with delivery, and side effects. A prospective study would improve acquisition of this data. Information to be collected could include: type of oxygen delivery system used, gas flow rate, time oxygen started and stopped, IWR protocols used, reasons for stopping, air breaks, change in symptoms of DCI, or any symptoms of oxygen toxicity. Oxygen therapy data should be collected for the whole patient journey, starting from on scene care through completion of treatment.

Despite this need for further research, pre-hospital care and transport of injured divers is well coordinated in Queensland. However, it is important for first responders to obtain early expert advice from an experienced diving physician to assist with decisions regarding on site treatment, retrieval urgency and platform selection as well as appropriate destination. Not all injured divers require recompression, such as divers with immersion pulmonary oedema or divers with mild DCS as recently defined,[28] and can be managed at local facilities with advice from diving experts. Early consultation with experts in the field will ensure that injured divers receive timely treatment at the most appropriate facility reserving aeromedical assets for those needing urgent transport.

Conclusions

A high proportion of injured divers received oxygen treatment while awaiting transport and were appropriately staged or primarily transported to Townsville for definitive care. In-water recompression was used in several cases of occupational diving. Pulmonary oxygen toxicity is a concern when providing extended multi-hour durations of oxygen therapy. The use of many different retrieval assets and legs may be necessary when dive sites are remote and distances to a hyperbaric facility are vast. Continuing education for retrieval physicians should address knowledge of diving related injuries and highlight cases that may benefit from expedited transfer. Improved documentation by all carers of injured divers may enhance the ability to understand the impact of oxygen therapy on divers' outcomes.

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Acknowledgements

Professor Peter A Leggat contributed substantially to the design of this study but died before the manuscript preparation. Alejandro 'Uso' Usobiaga Fabian for assistance with the geospatial mapping. Maps generated by Google Earth Pro, Maxar Technologies. Retrieval Services Queensland for providing data and access to medical records. Dr Clinton R Gibbs for reviewing cases for appropriateness of primary destination and staging. This project is part of a larger group of research studies for a doctoral thesis: "*Pre-hospital treatment of injured divers: oxygen delivery and retrieval considerations*."

Conflicts of interest and funding

This study was funded by a grant from the Australasian Diving Safety Foundation (ADSF). Professors Mitchell and Pollock are members of the editorial board of *Diving and Hyperbaric Medicine* but were not involved in the peer review or publication decision-making process for this article.

Submitted: 15 January 2025
Accepted after revision: 28 February 2025

Core outcome set for research in necrotising soft tissue infection patients: an international, multidisciplinary, modified Delphi consensus study

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Keywords
Gas gangrene; Hyperbaric oxygen treatment; Hyperbaric research; Intensive care medicine; Necrotising infections

Abstract
(Devaney B, Wackett JPC, Ma N, Nguyen A, Yogaraj V, Hedetoft M, Hyldegaard O, Burrell A, Mitra B. Core outcome set for research in necrotising soft tissue infection patients: an international, multidisciplinary, modified delphi consensus study. Diving and Hyperbaric Medicine. 2025 30 June;55(2):91–103. doi: 10.28920/dhm55.2.91-103. PMID: 40544137.)
Introduction: Necrotising soft tissue infections (NSTI) are serious infections associated with considerable morbidity and mortality. Heterogeneity of outcome reporting in the NSTI literature precludes the synthesis of high-quality evidence. There is substantial interest in studying the efficacy of hyperbaric oxygen treatment as an adjunctive treatment in NSTI. The aim of this study was to develop a set of core outcome measures for future trials evaluating interventions for NSTI.
Methods: A modified Delphi consensus method was used to conduct a three-round survey of a diverse panel of clinicians and researchers with expertise in NSTI, and patients with lived experience of NSTI. Participants rated the preliminary list of outcomes using a 9-point scale from 1 (least important) to 9 (most critical). The *a priori* definition of consensus required outcomes to be rated critical (score ≥ 7) by ≥ 70% of participants, and not important (score ≤ 3) by ≤ 15% of participants. After meeting consensus, outcomes were removed from subsequent rounds. Outcomes that did not meet consensus were included in subsequent rounds.
Results: Ninety-eight participants from 14 countries registered and 86%, 69% and 57% responded for each round, respectively. Outcome measures quantifying five core areas achieved consensus: Death, surgical procedures of debridements and amputations, functional outcome among survivors, measures of sepsis, including septic shock and organ dysfunction and resource use measured through length of hospital and intensive care unit stay.
Conclusions: This initial core set of outcome measures will be evaluated and optimised and can harmonise outcome measurements for investigations among patients with NSTI.

Introduction

Necrotising soft tissue infections (NSTI) are a group of rapidly progressive infections that can result in the destruction of skin, fat, fascia and muscle tissue and encompasses necrotising fasciitis, Fournier's gangrene, necrotising cellulitis and necrotising myonecrosis.[1] NSTIs are associated with considerable rates of morbidity and mortality, with a large Danish registry-based study demonstrating all-cause mortality rates of 19% at 30 days, 25% at 90 days and 30% at one year.[2] The cornerstones of treatment include urgent surgical debridement, broad-spectrum antibiotics and organ support in intensive care. Adjuvant therapies including hyperbaric oxygen treatment and intravenous immunoglobulin administration may also be used.[1]

A recent systematic review highlighted significant heterogeneity of outcomes reported in NSTI literature, with 311 different outcomes identified.[3] This profound heterogeneity precludes the synthesis of data for meta-analysis and the generation of high-quality evidence to assess interventions for NSTI. There has not previously been any standardisation or consensus amongst stakeholders regarding outcome measures that should be collected and reported in studies evaluating potential interventions for NSTI.[4] There is an urgent need to develop a core outcome set (COS) for use in all future clinical NSTI research.

A COS is a standardised set of outcomes that should be measured and reported on, as a minimum, in clinical trials of a specific condition or area of healthcare.[5] Standardisation of reportable outcomes improves the quality of trials and uniformity of data across centres, enabling critical comparison and analysis to improve research efficiency.[5] The use of a standardised COS also limits reporting bias which may occur via variable inclusion of selected outcomes, an issue that may be particularly relevant to NSTI research given the rarity of disease, and the variability in treatment practices.[1,5,6] Importantly, the use of standardised outcome sets enables higher quality evidence to substantiate and support the clinicians' choice of therapeutic interventions.

Hyperbaric oxygen treatment (HBOT) has been used in the treatment of NSTI since the 1960's and multiple observational studies indicate that this intervention strongly correlates with improved survival, particularly in the most severely unwell NSTI patients.[6,7] However, synthesis and interpretation of existing studies have been limited by marked heterogeneity of outcomes measured and uncertainty remains amongst the expert medical community regarding the role of HBOT for NSTI; uptake of this intervention is therefore highly variable and the establishment of a COS for NSTI would provide clarification and, hopefully, greater consensus on the utility of HBOT for NSTI.[3,6,8,9]

The objective of this study was to develop a COS for NSTI to be added to the Core Outcome Measures in Effectiveness Trials (COMET) database, by using a modified Delphi process to establish consensus across a group of key stakeholders. The aim is to improve consistency of reporting, reduce risk of reporting bias and enable higher quality meta-analyses. Ultimately, standardisation of core outcome reporting will enable more precise evaluation of treatment interventions and medical treatment decisions in the management of NSTI.

Methods

We obtained institutional ethics approval (447/23) from the Alfred Health Ethics Committee. Panel members were invited and presented with written information regarding the proposed study. Consent was implied by those who responded to the invitation and registered their details electronically.

STUDY DESIGN

We conducted a three-round modified Delphi consensus process to identify a recommended core outcome set for NSTI. The Delphi technique is widely used and allows for anonymous expert input while ensuring equal consideration of all opinions and synthesis of collective opinion on an international scale.[5,9,10] The study was registered *a priori* with the Core Outcome Measures in Effectiveness Trials (COMET; www.comet-initiative.org/delphimanager) Initiative. The surveys were hosted online via the COMET Initiative's DelphiManager software from the University of Liverpool, and sent to international clinicians and researchers with expertise in NSTI, as well as to patients with lived experience of NSTI and their caregivers.

The outcomes assessed encompass five core areas; death, physiological/clinical, life impact, resource use, and adverse events consistent with the taxonomy and outcome classification recommended by Dodd, et al.[9,11] Outcome measures were listed by core areas and presented sequentially in the survey. Survey respondents were a diverse panel of experts, fully anonymised and provided with key summarised information after each round. The proposed Delphi protocol aligned with the Core Outcome Set-STAndards for Development (COS-STAD) recommendations and was reviewed by Delphi experts and international experts in NSTI.[5,12]

PARTICIPANT RECRUITMENT

An expert Delphi panel was established to determine the COS for NSTI. A combined sampling strategy was used to recruit expert panel members to achieve a diverse representation of relevant stakeholders; clinicians, researchers and NSTI survivors or caregivers. A non-probability purposive sample of participants was recruited for the study. Given the variable global incidence and impact of NSTI and the objective to develop a COS of international applicability and validity, local and international researchers and clinicians were invited.[1,12] Researchers were identified from established NSTI research networks such as INFECT study group (an International and Multidisciplinary Project on Necrotizing Soft Tissue Infections, with 14 multidisciplinary partners from across Europe, Israel and the USA) the Collaborative Hyperbaric Medicine and Extreme Environment Research Association (CHYMAERA) network's necrotising infections subcommittee, and corresponding authors of peer-reviewed NSTI studies identified via systematic review. To encourage representation and participation from low- and middle-income countries, we invited NSTI stakeholders from different countries and the National Institute for Health and Care Research Global Health Research Unit on the Global Surgery India Hub. Clinicians with expertise in the management of NTSI were recruited from various specialty departments including plastic surgery, hyperbaric, infectious diseases, general surgery, and intensive care medicine.

Survivors or caregivers with personal experience of NSTI were included in the Delphi study to ensure shared decision-making during the process, and to appropriately reflect outcomes of importance to all stakeholders.[5,12] Survivors or caregivers were approached via online NSTI survivor support groups and Alfred Health NSTI consumers.

Participation was open to all relevant stakeholders and snowball sampling was utilised.[13] Research centres and departments were encouraged to invite additional qualified colleagues or survivors with experience in NSTI to contribute to the study.

Participants were invited to join the study through email correspondence and were provided with an information statement about the study objectives and requirements. Consent was implied by registration and participation via DelphiManager. There was no formal process of withdrawal of consent, but a degree of attrition was expected. All participants were at least 18 years old and identified as a relevant stakeholder in the NSTI field. Demographic information about panel members were collected on DelphiManager and customised to this study.

OUTCOME MEASURES

Generation of preliminary list of outcome measures

A systematic review was performed prior to this Delphi study to generate a comprehensive inventory of outcome measures reported in studies published from 2010 to 2020.[3] Three hundred and seventy-five studies were identified including 311 outcome measures which were reported and categorised into 11 outcome domains and five core areas, consistent with the taxonomy recommended by Dodd, et al.[11] The investigator group reviewed the list of outcomes identified in the systematic review and determined a shortlist of 50 outcomes to be presented to the expert panel. Non-specific outcome measures not feasible for collection in future large-scale clinical trials or highly case-specific outcomes which could not be generalised to all NSTI research or to limb or abdominal/pelvis NSTI, were excluded from the list. The 50 outcome measures were tabulated, written in non-technical language and provided to participants in the following core areas: Mortality/Survival (7), Physiological/Clinical (11), Life Impact (4), Resource Use (13), Adverse Events (3) for Round 1 of the Delphi study. Where applicable, additional information was listed under Help Text on DelphiManager to elaborate on specific scoring systems or outcome measures for participants.

Limb and abdomen and pelvis specific core outcome measures

Interventional and anatomically specific outcomes which were considered only relevant to NSTI of either the limbs (4) or abdomen and pelvis (8) were listed separately for consideration in additional sub-group outcome sets.

MODIFIED DELPHI PROTOCOL

Invited participants were emailed a link to register their details. Survey links were distributed to registered participants via the DelphiManager software platform; with each round of the survey approximately 15 minutes duration. Participants were invited to respond to each provided outcome using a 9-point Likert scale called the Grading of Recommendations Assessment, Development and Evaluation (GRADE) Scale, whereby 1–3 = not important, 4–6 = important but not critical, 7–9 = critical, as well as an option to select if unable to score.[5] Consensus criterion were defined *a priori* as greater than or equal to 70% of responses rating the domain as "*critical*" (a score of 7–9) and less than or equal to 15% of responses rating the domain as "*not important*" (a score of 1–3).[5,12] This consensus definition has been used in previous studies and ensures it accounts for major disagreement in a minority group in an outcome that reaches apparent consensus.[10,12] Anonymity of participants was preserved throughout the Delphi study which commenced on 26 March 2024 and concluded on 6 May 2024.

Round 1

Participants were presented with a tabulated list of preliminary outcome measures and asked to grade each outcome using the 9-point GRADE scale. Participants were also provided with the opportunity to include their rationale for outcome scoring, to give feedback on the survey and to suggest any additional outcomes for inclusion. Additional outcomes and feedback were analysed by the study team.

Round 2

Following completion of the first round, outcomes were analysed to determine which outcomes met *a priori* criterion for consensus; these were removed from subsequent rounds. Participants were presented with the outcomes that had met consensus, a summary of feedback, percentage score distribution for each outcome and their own scores from Round 1. Outcomes that had not already achieved consensus were presented once again for voting, as were additional outcome measures suggested by participants in Round 1. Participants were again asked to rate each outcome using the 9-point GRADE scale and were given the option to maintain or amend their rating based on reflection on group results. Participants also had the opportunity to provide rationale and feedback.

Round 3

Data from Round 2 were analysed to identify additional outcomes meeting consensus criteria, and participants were informed of these at the start of Round 3. They were invited to re-score the remaining outcomes that had not reached consensus using the 9-point GRADE scale. Participants were able to see the anonymised distribution of responses from

the preceding round as well as the rating they had allocated each outcome in the preceding round.

Following participant feedback regarding a series of very similar outcomes relevant to abdominal and pelvis NSTI (colostomy, ileostomy, stoma, faecal diversion), and due to the concern that having too many highly similar options may potentially prevent any from meeting consensus even if conceptually the participants agreed, the primary investigating team determined to only carry forward the most inclusive of these terms; faecal diversion. All other outcomes that had not yet met consensus were included in Round 3 for a final round of ratings. On completion of Round 3, participants were asked to provide information on their clinical specialty where relevant and years of experience. All participants who completed Round 3 were asked if they wished to be acknowledged by name in the manuscript and offered the option to download a certificate of their involvement.

Consensus meeting

Following the completion and analysis of Round 3 data, a consensus meeting was held by the investigator team to finalise the COS. All preliminary outcomes meeting consensus were reviewed to remove or consolidate highly similar or interchangeable outcomes to determine the final list of outcomes for the NSTI COS.

STATISTICAL ANALYSIS AND CONSENSUS

Response rates were defined as the proportion of recruited panel members who completed each survey round. Survey responses for each outcome were summarised with descriptive statistics. Outcomes not reaching consensus were included in the analysis of the median rating and interquartile range for the ratings received in the final round. No statistical power calculations were performed for this study.

Results

PARTICIPANTS

The expert panel comprised of a total of 98 participants from 14 different countries, with 59 from South Asia, 21 from Oceania, 10 from Europe, five from North America, and one each from Southeast Asia, East Asia and Western Asia (Table 1). Low and middle income countries were represented in the study with 55 participants from India and two from Nepal.[14] Participants also identified their relevant stakeholder groups with 26 (27%) clinical researchers, 64 (65%) clinicians, 2 (2%) researchers and three (3%) NSTI survivors/caregivers. Three (3%) participants did not identify their stakeholder group. The panel consisted of experts from a diverse range of specialties: general surgery (28%), hyperbaric medicine (19%), anaesthesia (15%), intensive care (14%), emergency medicine (6%), internal medicine (5%), orthopaedic surgery (5%) (Table 1). The median professional experience level for clinicians and clinician researchers was 21 years (IQR 8–23) and 15 (6–25) respectively (Table 1). Fifty-six (57%) participants completed all three-rounds of the Delphi survey.

CORE OUTCOME SET

Fifty preliminary outcome measures were synthesised from the systematic review and presented across seven core areas: Mortality/Survival (n = 7), Physiological/Clinical (n = 11), Resource Use (n = 13), Life Impact (n = 4), Adverse Events (n = 3), Limb-specific outcomes (n = 4), Abdomen/Pelvis-specific outcomes (n = 8) (Table 2).

Round 1

Ninety-eight participants registered in the study, and 84 (86%) completed Round 1. (Figure 1). Ten participants commenced but did not complete Round 1. All outcomes voted on were included in the data analysis. Of the 50 preliminary outcome measures presented, ten outcomes from four core areas met *a priori* criteria for consensus during Round 1 and were removed from subsequent rounds; Mortality/Survival (n = 3), Resource Use (n = 2), Adverse Events (n = 3), Limb-specific outcomes (n = 2) (Table 3). No consensus outcomes were achieved for Life Impact, Physiological/Clinical and Abdomen/Pelvis-specific core areas. An additional 28 outcome measures were suggested by panel members for consideration. Co-investigators reviewed these suggestions, and of these nine outcomes were added to the list of outcomes provided in Round 2 (Figure 1). The remaining 40 outcomes from the preliminary set were retained for voting (Figure 1).

Round 2

Those who completed Round 1 were invited to participate in Round 2, and 58 (67%) of the 86 participants responded to the Round 2 survey (Figure 1). One participant commenced but did not complete Round 2, and all votes were included in analysis. Of the 49 outcome measures evaluated, an additional three outcomes reached consensus (Table 3). No outcome measures for life impact and abdomen/pelvis specific core areas reached consensus. After review of the outcome measures list and panel feedback, co-investigators decided to consolidate "*colostomy*", "*ileostomy required*" and "*stoma*" to the more inclusive term "*faecal diversion*". Forty-three outcomes were retained for Round 3.

Round 3

Among participants invited to Round 3, 56 (97%) of participants responded (Figure 1). Of the remaining 43 outcome measures rated in Round 3, two outcome measures from the Life Impact core area and one from Mortality/Survival met consensus criteria. Detailed scores and distribution for each outcome measure across each round including final consensus status are presented in Table 3.

Table 1

Characteristics of panel members; ^clinicians could select more than one specialty area to capture primary and secondary fields of practice; *information was collected only from participants that complete Round 3 of the Delphi study; IQR – interquartile range; NSTI – necrotising soft tissue infections

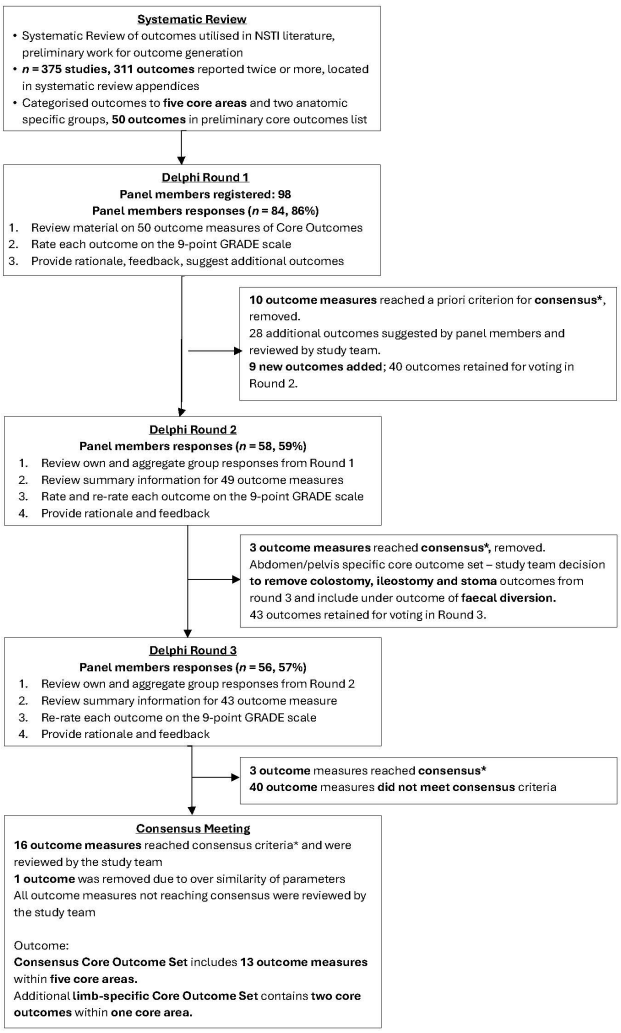
Characteristic	Round 1 (*n* = 98)	Round 2 (*n* = 59)	Round 3 (*n* = 56)
Country of practice, *n* (%)			
Australia	21 (21)	17 (29)	17 (30)
Belgium	1 (1)	1 (2)	1 (2)
Denmark	2 (2)	1 (2)	1 (2)
France	1 (1)	1 (2)	1 (2)
Germany	1 (1)	0	0
India	55 (55)	28 (47)	26 (46)
Ireland	1 (1)	0	0
Japan	1 (1)	1 (2)	1 (2)
Netherlands	2 (2)	2 (3)	2 (4)
Nepal	2 (2)	1 (2)	1 (2)
Oman	1 (1)	0	0
Singapore	1 (1)	1 (2)	0
Sweden	1 (1)	1 (2)	1 (2)
United Kingdom	1 (1)	1 (2)	1 (2)
USA	5 (5)	3 (5)	3 (5)
Other	2 (2)	1 (2)	1 (2)
Stakeholder, *n* (%)			
Clinician researchers	26 (27)	22 (37)	22 (39)
Clinician	64 (65)	33 (56)	30 (54)
Researcher	2 (2)	0	0
Consumer/NSTI survivor or caregiver	3 (3)	2 (3)	2 (4)
Other/not specified	3 (3)	2 (3)	2 (4)
Clinical specialty, *n* (%)^*			
Anaesthesiology			6 (15)
Emergency Medicine			3 (8)
General surgery			11 (28)
Hyperbaric medicine			8 (20)
Intensive care	Not collected		6 (15)
Internal medicine			2 (5)
Orthopaedic surgery			2 (5)
Paediatric anaesthesia			1 (3)
Paediatric surgery			1 (3)
Years of professional practice, median (IQR)*			15 (6–24)
Clinician researchers			15 (6–25)
Clinician			21 (8–23)

Table 2

Preliminary core outcome measures of necrotising soft tissue infections (core area, outcome domain, outcome measure) that were included in the study; outcome measures included as reported in systematic review by Wackett et al.[3]; outcome measures classified as per the COMET taxonomy recommended by Dodd et al.[9]; DAS-24 – Derriford Appearance Scale -24; ICU – intensive care unit; NICCE – Necrotising Infection Clinical Composite Endpoint; m-SOFA – modified Sequential Organ Failure Assessment score; SOFA score – Sequential Organ Failure Assessment score

Core area	Outcome domain	Outcome measure	Frequency reported in the literature
Death	Mortality/survival	Mortality without time specified	298
		In hospital mortality / 'survival to discharge'	94
		28-day mortality	20
		90-day mortality	19
		ICU mortality	13
		Mortality within 6 months / 180 days	12
		Mortality within 1 year	6
Physiological/ clinical	Musculoskeletal and connective tissue outcomes	Number of debridements required	151
		Number of procedures/surgeries required	86
	Skin and subcutaneous tissue outcomes	Skin graft required	88
		Surgical flap required	44
		Surgical reconstruction required	38
		Primary wound closure	22
		Wound healing time (cicatrisation time)	10
	Infection and infestation outcomes	SOFA score (Day 14)	4
		NICCE endpoint	3
		SOFA score (Day 28)	2
		m-SOFA (Day 14)	2
Life impact	Functioning	Medical outcomes Short Form-36	6
		Pain score (visual analogue scale)	2
	Emotional functioning/ wellbeing	Derriford appearance scale score	2
		DAS-24 questionnaire	1
Resource use	Hospital	Length of hospital stay	260
		Length of ICU stay (days)	103
		ICU-free days	7
		Ventilation (days)	33
		Ventilator-free days	9
		Days alive off life support at day 90	2
	Economic	Cost per patient	11
	Societal/carer burden	Discharged home	18
		Discharged to skilled nursing facility	9
		Discharged to rehabilitation	8
		Discharged to other hospital	6
		Days alive and out of hospital (by day 180)	6
		Discharged to hospice	3
Adverse events	Adverse events/effects	Septic shock	61
		Sepsis	46
		Organ failure / dysfunction	42
Limb-specific NSTI			
Physiological/ clinical	Musculoskeletal and connective tissue outcomes	Amputation performed	156
		Level of amputation	28
		Amputation during ICU stay	3
		Number of amputations	3
Abdomen/Pelvis-specific NSTI			
Physiological/ clinical	Gastrointestinal outcomes	Colostomy	75
		Faecal diversion	12
		Ileostomy required	5
		Stoma	5
	Renal and urinary outcomes	Suprapubic tube placement	21
		Cystostomy	34
	Reproductive system outcomes	Orchidectomy	46
		Penectomy	15

Figure 1
Flow diagram for modified Delphi consensus process; the *a priori* criteria for consensus were: ≥ 70% of responses rating the domain as 'critical' (a score of 7–9) and ≤ 15% of responses rating the domain as 'not important' (a score of 1–3); NSTI – necrotising soft tissue infection



By the end of the three-rounds of the Delphi survey, 16 outcome measures from five core areas and six domains had met consensus criteria; Mortality/Survival (n = 5), Physiological/Clinical (n = 1), Resource Use (n = 3), Life Impact (n = 2), Adverse Events (n = 3), Limb-specific outcomes (n = 2). No outcome measures reached consensus in the additional Abdomen/Pelvis-specific set.

Consensus review

At the final consensus meeting, outcomes of 28-day and 30-day mortality which had both met consensus criteria were considered too similar for both to be included in the core outcome set, and for pragmatic reasons, the investigator group decided to select one for recommendation only. Thirty -day mortality was the preferred choice after consideration of contemporaneous hospital and national administrative datasets.[15] Stakeholder ranking of 90-day mortality was reviewed; 39 (69.64%) stakeholders in Round 3 considered it to be critically important, and 1 (2%) considered it not important. Investigators agreed to accept that this met consensus criteria by rounding and recommend its inclusion in the COS. Consideration was also given to whether one of sepsis or septic shock should be removed and both were retained. The preliminary COS for NSTI is presented in Table 4.

Discussion

This COS is the recommendation of a minimum set of outcomes that should be reported in all studies for NSTI, however, it does not limit or prohibit the inclusion of other outcomes. NSTI can affect any anatomical region, each of which is likely to have outcomes of relevance to only that region. The study team set out to develop a core set of outcomes relevant to all categories of NSTI, with the addition of separate sub-sets to be collected for two of the most commonly affected anatomical regions; limb and abdomen/pelvis.[16,17] The aim in doing this was to identify outcomes considered critically important within each of these distinct anatomical sub-groups. Two outcome measures related to amputations reached consensus criteria in the Limb-specific core set, however, no consensus outcomes were reached in the Abdomen/Pelvis-specific core set. This may be attributed to the abundance of closely related outcomes, namely colostomy, stoma, ileostomy, and faecal diversion, that contributed to the lack of consensus amongst them. However, despite the decision to consolidate these outcomes into a single faecal diversion outcome after Round 2, it still did not meet consensus criteria, with only 43% of participants rating it as critically important with interquartile GRADE rating of 6–9 (Table 3). Potentially, faecal diversion may have been considered an intervention as opposed to an outcome measure in acute phase of perineal NSTI as a method to improve local wound treatment, with a definitive stoma requirement being considered the subsequent outcome.[18] The identification of an Abdomen/Pelvis-specific set of core NSTI outcomes remains a priority and should be further explored.

NSTIs have a significant life impact on patients.[14] Survivors have reported long-term physical, psychological and social consequences of NSTI which impact health-related quality of life and should be considered as part of the patient perspective in NSTI research.[14] Of the proposed ten outcome measures under the Life Impact core area in this study, only two reached consensus at the end of three rounds of voting; Medical Outcomes Short Form-36 (SF-36) and return to previous activities of daily living (ADLs).

The SF-36 is a 36-item health questionnaire developed in 1992 which assesses eight domains of health using scaled scores; physical functioning, role-physical functioning, bodily pain, general health, vitality, social function, role-

Table 3

Outcome measures (outcomes that did meet and did not meet consensus criteria + descriptive statistics); **a priori* criteria for consensus: ≥ 70% of responses rating the domain as 'critical' (a score of 7–9) and ≤ 15% of responses rating the domain as 'not important' (a score of 1–3); DAS-24 – Derriford Appearance Scale -24; EQ 5D – EuroQol 5 Dimension (quality of life measure); HAD scale – Hopsital Anxiety and Depression scale; ICU – intensive care unit; NICCE – Necrotising Infection Clinical Composite Endpoint; m-SOFA – modified Sequential Organ Failure Assessment score; PTSD – post traumatic stress disorder; SF36 – Short Form 36; SOFA score – Sequential Organ Failure Assessment score; VAS – visual analogue scale

Outcome measure by core area	Round 1				Round 2				Round 3				Decision*
	n votes	Score ≤ 3 *n* (%)	Score ≥ 7 *n* (%)	Median (IQR)	*n* votes	Score ≤ 3 *n* (%)	Score ≥ 7 *n* (%)	Median (IQR)	*n* votes	Score ≤ 3 *n* (%)	Score ≥ 7 *n* (%)	Median (IQR)	
Adverse events													
Organ failure/dysfunction	83	1 (1)	69 (83)	9 (7–9)									Consensus
Sepsis	83	1 (1)	68 (82)	8 (7–9)									Consensus
Septic shock	83	1 (1)	72 (87)	9 (7–9)									Consensus
Life impact													
Anxiety and depression at three months (HAD scale)					58	5 (9)	20 (34)	6 (4–7)	56	2 (4)	13 (23)	6 (5–6)	
DAS-24 questionnaire	78	10 (13)	34 (45)	9 (7–9)	54	7 (13)	23 (43)	6 (5–6)	52	6 (12)	13 (25)	6 (5–6.35)	
Derriford appearance scale score	75	6 (8)	25 (33)	6 (5–7)	52	4 (8)	11 (21)	6 (5–6)	50	3 (6)	9 (18)	6 (5–6)	
EQ5D-3L (at 30 days)					58	4 (7)	26 (45)	6 (5–7)	56	1 (2)	22 (39)	6 (5.75–7)	
EQ 5D-3L (at discharge)					58	4 (7)	17 (29)	6 (5–7)	56	3 (5)	12 (21)	6 (5–6)	
Medical Outcomes SF36	81	3 (4)	45 (56)	7 (6–8)	56	0	38 (68)	7 (6–7)	54	0	40 (74)	7 (6.25–7)	Consensus
Pain score (VAS)	85	5 (6)	45 (51)	7 (6–8)	58	2 (3)	23 (40)	6 (6-7)	56	2 (4)	13 (23)	6 (6–6)	
PTSD at three months (Impact of event scale)					57	4 (7)	16 (28)	6 (5–7)	55	1 (2)	10 (18)	6 (5–6)	
Return to previous activities of daily living					58	2 (3)	40 (69)	7 (6–8)	56	0	43 (77)	7 (7–8)	Consensus
EQ5D at three months					58	4 (7)	32 (55)	7 (5–8)	56	1 (2)	37 (66)	7 (6–7)	
Death													
28-day mortality	94	1 (1)	70 (74)	8 (6.3–9)									Consensus
30-day mortality					58	4 (7)	43 (74)	8 (6.25–9)					Consensus
90-day mortality	94	4 (4)	56 (60)	7 (6–8.8)	59	1 (2)	41 (69)	8 (6–9)	56	1 (2)	39 (70)	7 (6–7)	Consensus
ICU mortality	93	4 (4)	69 (72)	8 (6–9)									Consensus
In hospital mortality	94	0	75 (80)	8 (7–9)									Consensus
Mortality within one year	93	11 (12)	33 (35)	6 (4–7)	59	7 (12)	15 (25)	6 (4–6.5)	56	8 (14)	15 (27)	6 (5–7)	
Mortality within six months	94	11 (12)	44 (47)	6 (5–8)	59	5 (8)	20 (34)	6 (5–7)	56	6 (11)	15 (27)	5 (5–7)	

Table 3 continued.

Mortality without time specified	94	13 (14)	37 (39)	6 (4–8)	59	8 (14)	24 (41)	6 (3.5–7)	56	7 (13)	26 (46)	6 (3.75–7.25)	
Physiological / clinical													
m-SOFA (Day 14)	84	5 (6)	36 (43)	6 (5–8)	56	4 (7)	18 (32)	6 (5–7)	54	5 (9)	9 (17)	6 (5–6)	
NICCE endpoint	78	7 (9)	38 (49)	6 (5–8)	55	5 (9)	26 (47)	6 (6–8.5)	52	4 (8)	14 (27)	6 (5.8–7.3)	
Number of debridements	87	2 (2)	58 (67)	8 (6–9)	59	1 (2)	44 (75)	8 (6.5–9)					Consensus
Number of procedures/surgeries	87	2 (2)	55 (63)	7 (6-9)	59	2 (3)	36 (61)	8 (6–9)	56	3 (5)	32 (57)	8 (6–9)	
Primary wound closure	87	6 (7)	39 (45)	6 (5–8)	59	4 (7)	24 (41)	6 (5–7)	56	3 (5)	13 (23)	6 (5–6)	
Skin graft required	87	6 (7)	44 (51)	7 (5.5–8)	59	3 (5)	20 (34)	6 (5.5–7)	56	2 (4)	10 (18)	6 (6–6)	
SOFA score (Day 14)	87	7 (8)	47 (54)	7 (5–8)	59	7 (12)	28 (47)	6 (5–8)	56	6 (11)	17 (30)	6 (6–7)	
SOFA score (Day 28)	87	11 (13)	35 (40)	6 (5–7)	58	7 (12)	17 (29)	6 (5–7)	56	6 (11)	8 (14)	6 (5–6)	
Surgical flap required	87	7 (8)	43 (49)	6 (5–8)	59	4 (7)	19 (32)	6 (6–7)	56	2 (4)	11 (20)	6 (6–6)	
Surgical reconstruction required	87	4 (5)	55 (63)	7 (6–8)	59	2 (3)	36 (61)	7 (6–7)	56	2 (4)	35 (63)	7 (6–7)	
Wound healing time (cicatrisation time)	87	7 (8)	40 (46)	6 (5–8)	59	2 (3)	23 (39)	6 (5–8)	56	5 (9)	16 (29)	6 (5–7)	
Resource use													
Cost per patient	83	5 (6)	45 (54)	7 (6–8)	57	0	31 (54)	7 (6–9)	55	0	25 (45)	6 (6–9)	
Days alive and out of hospital (by day 180)	83	5 (6)	34 (41)	6 (5–8)	57	2 (4)	18 (32)	6 (5–7)	55	1 (2)	10 (18)	6 (5.5–6)	
Days alive off life support at day 90	83	8 (10)	33 (40)	6 (5–7)	57	3 (5)	20 (35)	6 (6–7)	55	2 (4)	12 (22)	6 (6–6)	
Discharge disposition					57	1 (2)	26 (46)	6 (6–7)	56	1 (2)	19 (34)	6 (5.75–7.25)	
Discharged home	84	4 (5)	53 (63)	7 (6–9)	58	0	44 (76)	8 (7–9)					Consensus
Discharged to hospice	83	6 (7)	32 (39)	6 (5–7)	58	4 (7)	13 (22)	6 (5.25–6)	56	0	8 (14)	6 (6–6)	
Discharged to other hospital	84	3 (4)	32 (38)	6 (5–7)	58	4 (7)	11 (19)	6 (5–6)	56	2 (4)	6 (11)	6 (5–6)	
Discharged to rehabilitation	84	4 (5)	33 (39)	6 (5–7.25)	58	2 (3)	16 (28)	6 (5–7)	56	2 (4)	11 (20)	6 (6–6)	
Discharged to skilled nursing facility	84	4 (5)	30 (36)	6 (5–7.25)	58	3 (5)	16 (28)	6 (5–7)	56	4 (7)	10 (18)	6 (6–6)	
ICU-free days	84	3 (4)	40 (48)	6 (5–7.25)	58	3 (5)	22 (38)	6 (6–7)	56	2 (4)	18 (32)	6 (6–7)	
Length of hospital stay	84	0	65 (77)	8 (7–9)									Consensus
Length of ICU stay (days)	84	0	69 (82)	8 (7–9)									Consensus
Ventilation (days)	84	3 (4)	51 (61)	7 (6–9)	58	2 (3)	37 (64)	7 (6–9)	56	2 (4)	37 (66)	8 (6–9)	
Ventilator-free days	84	4 (5)	35 (42)	6 (5–7)	58	3 (5)	18 (31)	6 (5–7)	56	1 (2)	17 (30)	6 (6–7)	
Limb-specific													
Amputation during ICU stay	81	8 (10)	40 (49)	6 (5–8)	56	4 (7)	25 (45)	6 (5.75–9)	54	5 (9)	27 (50)	6.5 (6–9)	

Table 3 continued.

															Consensus
Amputation performed	81	0	72 (89)	9 (8–9)											
Level of amputation	81	0	60 (74)	8 (6–9)											Consensus
Number of amputations	80	3 (4)	48 (60)	7 (6–9)	56	2 (4)	32 (57)	7 (6–9)	54	2 (4)	32 (59)	8 (6–9)			
Return to full function of affected limb					56	1 (2)	33 (59)	7 (6–8)	54	2 (4)	32 (59)	7 (6–7)			
Trunk-specific															
Colostomy	81	2 (2)	54 (64)	7 (6–9)	56	1 (2)	31 (55)	7.5 (6–8)							
Cystostomy	81	2 (2)	38 (47)	6 (5–8)	56	1 (2)	22 (39)	6 (5–8)	54	1 (2)	16 (30)	6 (5–7)			
Faecal diversion	81	0	45 (56)	7 (6–8)	56	0	28 (50)	6.5 (6–9)	54	0	23 (43)	6 (6–9)			
Ileostomy required	81	3 (4)	45 (53)	7 (6–9)	56	1 (2)	22 (39)	6 (5–8)							
Orchidectomy	81	1 (1)	44 (54)	7 (6–8)	56	1 (2)	31 (55)	7 (6–8)	54	1 (2)	24 (44)	6 (6–8)			
Penectomy	79	3 (4)	42 (53)	7 (6–8)	56	1 (2)	25 (45)	6 (6–8)	54	1 (2)	20 (37)	6 (6–8)			
Stoma	80	3 (4)	49 (61)	7 (6–9)	56	0	31 (55)	7 (6–9)							
Suprapubic tube placement	80	6 (8)	28 (35)	6 (5–7)	56	2 (4)	13 (23)	6 (5–6)	54	2 (4)	11 (20)	6 (5–6)			

emotional functioning and mental health.[19] Component analysis of survey results can also generate two summary scales of health; a Physical Component Score and a Mental Component Score.[20]

Health related quality of life outcomes, such as SF-36, are commonly incorporated into randomised controlled trials to consider patient specific outcomes of various conditions, however there are several challenges with its use. The results of SF-36 in several studies do not necessarily modify the interpretation of trial results even when discordant from primary efficacy outcomes, suggesting the need for standardised interpretation of patient outcomes.[21] Developed as a generic, multipurpose tool, the SF-36 has been shown to not capture the extent of profound psychological impacts, notably observed in NSTI survivors, compared to more targeted assessment tools such as the Hospital Anxiety and Depression Scale (HADS) and Impact of Events Scale (IES).[22] This suggests the potential need for an additional measure to detect the psychosocial impact of NSTI. HAD and IES were both proposed as outcomes as part of the Delphi survey after Round 1 but did not achieve consensus. Given the high sensitivity of the IES for mental health, the performance of IES in a yet unpublished systematic review of patient reported outcome measures in NSTI, and the profound psychological impact NSTI has on survivors, the authors suggest that IES may be a valuable tool to evaluate the psychological impact of NSTI.[22]

Once patients have survived NSTI, return to function emerges as a critical patient-specific outcome. Return to previous ADLs was proposed by a panel member at completion of Round 1 and subsequently included in Round 2 of the survey. The term ADL can be further subdivided into basic/personal ADLs and instrumental/extended ADLs, however universal agreement and consensus of what is recorded, scoring scale, quantifying functional limitation and the time frame of capture is unclear and can be problematic, and requires further study.

In considering the core area of resource use, panel members were provided with several discharge destination outcomes including discharge disposition, discharged home, discharged to hospice, discharged to other hospital, discharged to rehabilitation and discharged to skilled nursing facility. Of these, discharge home was the only outcome to meet consensus criteria with 76% rating it as critically important. All other discharge disposition related outcomes were predominantly rated between important and critically important (interquartile GRADE rating 5–7) (Table 3). This suggests a general agreement across the stakeholder groups of the importance for patients that have survived NSTI to ultimately be able to return home. Predicators of discharge disposition to other settings include patient factors such as age, gender and comorbidities, complications such as amputations and sepsis, complex care and persistent functional deficits, where patients would require ongoing rehabilitation or services.[23] Discharge disposition to

Table 4

Core outcome set; outcome measures reaching *a priori* consensus criteria classified as per the COMET taxonomy recommended by Dodd et al.[9]; the *a priori* criteria for consensus were : ≥ 70% of responses rating the domain as 'critical' (a score of 7–9) and ≤ 15% of responses rating the domain as 'not important' (a score of 1–3); ICU – intensive care unit

Core area	Outcome domain	Outcome measure
Death	Mortality/survival	In hospital mortality
		30-day mortality
		90-day mortality
		ICU mortality
Physiological/clinical	Musculoskeletal and connective tissue outcomes	Number of debridements required
Life impact	Functioning	Medical Outcomes Short Form-36 (SF36)
		Return to previous activities of daily living
Resource use	Hospital	Length of hospital stay
		Length of ICU stay (days)
	Societal / carer burden	Discharged home
Adverse events	Adverse events/effects	Septic shock
		Sepsis
		Organ failure/dysfunction
Limb-specific NSTI		
Physiological/clinical	Musculoskeletal and connective tissue outcomes	Amputation performed
		Level of amputation

non-home destinations is also indicative of poorer patient outcomes and has been associated with greater 30-day mortality and functional limitation.[24]

The most consistently important outcomes to the participants with lived experience of NSTI or caregivers were: SF-36, a simple quality of life assessment EQ-5D at 30 days, and 90-day mortality, indicating that what these stakeholders value most is quality of life and survival beyond the acute phase of NSTI.

There are several limitations to this paper. The COS developed in this study reflects the expert opinion on the topic, and therefore may be prone to bias of the participants involved. However, we endeavoured to minimise this potential bias by involving a large number of multinational stakeholders with diverse expertise in NSTI. Although thirteen outcomes comprise the determined COS for all NSTI, with two additional outcomes forming the Limb-specific COS, no outcomes reached consensus for the Abdomen/Pelvis-specific COS. This lack of abdomen/pelvis related core outcomes could result in increased heterogeneity in comparing outcomes of NSTI involving the abdomen, groin and perineum. Further work to develop an additional COS specific to abdominal/pelvis NSTI should be considered. Variability exists in the granularity of the outcomes chosen, from broad concepts (return to previous ADLs) to the use of a specific tool (SF-36) for assessing life impact. Mortality outcomes that met consensus have determined time-points (30- and 90-days), while other outcomes do not. Outcomes without specified time points may not adequately reduce the heterogeneity of data collected for meta-analysis, and future work should clarify recommended time points for collection of these data.[25] Although approximately one third of participants who completed all rounds of the Delphi were surgical specialists (general, orthopaedic and paediatric surgery) an absence of urologists and plastic surgeons and limited orthopaedic representation (5%) in the panel may have impacted the outcomes considered important in the additional anatomical and intervention sets.

Response rates between Round 1 and 2 of the Delphi dropped from 86% to 59% of those who had registered to participate, with an overall response rate of 57% by Round 3. While there is no formal guidance around sample size and acceptable response rate, several study design factors can increase the potential for attrition bias, which can contribute to a false sense of consensus in remaining participants leading to a response bias.[5] In this study, we initially recruited a large sample size of 98 participants across demographically and geographically diverse populations and expected a degree of attrition from the sample (Table 1). Limiting the preliminary list of outcomes and length of Delphi survey was also to minimise participant burden each round. Only those who had completed each round were invited to the subsequent round. Reminder emails were sent during the rounds to encourage response rates. However, despite the attrition rate, the distribution of clinicians to clinician researchers, NSTI

survivors and caregivers, and country of practice remained relatively consistent across all three rounds (Table 1), indicating that the results of the study remain representative of the stakeholder groups.

Finally, there are potential challenges relating to the development of COS and barriers to uptake in future studies. The lack of validated measurement instruments for certain core outcomes such as return to previous ADLs and organ failure/dysfunction increases the difficulty in determining what and how to measure and acts as a barrier to applying the COS.[26] Establishment of core measure instruments that have appropriate psychometric analysis and assessment for feasibility, validity and responsiveness would improve the COS.[10] Similarly, optimal timepoints for outcome assessments of functional limitation are yet to be established. A minimum set of timepoints (i.e. at discharge, three, six and 12 months) would ensure homogeneity of data and cross-study comparison whilst additional timepoints could be considered to better understand the trajectory of management and recovery, however many centres may not be adequately resourced to collect this data. Whilst the authors encourage collection of data at time points up to and even beyond 12 months, this has not been proposed in this minimum dataset. Therefore, development of a core measurement instrument set is an urgent priority to optimise the applicability and uptake of the COS for NSTI.

Because of the absence of consensus amongst NSTI experts regarding the utility of HBOT, NSTI treatment guidelines are inconsistent, and patients receive inequitable care locally and internationally.[6,8] The rarity of NSTI and of HBOT centres with critical care capabilities make it extremely challenging to perform adequately powered controlled studies of adequate scale. The development and consistent uptake of this COS for NSTI is anticipated to improve the quality of evidence to support or refute the role of HBOT (and other interventions) for NSTI, by providing more homogenous outcome reporting and increasing the data available for subsequent meta-analysis. Use of the COS in future trials can also provide researchers with assurance that they have selected outcomes determined to be critical by a large, multinational and multidisciplinary group of NSTI experts.

Conclusions

Using a three-round modified Delphi process, consensus on the content of an NSTI minimum outcome set was achieved. The COS developed through this process contains 13 outcomes from the following five core areas; Mortality/Survival (in-hospital mortality, 30 day mortality, 90-day mortality, ICU mortality), Physiological/Clinical (number of debridements), Life Impact (medical outcomes short form-36, return to previous activities of daily living), Resource Use (length of hospital stay, length of ICU stay, discharged home), Adverse Events (septic shock, sepsis, organ failure/dysfunction). Within the Limb-specific subset of outcomes, two additional outcomes met consensus within the Physiological/Clinical core area (amputation performed, level of amputation). Having developed a preliminary COS for NSTI using robust consensus methods, we encourage researchers to include these outcomes in future studies.

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Acknowledgements

The authors would like to acknowledge and thank all participants who gave their time for their valuable contribution and responses in the Delphi study and recruitment of participants, including in alphabetic order: Alfie J Kavalakat, Amit Gupta, Asif Mehraj, Bhargavi R Budihal, Darren Wolfers, David Cooper, Nicolas de Prost, Dipesh Duttaroy, Dr Anurag Amin, Dr Jyotsna Rani, Dr Monish S. Raut, Dr Srikant Agrawal, Dr Vishal Kumar, Dr. Satyendra Kumar Tiwary, Geoff Frawley, Geraldine Ooi, Jay Buckey, Krishna Kumar Govindarajan, Lovenish Bains, Mezhuneituo Raleng, Naveen Sharma, Paul Myles, Poorvikha S, Prafull Kumar Arya, Rahul Gupta, Robert van Hulst, Robert Weenink, Sandra Peake, Sanjana Agarwal, Sathiafrey D A, Sathish Muthu, Shankarsai Kashyap, Shrirang Vasant Kulkarni, Sumita Pradhan, Symen Ligthart, Tapan Patel, Terry Lane and Tomoko Fujii

Conflicts of interest and funding

DelphiManager software was purchased via funding from the Alfred Hyperbaric Unit Special Purpose Fund. OH received funding from the Ellab-fonden of Denmark. No conflicts of interest were declared.

Submitted: 6 October 2024
Accepted after revision: 28 February 2025

Effect of normobaric and hyperbaric hyperoxia treatment on symptoms and cognitive capacities in Long COVID patients: a randomised placebo-controlled, prospective, double-blind trial

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Keywords
COVID-19; Hyperbaric oxygen; Randomised controlled trial; SARS-CoV-2

Abstract
(D'hoore L, Germonpré P, Rinia B, Caeyers L, Stevens N, Balestra C. Effect of normobaric and hyperbaric hyperoxia treatment on symptoms and cognitive capacities in Long COVID patients: a randomised placebo-controlled, prospective, double-blind trial. Diving and Hyperbaric Medicine. 2025 30 June;55(2):104–113. doi: 10.28920/dhm55.2.104-113. PMID: 40544138.)
Introduction: Long COVID syndrome is a major health issue. Multiple treatments have been proposed but efficacy is inadequately investigated. Hyperbaric oxygen therapy (HBOT) has been promoted based on a small number of publications. As there is potential for a placebo effect and the financial cost of HBOT is high, we sought to investigate the effects of HBOT in Long COVID in a randomised trial.
Methods: We randomised 101 patients into four treatment groups, receiving 10 sessions of oxygen 'treatment' inside a pressure chamber, according to one of four modalities: A – 100% oxygen at 253 kPa (2.5 atmospheres absolute); B – 40% oxygen at 253 kPa; C – 100% oxygen at 101.3 kPa (1 atmosphere absolute); D – 21% oxygen at 101.3 kPa. Groups B and C thus received a similar effective oxygen dose of 101.3 kPa. Quality of life symptom scores (Visual Analogue Scale; EQ-5D-5L, C19-YRSm), a 6-minute walking test and five neurocognitive tests were administered before and after the treatment series. At three months post-treatment, a telephone questionnaire probed for lasting effects.
Results: All groups were comparable with regards to demographics, Long COVID symptoms and severity. After treatment, there were no significant differences in subjective symptoms, functional scores, and cognitive performance between any groups. The response to treatment was highly variable, with some patients in even the 'placebo' group D reporting a significant improvement in their well-being. This was not reflected in any objective outcome scores. No subgroups of patients responded better to any of the treatments.
Conclusions: There was no significant effect from different doses of oxygen in a hyperbaric chamber. It is possible that the very modest improvements reported in other studies were due to a placebo effect. Claims that HBOT has a significant effect on Long COVID need further investigation before indiscriminately prescribing or promoting HBOT.

Introduction

From 30 January 2020 to the 5 May 2023, the World Health Organization (WHO) declared SARS-CoV-2 (COVID-19) a pandemic. Official figures mention 765,222,932 cases and 6,921,614 deaths worldwide during this period, most probably a vast underestimation. Among patients recovering from the acute phase, a certain percentage was observed to have persisting symptoms, and in September 2020, International Classification of Disease (ICD) codes were created for this 'Post-COVID Condition'. In October 2021, the WHO published a clinical case definition for Post-COVID Condition, based on a Delphi consensus method.[1]

A post-COVID condition case was described as a patient who has a) a history of probable or confirmed SARS-CoV-2 infection, presenting b) usually three months or more from the onset of COVID-19 disease, c) symptoms that last for at least two months that d) cannot be explained by an alternative diagnosis.

The consensus text further specified that: "*Common symptoms include fatigue, shortness of breath, cognitive dysfunction but also others which generally have an impact on everyday functioning. Symptoms may be new onset, following initial recovery from an acute COVID-19*

episode, or persist from the initial illness. Symptoms may also fluctuate or relapse over time. A separate definition may be applicable for children".[1]

Post-COVID Condition (better known by the general public as 'Long COVID syndrome') is considered a major health issue after the COVID-19 pandemic. Although many patients seem to improve after two years, many more remain severely handicapped in their family, social and professional life. The exact prevalence is unknown. While initial estimates in 2021 mentioned that up to 10–20% of patients have persisting symptoms,[1] two papers in 2022 estimated the prevalence at 12.7%[2] and 'up to 45%'[3] respectively; a subsequent review in 2023 mentioned 6–10%.[4] In any case, in view of the numbers infected with SARS-CoV2, the number of patients with Long COVID is staggering.

Core symptoms have been defined[2] and may be classified as cardiopulmonary symptoms (chest pain, difficulties with breathing, and pain when breathing), musculoskeletal symptoms (painful muscles), sensory symptoms (ageusia or anosmia, tingling extremities, lump in throat, and feeling hot and cold alternately), and general symptoms (heavy arms or legs, and general tiredness). Cognitive impairment ('brain fog'), although not mentioned as a core symptom in the Ballering paper,[2] has been reported in 16–23% of a group of 740 patients at a mean of 7.6 months from COVID-19 diagnosis.[5]

The mechanism of disease has not been identified, and multiple hypotheses have been formulated based on observed biochemical changes.[6] Multiple treatments have been proposed and are actively pursued by patients; however, the efficacy of these treatments remains low and proper scientific evidence is often lacking.

Hyperbaric oxygen therapy (HBOT) has been proposed for treatment of Long COVID syndrome since 2021 and has been widely promoted in the Long COVID patient population (by means of internet chat groups) based on a small number of publications. The first published study, by Robbins et al. in 2021, reported statistically significant and large to very large effects on fatigue and cognitive functioning, after only 10 HBOT sessions.[7] In 2022, two more studies reported 'important subjective improvement' after a short series of HBOT (10 sessions).[8,9] As the logistic and financial cost of HBOT is important and as there is a high potential for a placebo effect, we sought to investigate whether 10 treatments of HBOT provide significant improvement of the symptoms and cognitive capacities of these patients using a prospective, randomised, and blinded placebo-controlled design.

Administering a 'true' placebo (21 kPa [0.21 atmospheres] oxygen) inside a hyperbaric chamber is difficult to near impossible, as even a 'sham' compression to 130 kPa (1.3 atmospheres absolute [atm abs]) with air breathing effectively yields a partial pressure of oxygen equivalent to breathing 27% oxygen at 101.3 kPa (1 atm abs), and thus could have a therapeutic effect. Therefore, rather than trying to devise a 'perfect sham' we sought to determine if different levels of oxygenation at partial pressures of 21 kPa (0.21 atm abs), 101.3 kPa (1 atm abs) or 253 kPa (2.5 atm abs), given in various combinations of pressure and inspired oxygen fraction, could have different therapeutic effects, and if so, whether there is a role for increased pressure as well. The 'null hypothesis' was that no combination would yield a better result than 21 kPa (0.21 atm) inspired oxygen at 101.3 kPa (1 atm abs) ambient pressure.

Methods

The research protocol was approved by the Hospital Ethics Committee of the University Hospital Brugmann, Brussels (B0772022000037) on 12 April 2022.

Patients were first recruited among Belgian military personnel by means of a call for participation by email to all service personnel. This was our primary recruitment population, based on previous research[10] (H. Mazibas, doctoral thesis) having identified more than 350 Belgian military Long COVID patients. However, owing to a lack of sufficient participants from this source, a second round of recruitment was undertaken by seeking participants through various self-help groups online (mainly Facebook). After preliminary screening by means of a short questionnaire, patients were invited to select one of several pre-defined treatment periods of two consecutive weeks.

The week before the start of each treatment period, the eligibility of patients was verified during a medical consultation, as was the absence of contra-indications for pressure chamber treatment. Then, after having signed informed consent, patients' COVID history, initial and persisting symptoms and signs, and previous treatments tried were noted in an unstructured manner, and they were subjected to a series of objective tests and subjective evaluation questionnaires, as described below.

Next, they were randomised (1:1 allocation using a 4-block randomisation table generated in MS Excel 365) into four treatment groups and received 10 sessions of oxygen treatment inside a pressure chamber, according to 4 different modalities: A – 100% oxygen at 253 kPa (2.5 atm abs); B – 40% oxygen at 253 kPa; C – 100% oxygen at 101.3 kPa (1 atm abs); D – 21% oxygen at 101.3 kPa. Groups B and C thus received a similar effective oxygen dose of 101.3 kPa. All treatments lasted 95 minutes, with 15 minutes of (real or simulated) compression, 70 minutes of treatment and 10 minutes of (real or simulated) decompression.

Patients were blinded to the exact oxygen dose they received, and all were subjected to significant pressure variations in the beginning and end of each treatment session. Patients in groups A and B were treated in the hyperbaric chamber of the Centre for Hyperbaric Oxygen Therapy (CHBO) of

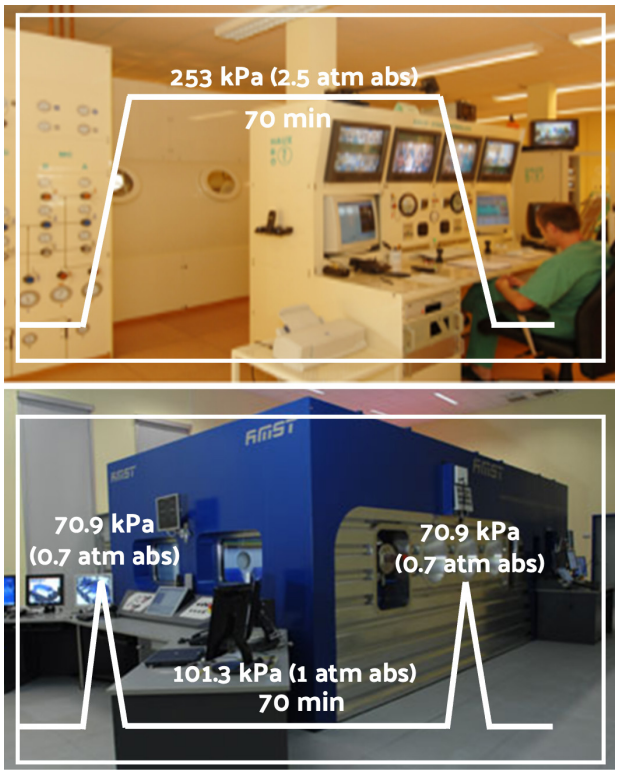
the Military Hospital in Brussels, Belgium, while patients in groups C and D were treated inside the hypobaric chamber of the Centre for Aerospace Medicine of the same hospital. Both treatment chambers are adjacent to the offices of the CHBO and all consultations, tests and evaluations were performed by the staff of the CHBO in the offices of the CHBO. Thus, the only variable in the treatment schedule was the actual treatment chamber. Actual pressure indications were blocked out in both treatment chambers. Patients in groups C and D were first decompressed to 10,000 feet altitude (70.9 kPa [0.7 atm abs])), then recompressed to ground level pressure, starting their treatment (either 100% or 21% oxygen) at the end of this decompression/compression period. Then, at the end of each treatment, the same decompression/compression was performed (Figure 1). This ensured that patients in all four groups had similar pressure-change related effects (notably, necessity of active or passive middle ear equalisation).

While the technical personnel responsible for administering the treatments obviously were not blinded to the gas breathed, the inside attendants were not aware of the oxygen pressure given. The attending physicians were instructed not to reveal the gas if required to attend to one of the patients in the study. The questionnaires and tests were administered by personnel unaware of the treatment group. Then, all the results were compiled in anonymised data sheets (MS Excel), and each group received a different group allocation letter (A, B, C, or D) by the principal investigator, who was not directly involved in the statistical analysis. The researchers performing the statistical analysis were thus equally unaware of the treatment groups they were analysing.

The 10 sessions were given daily over the course of two weeks, with a weekend break in between. During the week following completion of the 10 sessions, patients were again invited to a medical consultation, recording in a short questionnaire their subjective experience, as well as the occurrence of side effects and whether they were aware of the actual treatment modality. Also, we probed as to the subjective satisfaction of patients, asking them whether they would recommend their treatment to other Long COVID patients and whether they would be willing to pay for such a treatment, if required.

Then, the same questionnaires and tests were administered as before the start of the treatment. Quality of Life (QoL) symptoms were evaluated with a Visual Analogue Scale (VAS), the European quality of life 5-dimensions tool (EuroQoL EQ-5D-5L)[11] and the modified COVID-19 Yorkshire Rehabilitation Scale (C19-YRSm)[12] questionnaires. The VAS score evaluated the 'general quality of life', a score of 100 meaning 'feeling really great with no symptoms' and a score of 0 meaning 'feeling the worst I've ever felt'. The EQ-5D-5L and C19-YRSm scores measure specific symptoms and difficulties performing certain tasks and aspects of daily life, thus, a lower score on these scales indicates a better quality of life. EQ-5D-5L has a maximum score of 20 points, and C19-YRSm has a maximum score of 108 points. The subjective treatment effects were analysed as percents of the initial score, the initial score being considered '100'. For VAS, an 'after' score higher than 100 means improvement, for EQ-5D-5L and C19-YRSm, an 'after' score lower than 100 indicates improvement ('less difficulties').

Figure 1
Compression/decompression treatment profiles

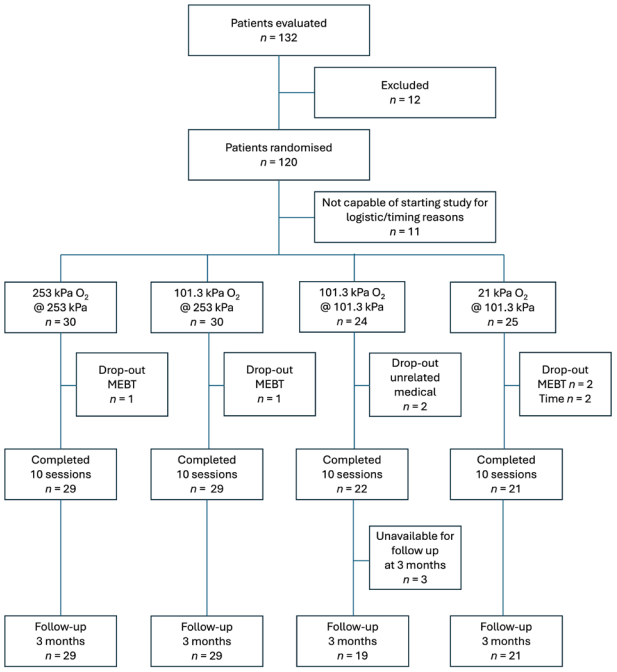


Physical condition was measured with a 6-Minute Walking Test (6MWT)[13] with peripheral oxygen saturation (SpO_2) measurement and the Borg Rating of Perceived Exertion (RPE) scale[14] before and after the test. The score was calculated as a percentage of normal performance (6MWD – 6-minute Walking Distance) for age and sex, according to the following formulae:[15]

Males: 6MWD = (7.57*body length [cm]) – (5.02*age) – (1.76*weight [kg]) – 309 m
Females: 6MWD = (2.11*body length [cm]) – (5.78* age) – (2.29* weight [kg]) + 667 m

Neurocognitive performance was evaluated with a computerised testing battery (Psychology Experiment Building Language, PEBL 4.1.9) using five different neurocognitive tests.[16] Short term memory was measured with Digit Span Backward (DSB) testing; speed of simple processing with Simple Reaction Time (REA); formal cognitive function with the Math Processing test (MathProc); hand-eye coordination with a Trail-making Test (PTrails) and spatial awareness with a Time Wall test (TimeWall).

Figure 2
Study flowchart. MEBT – middle ear barotrauma; Time – patient could not participate anymore because of time constraints



As there are no normal reference values available for each of these tests, individual results 'after' versus 'before' were calculated in percent, the initial results being considered '100'. For these scores, a score higher than 100 indicates improvement.

At three months post-treatment, a short telephone questionnaire probed for patient awareness of the study allocation, patient satisfaction and lasting effects.

Based on the single case series reporting on 10 patients[7] published prior to inception of the present study, we assumed an *a priori* effect size of 10% in the measured parameters, with a standard deviation of 5% in both groups; with an alpha error of 0.05 and a power of 0.90, requiring 18 subjects in each group (G*Power calculator 3.1 software, Heinrich Heine University, Düsseldorf, Germany).

Statistical analysis was performed on GraphPad Prism 10.0 for MacOS (GraphPad Software, Boston, MA).

Data are presented as mean (standard deviation [SD]). Normality of the data was verified by means of the Shapiro-Wilk test. Compared to baseline, data were analysed with a paired *t*-test for intragroup comparison. If gaussian distribution was not warranted, a Wilcoxon signed-rank test was preferred. Kruskal-Wallis or one-way analysis of variance (ANOVA) test with Bonferroni correction was used for intergroup multiple comparisons. Taking the baseline measures as '100', outcome measures were calculated as percents of the initial score for each exposure protocol, allowing an appreciation of the magnitude of change rather than the absolute values. Statistical significance was then assessed by means of a one-sample *t*-test.

Results

In total, 101 patients completed the study, of whom 98 were available for three months follow-up. After randomisation, 120 patients were scheduled to start, but 11 could not be included because of time constraints or logistic difficulties (unrelated to Long COVID). During the study period, four patients dropped out for medical reasons unrelated to Long COVID (two) or study logistics (two). Four patients dropped out because of middle ear barotrauma, two in the 2.5 ATA pressure groups (A and B) and two in the 101.3 kPa (1 atm abs) pressure groups (C and D). Three patients could not be contacted for the three month follow-up interview. Figure 2 shows the study flow diagram.

All groups were comparable with regards to demographics, previous history of burn-out, chronic 'psychophysical' illness (including fibromyalgia, chronic fatigue syndrome) or psychiatric disease, Long COVID duration, symptoms and severity (Table 1). All of the participants contracted COVID before the availability of SARS-CoV-2 vaccines, although most had been vaccinated when it became available.

After treatment, there was no significant difference in subjective symptoms (VAS), functional scores (EQ-5D-5L, C19-YRSm and 6MWT), and cognitive performance (PEBL) between the various treatment groups (Table 2). The response to treatment was highly variable, with some patients in even the 'most placebo' group D (21 kPa [0.21 atm] oxygen at 101.3 kPa [1 atm abs]) reporting a subjective improvement in their well-being. This resulted in some of the scores (marked in **bold** in Table 2) being significantly improved after the study treatment – however without a significant inter-group difference. We could not identify definite subgroups of patients responding better to any of the treatments. A more detailed analysis of the results of the C19-YRSm scores showed that patients with predominantly pulmonary symptoms seemed to have more improvement of these symptoms after a hyperbaric treatment at 253 kPa (2.5 atm abs); patients with systemic symptoms had an improvement with either 101.3 kPa (1 atm abs) or 253 kPa (2.5 atm abs) oxygen rather than 21 kPa (0.21 atm) oxygen; and that patients with predominant neurocognitive impairment (brain fog) apparently had fewer subjective complaints after treatments at 253 kPa (2.5 atm abs) (either 101.3 kPa or 253 kPa oxygen) (Table 3).

Side effects of the treatment were significant and mostly related to the confinement in a pressure chamber, wearing a mask. Middle ear barotrauma was rare, and equally distributed among the groups, and not substantially different from what has been reported in other HBOT studies. However, four patients had to stop the study because of middle ear barotrauma, two in each pressure condition. A

Table 1

Demographics and severity of Long COVID syndrome; *previous history of burn-out, psychiatric disease, chronic fatigue syndrome, fibromyalgia (see manuscript text); 6MWT – 6-minute walking test; C19-YRSm – modified COVID-19 Yorkshire Rehabilitation Scale; EQ-5D-5L – European quality of life 5-dimensions tool; ns – not significant ($P > 0.05$); QoL – quality of life; SD – standard deviation; VAS – visual analogue scale

Allocation	Group A	Group B	Group C	Group D	*P*-value
	253 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 101.3 kPa	21 kPa O_2 @ 101.3 kPa	
Age (years)	43.7 (SD 11.2)	49.4 (SD 10.3)	50.0 (SD 11.8)	46.8 (SD 8.2)	ns
Male sex	10/29 (34%)	15/29 (51%)	13/22 (58%)	13/21 (61%)	ns
Military personnel	10/29 (34%)	11/29 (37%)	8/22 (36%)	6/21 (29%)	ns
Long COVID (months)	21.46 (SD 9.34)	22.21 (SD 10.77)	21.67 (SD 9.49)	25.50 (13.44)	ns
Previous history*	6/29	4/29	3/22	3/21	ns
QoL VAS score	58/100	47/100	57/100	47/100	ns
EQ-5D-5L score	5/20	7/20	5/20	6/20	ns
C19-YRSm score	32/108	38/108	30/108	40/108	ns
Baseline 6MWT	87%	94%	96%	88%	ns
Disability from work	13/29 (45%)	14/29 (48%)	9/22 (41%)	10/21 (47%)	ns

Table 2

Change (percent of initial score) in quality of life scores and cognitive performance after treatment; baseline scores taken as 100; per-group values, one-sample Student *t*-test: $*P < 0.05$, $**P < 0.01$; § – multiple group comparison, Kruskal-Wallis test, right-most column, all non-significant (ns), $P > 0.05$; 6MWT – 6-minute walking test; C19-YRSm – modified COVID-19 Yorkshire Rehabilitation Scale; EQ-5D-5L – European quality of life 5-dimensions tool; DSB, REA, MathProc, Ptrails, TimeWall see Methods; ns – not significant ($P > 0.05$); PEBL – psychology experiment building language tests, see ref [16]; VAS – visual analogue scale; significant changes in bold (see Discussion for interpretation)

Allocation	Group A	Group B	Group C	Group D	*P*-value §
	253 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 101.3 kPa	21 kPa O_2 @ 101.3 kPa	
VAS	104.3	**81.67****	105.4	100.9	ns
EQ-5D-5L score	111.4	92.53	98.06	**80.87***	ns
C19-YRSm score	**67.42****	83.36	83.85	86.69	ns
6MWT	104.7	101.6	103.6	100.3	ns
PEBL – DSB	115.6	115.8	131.5	134.1	ns
PEBL – REA	96.51	105.3	100.7	101.1	ns
PEBL – MathProc	**109.2****	107.2	100.3	115.8	ns
PEBL – Ptrails	109.7	93.01	103.7	97.61	ns
PEBL – TimeWall	110.8	94.80	96.54	96.77	ns

significant logistical burden was reported: daily transport to the hyperbaric centre (some patients actually rented an apartment for the duration of the study), the fact that treatment consumed most of their daily time. Even if there were no direct costs involved for the participants, some may have spent significant amounts to organise their participation.

The telephone questionnaire at three months showed that none of the patients was aware of the actual treatment he/she had received. Patients from each group reported they felt the treatment had provided a 'real benefit', were glad to have participated and would be willing to pay for further treatment, if it were to be offered. However, most of the patients, even those who reported an improvement immediately after completion of the study period had returned to their pre-study condition when queried three months later, and only a small proportion of those not working at the start of the study had resumed a (part-time or full-time) professional activity. There was no significant difference in an inter-group analysis for any of these results (Table 4).

It is interesting to note that of the military patients, 30 of 35 (85.7%) were working at the start of the study, as opposed to 28 of 68 (41.2%) civilian patients. Military patients were

Table 3

Symptom improvement (number of points improved) as scored with C19-YRSm questionnaire, according to core symptom cluster (statistical significance not reached due to small numbers); figures marked in bold are discussed in the text; SD – standard deviation

Allocation	Group A	Group B	Group C	Group D	*P*-value
	253 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 101.3 kPa	21 kPa O_2 @ 101.3 kPa	
Pulmonary (max score = 24)	**4.16** (SD 0.69)	**4.27** (SD 0.71)	2.42 (SD 0.40)	2.17 (SD 0.36)	ns
Systemic (max score = 28)	**4.40** (SD 0.62)	**4.75** (SD 0.67)	**5.33** (SD 0.76)	2.50 (SD 0.36)	ns
Ear-Nose-Throat (max score = 8)	1.22 (SD 0.61)	2.60 (SD 1.30)	0.67 (SD 0.33)	1.75 (SD 0.87)	ns
Psychological (max score = 28)	5.25 (SD 3.30)	4.00 (SD 2.94)	4.00 (SD 2.82)	3.37 (SD 3.20)	ns
Neurological (max score = 20)	**3.08** (SD 0.61)	**4.63** (SD 0.92)	1.58 (SD 0.31)	2.06 (SD 0.41)	ns

Table 4

Questionnaire results (positive responses) after 3 months (scoring 0–5, scores > 3 counted as 'positive response'); multiple group comparison, Kruskal-Wallis test showed all changes non-significant, $P > 0.05$

Allocation	Group A	Group B	Group C	Group D
	253 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 253 kPa	101.3 kPa O_2 @ 101.3 kPa	21 kPa O_2 @ 101.3 kPa
Allocation concealment	29/29	29/29	22/22	21/21
'Felt a real improvement' after the treatment	20/29 (69%)	17/29 (59%)	9/22 (41%)	9/21 (43%)
'Happy to have participated'	25/29 (86%)	9/29 (31%)	17/22 (77%)	18/21 (86%)
'Would be willing to pay for further treatment'	22/29 (76%)	22/29 (76%)	10/22 (45%)	12/21 (57%)
Returned to professional activity at three months	4/29 (13%)	6/29 (20%)	2/22 (9%)	2/21 (9%)
Condition at three months similar compared to pre-study condition	18/29 (67%)	11/29 (38%)	13/22 (59%)	15/21 (71%)

also predominantly male (31 of 35, 88.6%), as opposed to civilian patients (21 of 68, 30.9% males).

Discussion

The evaluation of quality of life (QoL) and subjective well-being was performed with validated questionnaires, the more detailed one (C19-YRSm) having been specifically validated for Long COVID.[12] The 6MWT is a standardised, validated measure of physical exhaustion at exercise.[13] The PEBL neuro-psychometric testing battery evaluated specific domains shown to be affected by COVID infection, such as attention, processing speed, executive functioning, category fluency, memory encoding and recall.[17] Our evaluation battery of tests, both subjective and objective, was thus particularly adapted to the condition studied.

Even though some groups showed a significant effect on some scores and tests, there was no significant inter-group effect from different levels of oxygen breathing (21, 101.3 or 253 kPa [0.21, 1.0 or 2.5 atm]) in a pressure chamber. Our prospective, blinded, placebo-controlled study could thus not confirm the positive results of 10 sessions of HBOT (253 kPa oxygen), that previously published papers have reported. Neither was there any significant effect from breathing 101.3 kPa (1.0 atm) oxygen at either 101.3 or 253 kPa (1.0 or 2.5 atm abs) ambient pressure. Therefore, the null hypothesis (no combination would yield a better result than 21 kPa [0.21 atm] inspired oxygen at 101.3 kPa [1.0 atm abs] ambient pressure) cannot be rejected.

However, subjectively, in all groups a relatively high number of participants reported a positive effect of their treatment. This can only partially be explained by a detailed analysis of the predominant symptom cluster (Table 3). While it makes sense that pulmonary symptoms might be slightly more improved after a treatment at 253 kPa (there is a slight expiratory resistance of approximately 2–3 cm H_2O in the hyperbaric chamber breathing system, which might be equivalent to respiratory muscle training); while it may also make sense that breathing oxygen for 70 minutes per day could improve cognitive and systemic function slightly (hyperoxia has been shown to counteract inert gas narcosis effects[18–20] and, according to widespread belief, might

possibly improve cognitive function after alcohol use); this secondary analysis does not allow us to conclude that certain subgroups of patients would be better candidates for HBOT than others.

Other possible explanations for these subjective results may be the variability and fluctuation of Long COVID symptoms, and/or a placebo effect.

The symptoms and signs of Long COVID syndrome are highly variable and may be explained by many pathophysiological mechanisms.[6] No one single mechanism can explain all symptoms and signs, leading many to believe that Long COVID is an adverse (exaggerated) immune reaction targeting most, if not all, body systems and organs, albeit not all in an equal manner. Whether this immune reaction is caused by a continuous and excessive inflammatory response or to the continued presence of viral particles, is not known. In any case, the clinical course of Long COVID is fluctuating in time, with good periods alternating with exacerbations. There may be a gradual improvement over months or years, however, this may be difficult to appreciate because of the frequent relapses. This makes the evaluation of clinical efficacy of any treatment very difficult.

Patients become desperate because the medical world has no answer yet to their problem, and many feel that their symptoms are not well understood and/or minimised by their doctors, caregivers and (often also) their environment (work contacts, family). This desperation leads them to seek comfort in patient groups (such as on Facebook) where treatments are discussed and often recommended without there being any scientific proof (in essence, the personal experience of one or a few fellow sufferers makes them willing to also try these treatments).

In this regard, a remarkable similarity may be noted between Long COVID and other neuro-muscular syndromes, such as chronic fatigue syndrome and fibromyalgia.[21] While an organic cause, such as a chronic infection, is suspected to possibly be at the root of (some of) these syndromes, clear evidence that there is a causal relation is not yet available.[22] Long COVID, much like these other syndromes, may be susceptible to placebo response simply because the idea that 'someone takes their complaints and symptoms – finally – seriously' may already improve their general feeling of wellbeing. The three-case series,[7–9] published before we started our study (2021) and during our study period (2022 to mid 2023) were small (10, 12 and 59 patients respectively), uncontrolled, not blinded and evaluation was mainly subjective, and thus were highly likely to be subjected to placebo effects.

However, (even moderate) hyperoxia does play a role in inflammation and related processes, and thus, could exert an effect independent of pressure.

Oxygen plays a much greater role in our bodies than was previously appreciated. Not only a source of energy, oxygen serves as a signalling molecule and, while 'oxy-inflammation' certainly exists, oxygen at certain doses may have generalised anti-inflammatory effects, as can be determined in biochemical in-vivo studies such as performed by our own group.[23–26] Their clinical relevance, however, has not been determined. While providing extra oxygen to cells may seem a simple and easy way of modulating biochemical processes, the optimal dose of hyperoxygenation has yet to be defined. Low to moderate oxygen dose (30 to 142 kPa [0.30 to 1.4 atm]) administration has different effects than high-dose oxygen,[27,28] and the net effect seems to depend on the balance between oxidative effects and antioxidant counter-effects.[25] The optimal duration of repeat oxygen-mediated stimulation has been determined with reasonable success for certain conditions treated with HBOT. Some conditions require only 10 or less hyperbaric oxygen sessions, others would need 40 to 60 treatments for the clinical effect to reach a plateau. For conditions such as diabetic wounds or radiation cystitis, a clinical effect can usually be observed after 10 to 15 sessions. Which treatment duration would be necessary for a clinical effect in the case of Long COVID is not known. However, relying on biochemical changes alone to show a therapeutic effect is not ideal, as for many of the biochemical parameters that have been reported to change after oxygen stimulation, 'normal' values are not known or there may be a circadian or other fluctuation that is as yet unexplored.

The study treatments were chosen to allow for an evaluation of hyperoxygenation at two levels, 101.3 and 253 kPa (1.0 and 2.5 atm). The reasons behind this choice were threefold. First, it allowed to treat patients in mixed groups inside a single pressure chamber: the chambers are equipped with individually switchable breathing gas mixtures, and patients in the hyperbaric chamber were treated at our standard treatment pressure of 253 kPa (2.5 atm abs), either receiving 100% oxygen (for 253 kPa [2.5 atm] oxygen) or 40% oxygen (nitrox 40, for 101.3 kPa [1.0 atm] oxygen). In the other pressure chamber, the hypobaric chamber, patients were treated at 101.3 kPa (1.0 atm abs), breathing either 100% oxygen (for 101.3 kPa [1.0 atm] oxygen) or air (for 21 kPa [0.21 atm] oxygen). The second reason these oxygen pressures were chosen, is that – in case 101.3 kPa (1.0 atm) oxygen would be found to have a therapeutic effect and air not – this would open the path to a possible treatment with normobaric oxygen mixtures, which would obviously be easier to make available to many more patients without needing the logistics and costs of a hyperbaric treatment. Finally, by incorporating an 'intermediate' level of hyperoxia in our study protocol, this allowed us to design the protocol with an effective placebo for both 'high' and 'intermediate' hyperoxic treatments.

In both pressure chambers (in all study groups) there was, at the start and end of each treatment, a (de)pressurisation

phase during which active or passive ear equalisation manoeuvres were needed. Not surprisingly, middle ear barotrauma did occur in all groups, though seldom severe enough to warrant interruption of the study. However, this may have contributed to a placebo effect in all groups, which was intentional as the aim of the study was to verify only the therapeutic effect of hyperoxygenation, not the combined effects of oxygen and the 'hyperbaric treatment setting'. Therefore, the expectations of all patients and the 'ritual' surrounding the administration of the treatments needed to be as similar as possible.[29]

In addition to creating similar environments and subjective experience for all study groups, care was taken to ensure that no patient felt he or she was in a 'less valuable' group. It was explained that the different dosages of oxygen given, by their biological effect, or the breathing from a mask inside a pressure chamber, by a mechanical, respiratory training effect, could all lead to a beneficial therapeutic result. Furthermore, no patient was ever charged for any of the treatments or consultations, as this was a scientific study. Finally, all patients received the formal promise that, should one oxygen dosage or regimen prove to be significantly effective, they would be offered a new course of the 'most effective' treatment free of charge in our institution, the Military Hospital being a non-commercial medical institution.

Since our study started, the results of a prospective, randomised controlled trial (RCT), were published comparing a series of 40 HBOT sessions (100% oxygen, 203 kPa) with a series of 'placebo' treatments (breathing air at 104.4 kPa) in a hyperbaric chamber.[30] This paper, which is to date the only randomised controlled trial on HBOT for Long COVID,[31] reports a small but statistically significant improvement in certain neuro-psychometric domains, as well as changes in perfusion MRI imaging of the brain. While this study shows some morphological and functional changes in patients after 40 HBOT sessions, it is not at all clear whether this resulted in a significant and meaningful improvement in their clinical condition. Even though this study claims to be 'blinded and placebo-controlled', the possibility remains that the observed changes were induced by a placebo effect.

The high probability of placebo effects in HBOT has been discussed extensively before,[32,33] and has been considered an important factor in the proclaimed results of open-labelled studies (using either HBOT or so-called 'mild hyperbaric therapy'), cross-over studies or studies using as 'sham' a hyperbaric chamber compression to 132 kPa.[33,34] All these publications, based on which HBOT or 'mild hyperbaric therapy' has been advocated for chronic debilitating diseases (including chronic traumatic brain injury,[35,36] chronic fatigue syndrome,[37] cerebral palsy,[38] autism,[39] fibromyalgia,[40,41] chronic stroke[42] and post-traumatic stress disorder[43]) fail to take the possibility of placebo effect into account. In some of these studies, functional brain imaging (f-MRI, SPECT) is used to objectively demonstrate a change after hyperbaric therapy. However, it has been shown that placebo effects, notably those induced by a positive expectation, can induce observable changes in brain metabolism almost to the same level as 'true' treatment.[29] Patients are willing to pay a sometimes-hefty price for hyperbaric oxygen treatments – which is often cited as proof 'that the treatment must be effective'. However, placebo effect may also play a significant role here; it has been experimentally shown that the price of an ineffective treatment increases the perceived effect, as well as the willingness to administer more doses of the expensive drug.[44] Recently, it was shown that placebo treatment, if causing some physical discomfort to the patient, also increases the placebo's 'perceived action' in comparison to an identical, but fully inert placebo, even inducing changes in cerebral fMRI images.[45]

In the Zilbermann study,[30] the 'control' condition consisted of a compression to only 122 kPa (1.2 atm abs) followed by gradual decompression to 104.4 kPa (1.03 atm abs). While the 'ritual' and 'expectations of improvement' may have been similar in both groups, it seems unlikely that significant middle ear discomfort was present in control patients. In most cases, significant middle ear discomfort and barotrauma only shows after a pressure gradient of more than 30 kPa (0.3 atm).[46,47] This could very well explain the larger proportion of patients responding to 'true' hyperbaric oxygen treatment. Therefore, the results reported in this study should be interpreted with caution.

Conclusions

Our prospective, randomised, placebo-controlled study did not show a significant effect from different levels of oxygen breathing (21, 101.3, or 253 kPa [0.21, 1 or 2.5 atm]) in a pressure chamber. The positive results from 10 sessions of HBOT at 253 kPa (2.5 atm) oxygen, as reported in previous studies are not confirmed in our study. Although our treatment course was shorter than the 40 sessions recently published, our results suggest that the overall very modest clinical improvements reported in that study may very well have been due to a placebo effect.

Because of the potentially high logistic burden and financial cost of HBOT and the 'false hope' that such a treatment may give, the claims that HBOT has a significant effect on Long COVID need to be further verified before indiscriminately prescribing or promoting HBOT.

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Data availability

The data that support the findings of this study are not openly available due to reasons of sensitivity and are available from the corresponding author upon reasonable request. Data are located in controlled access data storage at the Belgian Defence Military Hospital servers. The full study protocol and all questionnaires are available upon simple request.

Acknowledgements

We wish to thank all Long COVID patients for their enthusiastic and motivated participation in this study, the medical and paramedical personnel of the Centre for Hyperbaric Oxygen Therapy (CHBO) and the Centre for Aerospace Medicine of the Military Hospital Queen Astrid, for their continued support and assistance, and the Military Hospital authorities for allowing the hyper- and hypobaric chambers to be used for clinical research.

Conflicts of interest and funding: nil

Submitted: 9 December 2024
Accepted after revision: 30 March 2025

Diving practices in technical divers' community and behaviour towards self-reported unusual symptoms

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Keywords
Decompression illness; Diving incidents; Epidemiology; Helium; Health status; Mixed gas; Survey

Abstract
(Gouin E, Monnot DPM, Michot T, Guerrero F, Blatteau J-É. Diving practices in technical divers' community and behaviour towards self-reported unusual symptoms. Diving and Hyperbaric Medicine. 2025 30 June;55(2):114–125. doi: 10.28920/dhm55.2.114-125. PMID: 40544139.)
Introduction: The use of gas mixtures containing helium for deep recreational diving is increasingly common, involving complex logistics and decision-making compromises. The characteristics and inherent risks of this practice remain poorly documented. This study aims to provide an epidemiological inventory of practices and diving-related incidents within the technical diving community.
Methods: An international online survey was disseminated on social networks targeting certified trimix divers. It collected demographic data, diving experience, and dive management practices, along with self-reported unusual symptoms, treatments, and outcomes following trimix dives.
Results: A total of 558 questionnaires were analysed, predominantly from males (92%), mostly over 46 years old (61%), with high certification levels and recreational diving purposes. Forty-two percent reported one or more medical risk factors related to diving. Rebreather use was prevalent (79% at least occasionally). Decompression was primarily managed using compartmental models (85%) with gradient-factors adjustment. Dive planning varied significantly among individuals. Gas density at depth frequently exceeded the current recommendations. Ten percent had experienced symptoms suggestive of gas toxicity, mainly related to nitrogen narcosis. Thirty-six percent (199/558) reported experiencing, at least once, symptoms of diving-related incidents, with 61% (n = 121/199) expressing certainty. In 48% (120/261) of incidents involving decompression sickness (DCS) or breathing symptoms, no treatment was initiated. Among episodes involving DCS symptoms (n = 254), 42% received normobaric oxygen, and 23% sought medical advice, while 16% were treated with hyperbaric oxygen. Only 2.5% reported probable long-lasting sequelae.
Conclusions: The diversity of practices highlights the lack of robust scientific data supporting them. The accident rate in mixed-gas diving may be higher than in typical scuba air diving, though mostly of mild severity. Treatment appears to be neglected despite divers' high knowledge levels. Continued research into decompression and the physiological effects of these dives is essential, along with ongoing awareness and education efforts in diving first aid within this exposed community.

Introduction

'Technical diving' is variably defined but experts agree that the term applies when helium based mixed-gases are used to conduct deeper and longer dives. These dives entail a rapidly accumulated decompression obligation and specific risks associated with exceeding the limits of recreational diving.[1]

Although training standards for technical diving vary by certification agencies, all require advanced recreational diving experience, often including an enriched air nitrox qualification.[2,3] Thus, the technical community might be more experienced with a high level of diving related knowledges than traditional recreational divers from which they are derived. Despite sharing a common legacy, the specific characteristics, practices, and habits of this technical

community remain poorly documented. It is unclear whether this in-depth training combined with risk management awareness can influence planning and behaviour in the event of an accident.

Dive profile elaboration is critical to consider for technical divers. The execution of trimix dives involves a wide range of planning approaches, including equipment consideration, gas management, decompression strategies, and more with many differences within this community.[4] Many procedures remain untested and have not yet been developed nor validated for these types of dives.[5]

Diving exposes the diver to a risk of decompression sickness (DCS), and hyperbaric oxygen therapy (HBO) is the definitive treatment.[6] A DAN Indo-Pacific study suggests that recreational diving population is getting older, increasing the likelihood of medical conditions,[7] and the magnitude of this in the technical diving community remains unknown. While many thousands of technical dives have been conducted safely, the incidence of DCS is unidentified. Clinical expression of DCS might differ from recreational epidsodes.[8–10] In Finland, there has been a rise in treated cases among technical divers, likely linked to the activity's growing popularity. Technical divers are more likely to receive normobaric first aid oxygen (FAO_2) before HBO treatment compared to recreational divers.[9] A recent study indicated a high incidence of DCS among Finnish technical divers, with most of them opting for self-treatment of mild symptoms without consulting a physician or receiving HBO.[11] Therefore, incidents may be under-reported in this population as observed in non-technical recreational divers.[12]

The objective of this survey was to establish the demographic profile and current practices of technical divers. Additionally, it examined the incidence of pathological symptoms and associated healthcare interventions. Exploring the technical divers' characteristics and activities will facilitate risk assessment, ultimately helping to better meet the community's needs.

Methods

The study was approved by the data protection officer of Western Brittany University in accordance with the European Union's General Data Protection Regulation (ref-21042). Participation was voluntary, and responses were confidential.

DATA COLLECTION AND PROCESSING

A cross-sectional survey was conducted using bilingual (English and French) anonymous questionnaires via Google Forms (Google LLC, CA, USA) to facilitate international dissemination. The survey was tested by twelve 'mixed-gas recreational divers of varied experience and revised before distribution. It was shared through social media (Facebook®, Menlo Park, CA, USA) within technical diving groups from 21 December 2021 to 20 February 2022. Participation was limited to divers certified in mixed-gas bounce diving. The average time to complete the questionnaire was estimated at 10 minutes. It included 32 mandatory questions, plus four additional questions specifically for rebreather users. Among the 32 questions, six were conditional, leading to 26 further questions related to each specific condition investigated (*Supplementary Appendix 1).

The first part of the survey gathered information about sex, age, weight, height, home country, putative diving risk factors such as active smoking, arterial hypertension, diabetes mellitus, heart disease history (heart attack, valvular disease, or arrhythmia) and low physical activity (defined as moderate intensity exercise below 60 minutes per week). Obesity was defined by a BMI ≥ 30 $kg.m^{-2}$. Diving experience was assessed by the total years of scuba and trimix practice, the certification level and the number of dives. Questions regarding diving equipment mainly used in open circuit (OC) and rebreather (RE) and type of diving suit were included. There were questions on the diving environment such as sea, lake, cave, water temperature typically encountered, and affiliations were also investigated.

The second part of the survey was designed to collect information on the decompression algorithm used, oxygen partial pressure (PO_2) setpoint (in rebreather diving), bottom gas mix preferences, and gradient factors (GFs) for Bühlmann's model users across three target depths: 50, 80 and 100 metres of seawater (msw). Based on answers, the inspired PO_2, the equivalent narcotic depth (END, i.e., the air diving depth that would produce the same amount of narcosis as the trimix at its target depth) and the gas density for each maximal depth were calculated.[1]

The third part was oriented to occurrence of subjective clinical symptoms as previously described,[12] actions taken in response to symptoms (i.e., self or medical treatment) and long-lasting sequelae after symptoms in mixed-gas diving. Questions regarding gas-toxicity covered symptoms of narcosis (i.e., unusual euphoric feeling, concentration disorders or alteration in judgement at depth), loss of consciousness (LOC) at depth, or high-pressure nervous syndrome (HPNS, i.e., uncontrollable shaking of limbs or whole body excluding cold shivering, usually only apparent at extreme depths). Symptoms compatible with DCS were suggested by unusual tiredness, arm, leg, or articular pain, dizziness, vomiting, ear ringing, or hearing impairment, and acute back pain, tingling, or a decreased limb strength. Persistent breathing difficulties after surfacing, with or without foamy sputum, were also investigated. Given narcosis is a predictable biochemical consequence of deep

***Footnote:** Supplementary Appendix 1 is available to download from: https://www.dhmjournal.com/index.php/journals?id=354

diving, it was not classified as a diving-related incident in this study. Similarly, barotrauma, the leading cause of diving injury and primarily affecting beginners, was not investigated and not considered in this definition.[12]

STATISTICAL ANALYSIS

Most responses were analysed descriptively. Continuous variables are presented as mean (standard deviation [SD]) when normally distributed and median and interquartile range (IQR) when normality test fail. Categorical variables are presented as counts and percentages. Comparisons between discrete variables were performed using Fisher's exact test. Data processing and analyses were conducted using R version 4.3.2 basic configuration. Statistical significance was defined as a P-value < 0.05.

Results*

*Originally submitted tables which, in Tables 2, 4 and 5 include detailed data broken down by nationality of respondents, have been included in *Supplementary Appendix 2.

During the study period 559 responses were received. One was excluded due to incoherent answers.

DESCRIPTION OF THE TRIMIX DIVER COMMUNITY

Thus, 558 were collected for analysis purpose (514 males and 44 females). The age classes were 18–25 for 11 (2%), 26–35 for 66 (11.8%), 36–45 for 143 (25.6%), 46–55 for 212 (38%) and older than 55 years for 126 (22.6%) divers. The distribution by country is shown in Table 1. Table 2 depicts medical conditions known as a risk factors declared by divers including obesity. Twenty-three (4.1%) divers reported at least two risk factors. All were male (Table 3). Considering obesity as a risk factor, 323 (57.9%) reported none, including 32/44 (72.7%) of the females.

In relation to scuba diving experience, 16 (2.9%) declared practising diving for less than five years, 77 (13.8%) between 6–10 years, 161 (28.9%) between 11–20 years and 304 (54.5%) for over 20 years. The trimix experience is shown in Table 1. Three-hundred-forty-seven (62.2%) held the highest trimix certification level, including 20/44 (45.5%) of the females. Dive parameters associated with different certification levels vary, but an indicative classification is as follows: Helitrox/basic mixed-gas diver – maximum depth 45 msw and helium fraction ≤ 35%; Trimix/mixed-gas – maximum depth 60–70 msw and minimum oxygen fraction 16–19%; Advanced Trimix/advanced mixed-gas – maximum depth 100–120 msw with unlimited helium fractions and hypoxic mixes as required.

Four hundred and four (72.4%) technical divers were engaged solely in recreational diving activity. One-hundred-and-five (18.8%) reported a teaching activity (instructor), and 30 (5.4%) had other professional diving activity such as military, media, scientific diving. Sixteen (2.9%) combined these two activities, while seven (1.3%) were involved exclusively in other professional activities without any recreational diving practice. Six (13.6%) females reported diving for occupational purposes. More than one training organisation in their technical diving certifications were reported by 255 (45.7%). The agencies most represented were TDI (Technical Diving International, n = 260, 46.6%) and IANTD (International Association of Nitrox and Technical Divers, n = 217, 38.9%).

CURRENT PRACTICES

Rebreathers were used, at least occasionally, by 441 (79%) of respondents. Open circuit scuba was used exclusively by 75/191 (39.3%) of 'mixed-gas' and 36/347 (10.4%) of 'advanced mixed-gas' certified divers (Table 1). Age range did not influence the apparatus preference (P = 0.09). Dry suits were used by 479 (85.8%) divers, among which 156/479 (32.6%) also utilised a dry suit heating system. Divers reported mainly practising technical diving in their home country for 357 (64%) and abroad for 88 (15.8%). The others dive equally between the two. They dive, at least in part, in cave or lake (and quarry) for 145 (26%) and 202 (36.2%) respectively (Figure 1).

To manage decompression, 476 (85.3%) divers declared using the Bühlmann's model while 75 (13.4%) used bubble models (Reduced Gradient Bubble or Varying Permeability Models). Seven (1.3%) didn't answer. The survey focused on user-adjusted low-GF and high-GF for Bühlmann algorithm (Figure 2). The setting remained unchanged by 162/476 (34%) irrespective of the depth. The calculated median (IQR) density of bottom gas was 5.8 (5.5–6.9) and 5.9 (5.3–6.6) $g.L^{-1}$ in OC and RE respectively. Sixteen/301 (5.3%) respondents for rebreather diving didn't use helium at 50 msw (i.e., they used air diluent), while 4/186 (2.2%) used heliox (i.e., oxygen-helium mix with no nitrogen) for 100 msw dives. Values exceeding ideal and recommended maximum gas density are shown in Table 4. For rebreather dives, the chosen trimix diluent resulted in a PO_2 ≤ 1.1 bar at the maximal depth for 236/301 (78.4%), 204/234 (87.2%), 174/186 (93.6%) and an END ≤ 30 msw for 233/301 (77.4%), 139/234 (59.4%), 138/186 (74.2%) at 50, 80 and 100 msw respectively. At maximal depth, a PO_2 > 1.4 bar and > 1.6 bar were exceeded for 18/205 (8.8%) and 6/205 (2.9%) OC respondent divers. Rebreathers allow breathing at a constant PO_2 'set point' chosen by the user. The most common PO_2 set point declared was 1.3 bar (n = 302/441, 68.5% and n = 247/441, 56% at the bottom and during the

***Footnote:** Supplementary Appendix 2 is available to download from https://www.dhmjournal.com/index.php/journals?id=354

Table 1

Comparative table of the entire study population, distinguishing between divers with no reported incidents and those with at least one (n = 121) diving-related incidents; only responses expressing certainty of a symptomatic problem (or not) are considered. Diving-related incidents encompassed biochemical (gas related – but not nitrogen narcosis), decompression sickness or pulmonary symptoms during or after trimix dives. France-OT – overseas French territories; NZ – New Zealand; UK – United Kingdom

Parameter	Questionnaire options	Overall *n* (%)	No Diving incident *n* (%)	≥ 1 Diving incident(s) *n* (%)
Experience since first trimix certification (Years)	< 1	35 (6.3)	20 (8.2)	2 (1.7)
	1–5	201 (36)	100 (40.8)	34 (28.1)
	6–10	152 (27.2)	56 (22.9)	39 (32.2)
	11–20	130 (23.3)	55 (22.5)	29 (24)
	> 20	40 (7.2)	14 (5.7)	17 (14.1)
	Sum	558 (100)	245 (100)	121 (100)
Level of trimix certification	Helitrox	20 (3.6)	11 (4.5)	–
	Trimix	191 (34.2)	103 (42)	23 (19)
	Advanced Trimix	347 (62.2)	131 (53.5)	98 (81)
	Sum	558 (100)	245 (100)	121 (100)
Number of trimix dives	< 20	85 (15.2)	46 (18.8)	12 (9.9)
	20–50	129 (23.1)	65 (26.5)	15 (12.4)
	51–100	98 (17.6)	46 (18.8)	20 (16.5)
	101–500	172 (30.8)	62 (25.3)	46 (38)
	> 500	74 (13.3)	26 (10.6)	28 (23.1)
	Sum	558 (100)	245 (100)	121 (100)
Frequency of trimix practice (Dives per year)	< 5	90 (16.1)	47 (19.2)	11 (9.1)
	6–10	111 (19.9)	58 (23.7)	16 (13.2)
	11–20	121 (21.7)	57 (23.3)	22 (18.2)
	21–30	94 (16.8)	32 (13.1)	28 (23.1)
	> 30	142 (25.5)	51 (20.8)	44 (36.4)
	Sum	558 (100)	245 (100)	121 (100)
Trimix breathing equipment used	Rebreather	282 (50.5)	124 (50.6)	104 (52.3)
	Open Circuit	117 (21)	61 (24.9)	31 (15.6)
	Both	159 (28.5)	60 (24.5)	64 (32.2)
	Sum	558 (100)	245 (100)	121 (100)
Country of residence	France	221 (39.6)	106 (43.3)	43 (35.5)
	UK	61 (10.9)	22 (9)	17 (14.1)
	Belgium	54 (9.7)	28 (11.4)	11 (9.1)
	Germany	41 (7.4)	17 (6.9)	10 (8.3)
	Switzerland	30 (5.4)	11 (4.5)	8 (6.6)
	USA	24 (4.3)	10 (4.1)	4 (3.3)
	France-OT	22 (3.9)	11 (4.5)	2 (1.7)
	Canada	19 (3.4)	8 (3.3)	5 (4.1)
	Australia-NZ	12 (2.2)	6 (2.5)	2 (1.7)
	Other	74 (13.3)	26 (10.6)	19 (15.7)
	Sum	558 (100)	245 (100)	121 (100)
Most common water temperature (°C)	< 8	107 (19.2)	45 (18.4)	24 (19.8)
	8-20	331 (59.3)	144 (58.8)	72 (59.5)
	20-25	70 (12.5)	32 (13.1)	15 (12.4)
	> 25	50 (9)	24 (9.8)	10 (8.3)
	Sum	558 (100)	245 (100)	121 (100)

Table 2
Medical risk factors related to diving reported by respondents; the total of 555 only relates to subjects for whom body mass index (BMI) information is available; + Ob – number of respondents with both the specified condition and a BMI ≥ 30 kg.m^{-2}

General population		Overall conditions			Detailed risk factors and obesity (Ob)											
					Arterial hypertension		Diabetes mellitus		Heart disease		Low physical activity		Smoking			
Sex	*N*	BMI kg.m^{-2} Mean (SD)	BMI ≥ 30 kg.m^{-2} *n* (%)	All risk factors (Cumulative) Mean (SD)	*n*	+ Ob *n* (%)	*n*	+ Ob *n* (%)	*n*	+ Ob *n* (%)	*n*	+ Ob *n* (%)	*n*	+ Ob *n* (%)		
Male	511	26.9 (3.8)	98 (19%)	163 (32)	38 (23)	41	14 (34)	16	4 (25)	11	3 (27)	88	21 (24)	40	6 (15)	
Female	44	24.9 (5)	7 (16%)	8 (18)	3 (38)	2	1 (50)	–	–	–	–	4	2 (50)	2	–	
Total	555	26.8 (3.9)	105 (19%)	171 (31)	32.9 (2.8)	41 (24)	43	15 (35)	16	4 (25)	11	3 (27)	92	23 (25)	42	6 (14)

Table 3
Accumulated medical risk factors related to diving reported by technical diving subjects

Condition	***n* (%)**
Subjects with no risk factors	386 (69.2)
Subjects who declared one risk factor, *n* = 149 (26.7%)	
Low physical activity	76 (13.6)
Smoking	29 (5.2)
Arterial hypertension	28 (5)
Diabetes mellitus	9 (1.6)
Heart disease	7 (1.3)
Subjects who declared two risk factors, *n* = 18 (3.2%)	
Low physical activity + Smoking	6 (1.1)
Arterial hypertension + Low physical activity	5 (0.9)
Arterial hypertension + Smoking	3 (0.5)
Arterial hypertension + Diabetes mellitus	2 (0.4)
Heart disease + Smoking	1 (0.2)
Diabetes mellitus + Low physical activity	1 (0.2)
Subjects who declared three risk factors, *n* = 2 (0.4%)	
Arterial Hypertension + Low Physical Activity + Smoking	1 (0.2)
Arterial hypertension + Diabetes mellitus + Low physical activity	1 (0.2)
Subject having declared four risk factors, *n* = 1 (0.2%)	
Arterial hypertension + Diabetes mellitus + Heart disease + Low physical activity	1 (0.2)
Subjects who declared five risk factors, *n* = 2 (0.4%)	
Arterial hypertension + Diabetes mellitus + Heart disease + Low physical activity + Smoking	2 (0.4)
Total	***n* = 558**

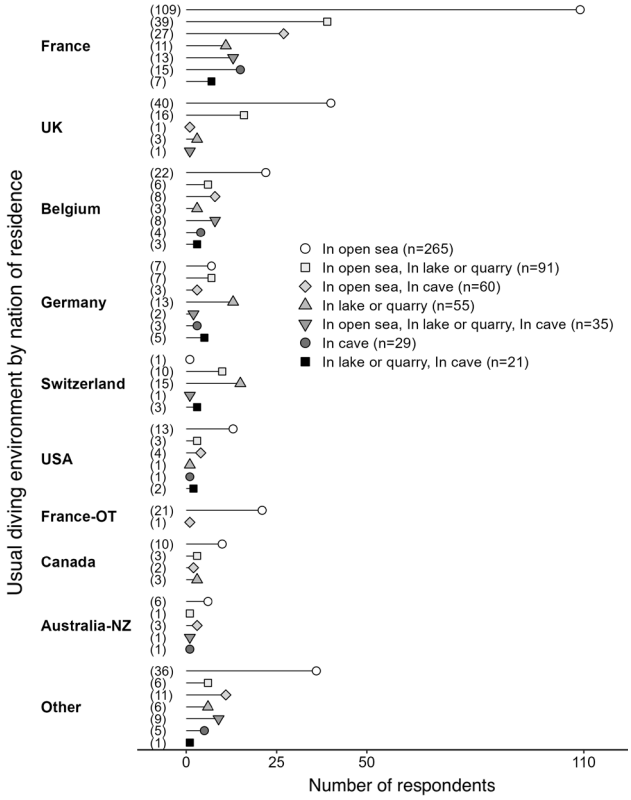
ascent time respectively). From the 6-msw decompression stop, 338/441 (76.6%) declared setting their $PO_2 \geq 1.4$ bar (Table 5).

SELF-REPORTED ABNORMAL PATHOLOGICAL SYMPTOMS

Self-reported diving-related symptoms covered all participants' mixed-gas diving experiences, including gas toxicity, DCS, and pulmonary symptoms (Table 6). The most frequent gas-toxicity symptom was 'euphoric feeling'. It

Figure 1

Trimix diving environment related by nation of residence; France-OT – Overseas French territories; NZ – New Zealand; UK – United Kingdom; USA – United States of America



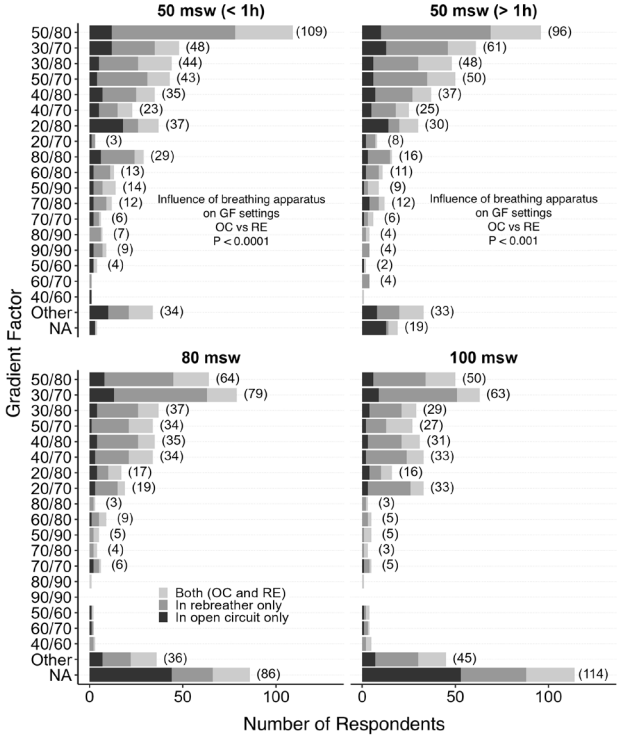
was noted by 3/20 (15%) of basic trimix divers and 39/538 (7.3%) with higher levels of certification.

Sixty-four percent (n = 359) of divers reported having never experienced any diving-related incidents, among which 114/359 (31.8%) remained uncertain. Conversely, 199 (35.7%) experienced an incident at least once. That concerned 13/44 (29.6%) of the females, independently of the degree of certainty. Fifty-nine (10.6%) divers declared more than one event. Seven (1.3%) (five definite) respondents experienced breathing trouble, exclusively in rebreather diving. All were male and no one was older than 55 years old.

Regardless of the type of DCS symptoms and the degree of certainty (n = 254 events), FAO_2 was received in 107/254 (42.1%) events and medical advice was sought in 59/254 (23.2%). Forty-one/254 (16.1%) were treated with HBO (Table 7). In 120/254 (47.2%) events, divers did not report having initiated any treatment. When musculoskeletal pain was declared, 33/101 (32.7%) took antalgic drugs by themselves. Divers received significantly more frequent care when the symptoms were identified as pathological with certainty rather than with a doubt ($P < 0.0001$). When symptoms appeared more severe, suggestive of inner-ear or neurological conditions, divers were more likely to consult a

Figure 2

Gradient Factor (GF) choices related to dive profile; the one-hour limit in the 50 msw dives is the total ascent time (TTS; Time to surface) including ascent with any decompression obligations. GF are expressed by a combination of low / high (see text for an explanation). A total of 53 different combinations were declared regardless of the dive profile. For a 50 msw dive, the TTS had no significant effect on settings (P = 0.6). However, the breathing apparatus (OC vs RE) used led to significant differences in GF parameters regardless of dive time (see figure). GF settings were not significantly influenced by depth at 80 and 100 msw (P = 0.4) nor by the breathing apparatus at those depths (P = 0.1)



doctor than in other cases (n = 12/31, 38.7% vs n = 47/222, 21.2% P = 0.04). However, there was no difference in use of FAO_2 in these more severe cases when compared to milder cases (n = 14/30, 46.7% vs n = 93/220, 42.3% P = 0.7) or even in accessing HBO treatment (n = 7/31, 22.6% vs n = 34/223, 15.3% P = 0.3). Five/199 (2.5%) divers declared suffering from long-lasting sequelae after DCS symptoms. Four received FAO_2 and only one HBO treatment. After they experienced breathing issue, only two divers used FAO_2, and one sought medical advice.

Discussion

DEMOGRAPHIC DESCRIPTION

The use of rebreathers has become mainstream in technical diving, particularly for deep dives. This study reveals significant variations in planning behaviors, with some diver practices not always aligning with current recommendations. This could highlight either a lack of robust scientific data

Table 4

Proportion of divers exceeding the ideal (5.2 g·L^{-1}) and maximum recommended (6.2 g·L^{-1})[21] gas density on dives stratified by depth and underwater breathing apparatus used; gas density calculation was based on respired gas at maximum depth. For rebreathers, the calculation is based on mixed-gas diluent composition and the bottom oxygen partial pressure set point breathed in the loop; msw – metres of seawater

Breathing apparatus	At 50 msw			At 80 msw			At 100 msw		
	Overall *N* (%)	> 5.2g·L^{-1} *n* (*n*/*N*%)	> 6.2g·L^{-1} *n* (*n*/*N*%)	Overall *N* (%)	> 5.2g·L^{-1} *n* (*n*/*N*%)	> 6.2g·L^{-1} *n* (*n*/*N*%)	Overall *N* (%)	> 5.2g·L^{-1} *n* (*n*/*N*%)	> 6.2g·L^{-1} *n* (*n*/*N*%)
Rebreather	301 (54.8)	181 (60.1)	27 (9)	234 (60.5)	200 (85.5)	113 (48.3)	186 (62.4)	172 (92.5)	80 (43)
Open circuit	113 (20.6)	85 (75.2)	21 (18.6)	41 (10.6)	36 (87.8)	30 (73.2)	21 (7.1)	21 (100)	17 (81)
Both	135 (24.6)	69 (51.1)	14 (10.4)	112 (28.9)	75 (67)	48 (42.9)	91 (30.5)	67 (73.6)	33 (36.3)
Total	549 (100)	335 (61)	62 (11.3)	387 (100)	311 (80.4)	191 (49.4)	298 (100)	260 (87.3)	130 (43.6)

Table 5

Oxygen partial pressure setpoint selected by rebreather users related to the phase of the dive; DNK – don't know / no position

Partial pressure of oxygen set point							
1.1 bar *n* (%)	1.2 bar *n* (%)	1.3 bar *n* (%)	1.4 bar *n* (%)	1.5 bar *n* (%)	1.6 bar *n* (%)	DNK *n* (%)	Sum *n* (%)
During bottom time							
14 (3.2)	98 (22.2)	302 (68.5)	22 (5)	3 (0.7)	1 (0.2)	1 (0.2)	441 (100)
During ascent							
	59 (13.4)	247 (56)	76 (17.2)	45 (10.2)	12 (2.7)	2 (0.4)	441 (100)
From 6-msw decompression stop							
		99 (22.5)	74 (16.8)	87 (19.7)	178 (40.4)	3 (0.7)	441 (100)

supporting these guidelines or a diversity in teaching and individual approaches. Estimating the number of technical divers is challenging, but recent data suggest there are about 20,000 active rebreather divers worldwide.[13] Among this community, the number of mixed-gases certified divers remains unknown. While the proportion of trimix divers represented by the present study cannot be estimated, this work provides one of the first representations of this community that moves beyond anecdotal evidence.[14]

In recreational diving, it is common knowledge that there are more males than females, and most of divers hold beginner level certifications and dive occasionally. Most divers are age 30–40, with females representing 17–37% of the population.[15] In contrast, technical divers are generally older, with two-thirds of respondents over 46 years old; a trend consistent with other recent studies.[9,11,13] Significant diving experience remains a prerequisite for technical diving and most respondents have reached the maximal trimix certification. However, this may evolve with the possibility of training in 'light' recreational trimix (helium fraction < 35% and 45 msw maximal depth) from advances diver with a minimum experience of 40-50 dives.[2,3] Female representation, already low in recreational diving, is even smaller in technical diving, ranging from 7–16% in previous studies, and 8% in the present study.[11,16] This sex disparity could partly be explained by how the survey was distributed, as social media usage differs by gender.[17] Additionally, gender differences in diving practices have been noted, with technical and equipment-focused aspects potentially contributing to a predominantly male community.[18] However, a new generation of female divers is emerging, increasingly participating in traditionally male-dominated activities.

One third of technical divers reported having a condition considered as a medical diving risk factor that is consistent with the recreational diving community, with a progressive increase with age.[7,19] Despite this, the prevalence of most conditions is lower than in the global population and may be the subject of preventive actions.[20] Obesity, a major risk factor for metabolic and cardiovascular diseases, is over-represented among divers. Most of the cardiorespiratory diseases or diabetes were historically considered a contraindication for scuba diving though this position has evolved through better understanding and medical supervision of these conditions in diving. Promoting physical exercise associated with health and diet rules must be

Table 6
Self-reported diving-related symptoms in trimix diving; HPNS – high pressure nervous syndrome

Event evocative of gas effect/toxicity			
Questionnaire response	Narcosis *n* (%)	Loss of consciousness *n* (%)	HPNS *n* (%)
Never reached depth > 100 msw			284 (50.9)
Definite no	464 (83.2)	545 (97.7)	255 (45.7)
Probably not but doubtful	52 (9.3)	6 (1.1)	10 (1.8)
Yes, potentially but doubtful	22 (3.9)	3 (0.5)	3 (0.5)
Definite yes	20 (3.6)	4 (0.7)	6 (1.1)
Total	558 (100)	558 (100)	558 (100)

Event evocative of decompression sickness					
Questionnaire response	Unusual intense tiredness *n* (%)	Musculoskeletal pain *n* (%)	Dizziness / hearing trouble *n* (%)	Neurological trouble *n* (%)	Breathing trouble *n* (%)
Definite no	307 (55.0)	417 (74.7)	519 (93.0)	531 (95.2)	545 (97.67)
Probably not but doubtful	129 (23.1)	40 (7.2)	18 (3.2)	17 (3.1)	6 (1.1)
Yes, potentially but doubtful	61 (10.9)	39 (7.0)	3 (0.5)	4 (0.7)	2 (0.4)
Definite yes (one time)	27 (4.8)	34 (6.1)	14 (2.5)	5 (0.9)	4 (0.7)
More than one time	34 (6.1)	28 (5.0)	4 (0.7)	1 (0.2)	1 (0.2)
Total	558 (100)	558 (100)	558 (100)	558 (100)	558 (100)

encouraged to limit the risk of medical incidents. Periodic assessments by a competent diving practitioner should be appropriate for these exposed divers to prevent risk.

DIVING HABITS

Training agencies typically limit technical diving training to depths of 100–120 msw, making the dive profiles in this study representative of mainstream technical diving.[1–3] One of the major challenges for divers is the uncertainty surrounding decompression safety, which involves various factors such as algorithm configuration, gas choices, oxygen exposure, and ascent speed.[5]

To minimise nitrogen narcosis and gas density, higher helium fractions are used at greater depths.[1] Divers are proficient in managing oxygen exposure and calculating END. However, gas density often exceeds rebreather recommendations, which set an ideal gas density at 5.2 $g.L^{-1}$ and a goal of not exceeding 6.2 $g.L^{-1}$.[21] Exceeding these limits increases the work of breathing and can impair the ventilatory response to rising CO_2 levels, potentially leading to hypercapnia, immersion pulmonary oedema (IPO), and even fatal outcomes.[22,23] In OC, pulmonary constraints are presumed to be lower, allowing for higher tolerances, although no international consensus exists. For instance, French commercial diving regulations set a maximum gas density of 9 $g.L^{-1}$. Very few divers have reported respiratory symptoms suggestive of IPO, despite the suspected contribution of the hydrostatic load potentially induced by rebreather use and increased gas density.[23] The reasons for limiting helium fraction are cost considerations (especially in OC diving) and shortening the decompression obligation by reducing the 'helium penalty'.[5] The financial aspect must be no longer be a concern in technical diving since rebreather use is becoming more common. From this point of view, it seems important to raise community awareness of the impact of gas density on the risk of hypercapnia and the potential increased risk of DCS with CO_2 retention during bottom phase of a dive.[24]

Choosing the right decompression algorithm is a delicate balance between minimising time in the water and ensuring a safe decompression.[5] Compartmental models such as Bühlmann's, and related derived algorithms are widely used. There was previously a widespread belief that bubble algorithms, which promote 'deep-stops', were more efficient but recent data support the opposite.[5,16] User-adjustable GFs result in a modified decompression profile so that the low-GF number influences the depth of the first-stop, while the high-GF number affects the duration of shallower stops.[5] The numbers themselves represent the percentage of the allowable Buhlmann supersaturation in the notional leading tissue (closest to the Bühlmann supersaturation limit) at the first stop (low number) and on arrival at the surface (high number). Planning strategies vary widely between divers,

Table 7

Symptoms suggestive of decompression sickness and healthcare management; DNK – don't know / no position; FAO_2 – normobaric first aid oxygen; HBO – hyperbaric oxygen

Symptom description	Questionnaire answers	FAO_2			Seek medical advice			Receive HBO therapy		Long lasting sequelae		
		Yes	No	DNK	Yes	No	DNK	Yes	No	Yes	No	DNK
Unusual intense tiredness	Yes, potentially but doubtful	13	46	2	3	57	1	2	59			
	Yes (one time)	10	17	0	3	24	0	3	24			
	More than one time	16	18	0	10	24	0	5	29			
	Total	39 (32.0)	81 (66.4)	2 (1.6)	16 (13.1)	105 (86.1)	1 (0.8)	10 (8.2)	112 (91.8)			
Musculoskeletal pain	Yes, potentially but doubtful	7	31	1	6	33		3	36	2	34	3
	Yes (one time)	27	7	0	15	19		14	20	1	33	0
	More than one time	20	8	0	10	18		7	21	0	26	2
	Total	54 (53.5)	46 (45.5)	1 (1.0)	31 (30.7)	70 (69.3)		24 (23.8)	77 (76.2)	3 (3.0)	93 (92.1)	5 (5.0)
Dizziness and hearing trouble	Yes, potentially but doubtful	0	3		0	3		0	3	0	3	0
	Yes (one time)	8	6		7	7		4	10	1	12	1
	More than one time	0	4		2	2		0	4	0	4	0
	Total	8 (38.1)	13 (61.9)		9 (42.9)	12 (57.1)		4 (19.1)	17 (81.0)	1 (4.8)	19 (90.5)	1 (4.8)
Neurological trouble	Yes, potentially but doubtful	2	1	1	0	4		1	3	1	3	
	Yes (one time)	3	2	0	3	2		2	3	0	5	
	More than one time	1	0	0	0	1		0	1	0	1	
	Total	6 (60)	3 (30)	1 (10)	3 (30)	7 (70)		3 (30)	7 (70)	1 (10)	9 (90)	

with choices often based on experience or beliefs rather than scientific evidence.[4] The use of GFs is not directly linked to experimentally validated decompression profiles.[5] Our study shows that divers tend to lower their GF settings with increasing depth. The practice of deep stops has been heavily debated, particularly for air dives, where nitrogen loading is high.[25] The optimal decompression path, especially when managing both helium and nitrogen, remains unresolved. Helium's lower solubility and faster washout suggest decompression should begin earlier in helium-based dives, though without reaching the classical 'deep stop' thinking.

During decompression, the inspired oxygen fraction is progressively increased to accelerate the elimination of inert gases. In OC, the gas mixes carried and breathed determines the PO_2 at each depth, requiring gas switches to optimise decompression during ascent. Oxygen toxicity is less of a concern in OC since the PO_2 peak is generally breathed for relatively short periods. However, in rebreather diving, high PO_2 levels are maintained throughout most of the dive, typically at a set point of 1.3 to 1.4 bar, which is considered safe. Short exposures to 1.6 bar are tolerated by most agencies.[2,3] Although most divers respect these limits, two-thirds reported using a $PO_2 \geq 1.4$ bar during decompression. Oxygen toxicity is cumulative and can lead to seizure and drowning. Exceeding current exposure limits doesn't appear to cause significant decrease in lung function, although some symptoms consistent with oxygen toxicity (chest tightness or dry cough) have been described by technical divers.[26] Given that decompression times often exceed two or three hours, exposure to high PO_2 levels during the ascent may quickly exceed safe neurological toxicity thresholds.[27] Other factors, such as hypercapnia, thermal stress, and medication, can exacerbate susceptibility. A reasonable balance can be achieved by keeping $PO_2 \leq 1.3$ bar during the bottom phase, where the reduction in inert gas uptake is modest to safely manage oxygen during shallow decompressions stops.

DIVING RELATED INCIDENTS

More than a third of respondents reported symptoms suggestive of diving-related incidents. Although not considered as an injury or incident, narcosis was rarely mentioned due to compliance with END limits. Most serious gas-toxicity symptoms seem uncommon but remain life-threatening. This contrasts with military diving, where equipment and procedures are different, and where gas toxicity was found to be the most common diving incident, with hypercapnia and hyperoxic seizures frequently reported.[28]

DCS may present with a wide range of symptoms sometimes making the diagnosis difficult. In retrospective recreational diving surveys, the incidence of self-reported symptoms was around two per 10,000 dives and 15% of divers reported potential DCS histories. Severe cases accounted for 15–27% of these reports.[12,29] The incidence may be higher among technical divers, but few data are available.[9,11] This was previously discussed by Tuominen, who reported an incidence of 91 per 10,000 dives, with 31% of divers experiencing DCS symptoms during a one-year follow-up period.[11] Nearly all reported symptoms in technical diving are considered 'mild' as characterised by an international consensus.[30] Constitutional symptom and musculoskeletal pain are predominant (88% of cases), while neurological impairment is uncommon in helium mixed-gas diving, consistent with the literature.[9,11]

Several studies have demonstrated that first aid for diving injuries is often inadequate.[11,12,18] In recreational diving, 32% of divers with symptoms did not receive any treatment.[12] In the present study, half of the respondents did not undertake any treatment. Although technical divers are presumed skilled with easy access to oxygen, only 42% used FAO_2. Neglect of these symptoms seems to be related to the estimated level of severity, as has already been highlighted elsewhere.[12] This behavior may lead to the appearance of distant complications such as dysbaric osteonecrosis (DON) in this population, though despite the theoretical risk, clinically apparent cases still seem rare.[10] Among recreational divers who have presented DCS symptoms, 23% have declared long-term consequences compared to only 2.5% in our population.[12] The predominance of mild symptoms in technical diving might explain this difference.[11] However, DON may become symptomatic years later, potentially leading to an underestimation of their severity in the absence of systematic imaging evaluation. Raising awareness about the recognition of symptoms and proper first aid still appears necessary among these exposed divers.

LIMITATIONS

This study faced several limitations. Firstly, the dissemination channel may have introduced recruitment bias, and the response rate is unknowable. The most active divers on social media are likely those more engaged in the community. Their presence may be age- or sex-dependent. Secondly, there is a significant imbalance in the respondents' distribution by country, with a predominant representation from Europe. Consequently, no formal analysis of regional variation could be drawn. Finally, like all surveys, the methodology induces recall bias, leading to potential over- or under-reporting of symptoms frequency, severity or reactions.

Conclusions

The diversity of practices highlights the lack of robust scientific data supporting them, and controversies and discussions are still ongoing. The issue of gas density does not appear to concern divers, even though it could have detrimental effects. The incident rate in mixed-gas diving may be higher than in recreational diving, albeit with mostly mild severity. Treatment of DCS symptoms often appears to be neglected despite divers' high level of knowledge. The prognosis often appears to be favorable, although it could be speculated there might be an increasing incidence

of DON over time. Continued efforts in awareness and education regarding training standards and diving first aid are essential for this exposed community. The results of this study could provide valuable insights to enhance training recommendations and inform future research initiatives.

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Acknowledgement

The authors thank technical divers for their responses and the interest they show in advancing their field. We are grateful to Dr Emmanuel Dugrenot from DAN for his assistance in proofreading the manuscript.

Conflicts of interest and funding: nil

Submitted: 4 November 2024
Accepted after revision: 28 February 2025

Effects of hyperbaric oxygen therapy initiation latency on auditory outcomes following acute acoustic trauma

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Keywords
Hearing loss; Hyperbaric research; Treatment delay

Abstract
(Manheim M, Mogilevsky L, Geva A, Knoll O, Zehavi G, Gur I. Effects of hyperbaric oxygen therapy initiation latency on auditory outcomes following acute acoustic trauma. Diving and Hyperbaric Medicine. 2025 30 June;55(2):126–135. doi: 10.28920/dhm55.2.126-135. PMID: 40544140.)

Introduction: Hyperbaric oxygen (HBO) is a potential adjunct treatment to improve hearing following acute acoustic trauma. However, the optimal time frame for HBO initiation has not been elucidated.

Methods: Patients exposed to intense noise as part of active military service that met our audiometric criteria were referred for combined HBO (253 kPa for 80 min, treatment numbers titrated to response) and corticosteroid treatment. The primary outcome was defined as an improvement of at least 10 dB in any of the measured high pure tone frequencies (3, 4, 6 or 8 kHz). Additional outcomes included the absolute change in high pure tone (3, 4, 6 and 8 kHz) summation (HPTS), relative change in HPTS compared to baseline (rHPTS) and the proportion of patients returned to auditory combat readiness.

Results: Of 129 ears (103 patients) included in the final analysis, 59/67 (88%) of the patients treated within seven days but only 14/25 (56%) of patients treated 21 days or more from exposure met the primary outcome (Bonferroni adjusted $P = 0.002$). Similarly, HPTS improvement (55 dB vs -5dB), rHPTS improvement (55% vs 3%) and return to combat readiness (32/56 (57%) vs 3/20 (15%)) were significantly ($P < 0.001$, $P < 0.001$ and $P = 0.017$, respectively) more pronounced in patients treated earlier. These results were unchanged despite adjusting to age, degree of initial hearing loss and the mechanism of injury.

Conclusions: Early initiation of HBO following acute acoustic trauma is associated with improved response to therapy. The optimal treatment latency appears to be within seven days from injury, with response rates dropping when treatment is delayed beyond three weeks.

Introduction

Acute acoustic trauma (AAT) is the leading cause of newly diagnosed preventable hearing disability in young adults.[1] Beyond direct mechanical damage to the cochlear hair bundles, the acoustic overstimulation at the heart of this condition leads to massive neurotransmitters and cytokine release.[2] The resultant inflammation and decreased cochlear blood flow cause inner ear hypoxia, furthering the damage through free radicals and proinflammatory cytokines, in a vicious cycle propagating the sensory neuronal damage. This damage often manifests clinically as any combination of sensorineural hearing loss, tinnitus, hyperacusis or auricular fullness.[3,4]

Consequently, several studies have examined the efficacy of hyperbaric oxygen (HBO) therapy for AAT, as an adjunct to well-established standard of care of oral, intravenous or intratympanic glucocorticoids.[5–7] The timing of HBO therapy initiation after AAT seems to be of utmost importance, as demonstrated in studies comparing early (up to two days) versus late treatment.[8,9] Limited data from animal models showed HBO treatment to be most efficacious when initiated 1–7 days post exposure.[3] However, there is a paucity of evidence regarding the optimal initiation time for HBO treatment for AAT in humans.

One study described patients treated within one week from exposure, in whom improvement was significant and seemed to be more pronounced with earlier initiation within this timeframe.[8,10] Another reported a significant improvement in hearing thresholds when HBO was initiated within five days from exposure in a small sample of 22 ears.[11] A third found that initiation of treatment (steroids with or without HBO) within seven days from injury was more effective compared to later treatment (74% versus 53% of ears showed significant audiometric improvement). However, in this work only patients failing to improve with pharmacological

treatment received HBO therapy, thus the exact contribution of HBO therapy remains undetermined.[12]

Other works included only patients treated very shortly after (up to 43 hours)[13] or within four days[14] from noise exposure. Most of the aforementioned studies were conducted in the setting of a professional army during peace-time, and were therefore limited in sample size and in patients' age-range. We aimed to elucidate the relationship between HBO therapy initiation latency and hearing improvement in AAT, accounting for other potential factors such as patient age and corticosteroid treatment latency.

Methods

This human study was approved by our institutional ethics committee (approval #2280-2021). A requirement for consent was waived due to the retrospective nature of this study.

POPULATION AND SETTING

Patients who reported themselves as being potentially exposed to intense noise as part of active (conscription or reserve) military service were evaluated by audiometry. Intense noise was very broadly defined to include any subjective exposure, including any explosion or shooting that caused discomfort to the service member regardless of the presence of auditory protection. All such service members were encouraged to undergo a full auditory evaluation by a speech therapist at the earliest operationally feasible time. Since audiometry is only performed at baseline for very few professions as required by law (e.g., pilots and divers), hearing was assumed to be normal at baseline unless contrary evidence was available (as detailed below). Otoscopy was performed in all patients before referral. Audiometry was deferred to at least 48 h post-exposure for practical reasons.[8] If a recent (i.e., performed over the previous 72 h) audiogram was not available, a repeated audiogram was completed upon admission.

Since this process was initiated by the patient and performed outside the theater of operations, the delay to the initial evaluation (and as a consequence, the HBO therapy latency) was highly variable. While prone to selection bias (e.g., patients with very severe injuries were more likely to be evacuated promptly), this variability served as an important inference point in our data.

Those deemed potentially suitable for HBO therapy at initial assessment were prescribed oral prednisone for a total of 14 days (see regimen below), and were concomitantly referred to further evaluation at the Israeli Naval Medical Institute (INMI). We recommended the addition of HBO therapy in the following instances: 1) a sensorineural hearing threshold of ≥ 45 dB in at least one pure tone frequency; 2) a sensorineural hearing threshold of ≥ 40 dB in at least two frequencies; or 3) a sensorineural hearing threshold of ≥ 35 dB in at least three frequencies. As per current policy, audiometry is not performed at baseline for the absolute majority of conscripts. In the rare cases where previous audiograms were available, we only considered the change from the previous examination – i.e., a worsening of at least 45 dB in one, 40 dB in two or 35 dB in three frequencies compared to baseline justified treatment. Patients who had not already been prescribed with oral prednisone received it in line with the aforementioned protocol upon admission. Contraindications to HBO therapy included the inability to equalise middle ear pressure; severe pulmonary pathology that could result in pneumothorax; and lack of patient consent.

Inability to comply with treatment protocol for any reason (e.g., withdrawal of consent, adverse reactions to HBO or prednisone) led to the discontinuation of HBO therapy. Patients unable to complete the full course of recommended treatment sessions were excluded from the final analysis. In view of the mounting evidence of a distinct and dissimilar pathophysiology,[15] patients with sudden sensorineural hearing loss patterns consistent with sudden idiopathic hearing loss – i.e., diffuse sensorineural loss and discordant exposure history, that is no noise exposure whatsoever – were excluded from this analysis despite being treated with HBO.

TREATMENT PROTOCOL

All patients were prescribed a course of oral prednisone (60 $mg \cdot d^{-1}$ for seven days, followed by 40 $mg \cdot d^{-1}$ for three days, 20 $mg \cdot d^{-1}$ for two days and 10 $mg \cdot d^{-1}$ for two days). This glucocorticoid treatment regimen was started prior or concomitantly with HBO administration and continued for 14 days (including tapering down), irrespective of the duration of HBO therapy. Patients were pressurised to 253 kPa (2.5 atmospheres absolute), followed by four intervals of pure oxygen breathing for 20 minutes each, separated by 5 minutes of air breathing. Repeat audiometry was performed every five treatments. Treatments were continued until a return to baseline (assumed to be normal, i.e., thresholds below 20 dB in all pure tone frequencies) or no meaningful (≥ 10 dB) change in any frequency on two consecutive audiograms was observed. The air breaks were included to address the risk of central-nervous-system oxygen toxicity, shown to be higher in patients treated with corticosteroids.[12]

OUTCOME MEASURES

All audiograms were performed by a certified speech therapist in a calibrated audiometer (AC40 Interacoustics, Denmark). The primary outcome of minimal response to therapy was defined as an increase of at least 10 dB in any of the high pure tone frequencies measured (3, 4, 6 or 8 kHz).[11] Secondary outcomes included the absolute change in the high pure tone summation (HPTS), i.e., the sum of change in the pure tone thresholds of 3, 4, 6 and 8 kHz; the relative change in high pure tone summation ratio (rHPTS),

defined as the ratio of HPTS/[sum of 3, 4, 6 and 8 kHz on the initial audiometry][8] and the proportion of soldiers returned to auditory combat readiness (defined as maximal bone conduction thresholds of 25 dB on 3–4 kHz or 60 dB in 6–8 kHz).

STATISTICAL ANALYSIS

Standard descriptive statistics were used to summarise population characteristics. We used a Chi-square test for categorical variables, Mann-Whitney U test for nonparametric variables and student's unpaired *t*-test for normally distributed continuous variables. Fisher's least significant difference correction was applied when applicable to adjust for multiple comparisons. Categorical variables were described using proportions and percentages, non-parametric variables with median and interquartile range (IQR) and normally distributed continuous variables as mean with standard deviation (SD).

Multivariate logistic regression modeling was performed using Pearl and Reed's method, with a generalised linear model (GLM) implemented for the uni and multivariate analysis of normally distributed outcome measures. The Shapiro-Wilk method was used to test for the normality of distribution of residuals. We used the Pearson correlation coefficient to determine possible correlations between independent variables; only variables not co-related ($r \leq 0.7$) to other predictors and which significantly predicted the outcome measure ($P > 0.1$) on univariate analysis were included in the model. A two-sided $P < 0.05$ was considered statistically significant for all tests. All statistical analysis was performed using R software version 4.2.1.

Results

Of 138 patients referred for our evaluation, 111 met the criteria for HBO therapy in combination with steroids. Twenty-seven were not included due to difficulty equalising middle ear pressures (n = 5) or refusal of treatment (n = 22), and eight were excluded due to inability to follow the treatment protocol. A total of 129 ears (103 patients) were included in the final analysis. Of these, 64 (62.1%) were reservists and 39 were either conscripts or professional servicemen. None had any previously documented or self-reported prior AAT or any other auditory problem. HBO therapy began within seven days after noise exposure in 67 ears (52%), 8–14 days post exposure in 24 ears (19%), 15–21 days after in 13 ears (10%) and more than three weeks after exposure in 25 ears (19%). A Consolidated Standards of Reporting Trials (CONSORT) diagram summarising the data mining and filtering process is presented in Figure 1, with the study groups' baseline characteristics and symptoms upon presentation outlined in Table 1. Signs upon presentation, including otoscopy and audiometry, are summarised in Table 2 and presented in Figure 2.

Figure 1

Study phases presented according to CONSORT guidelines; [1]see text of HBO treatment criteria [2]see text for definition of sudden sensorineural hearing loss (SSNHL); HBO – hyperbaric oxygen, INMI – Israel Naval Medical Institute

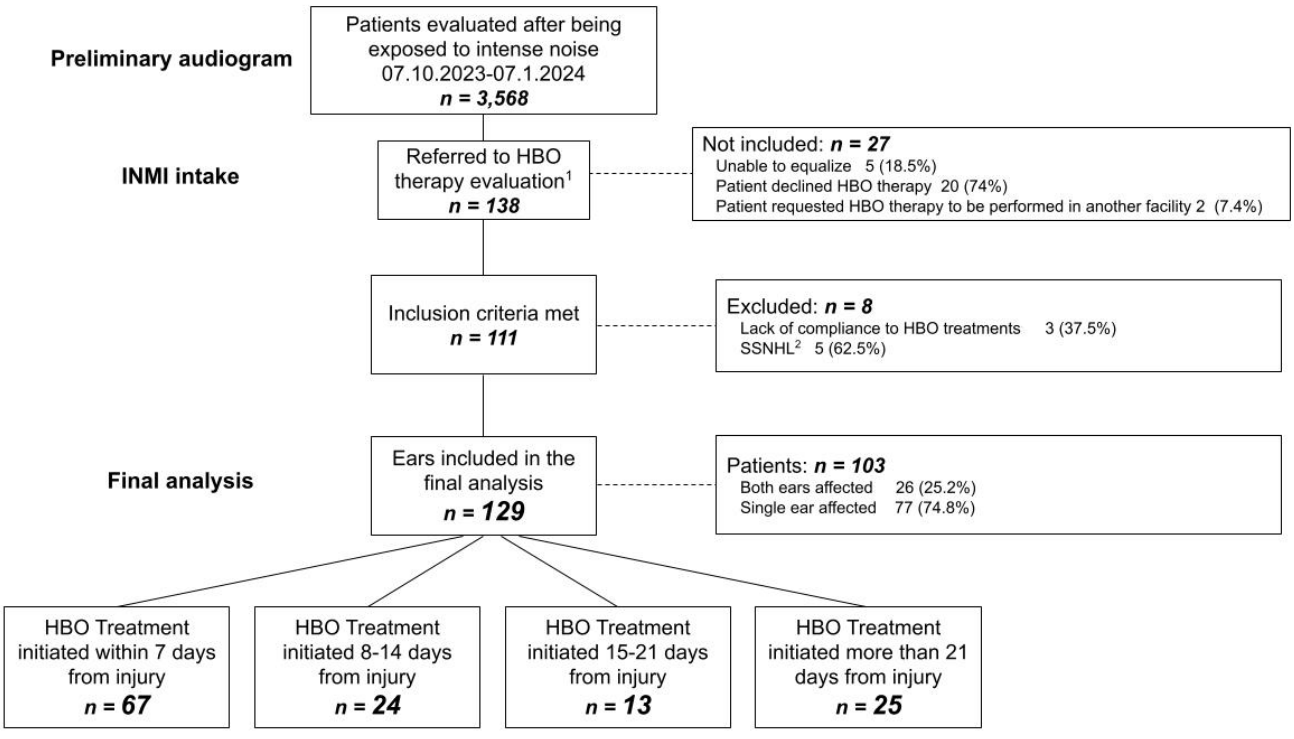


Table 1

Baseline characteristics and symptoms upon presentation for subjects stratified according to latency from noise exposure to hyperbaric oxygen (HBO) treatment; IQR – interquartile range

Characteristic	Overall *n* = 129	≤ 7 days *n* = 67	8–14 days *n* = 24	15–21 days *n* = 13	> 3 weeks *n* = 25
Age, Median (IQR)	23 (20–30)	22 (20–29)	29 (21–32)	24 (21–30)	23 (22–36)
Left ear, *n* (%)	72 (56)	37 (55)	13 (54)	8 (62)	14 (56)
Days from exposure to steroid initiation, Median (IQR)	5 (3–12)	3 (2–4)	10 (6–12)	15 (8–18)	23 (12–28)
Days from exposure to HBO therapy initiation, Median (IQR)	7 (4–17)	4 (3–6)	12 (10–14)	17 (17–19)	25 (23–28)
Tinnitus at admission, *n* (%)	112 (87)	59 (88)	22 (92)	12 (92)	19 (76)
Subjective feeling of auricular fullness on initial evaluation, *n* (%)	58 (45)	35 (52)	8 (33)	7 (54)	8 (32)
Subjective perception of impaired hearing at admission, *n* (%)	83 (64)	44 (66)	14 (58)	6 (46)	19 (76)
Auricular pain on initial evaluation, *n* (%)	14 (11)	7 (10)	5 (21)	2 (15)	0 (0)
Hyperacusis at admission, *n* (%)	21 (16)	11 (16)	4 (17)	3 (23)	3 (12)
Dizziness or vertigo on initial evaluation, *n* (%)	10 (7.8)	9 (13)	1 (4.2)	0 (0)	0 (0)

Table 2

Signs and findings upon presentation

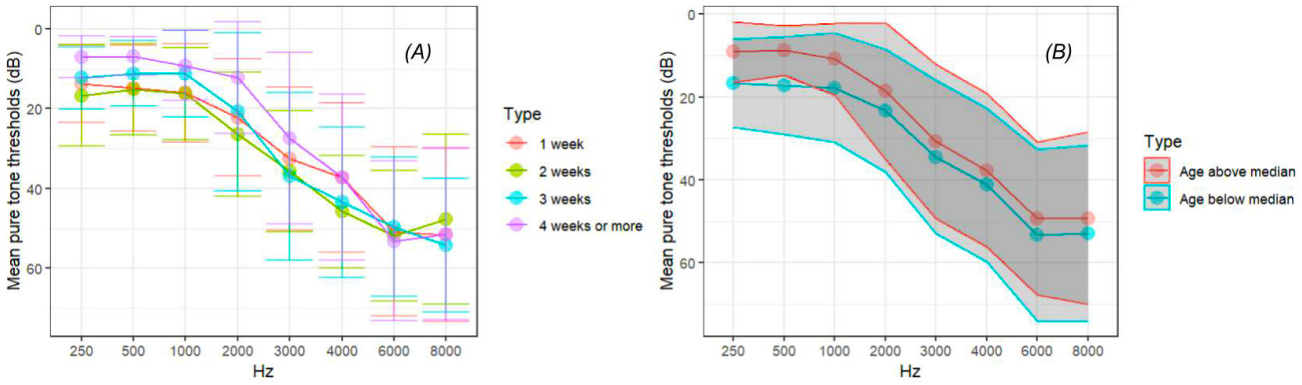
The baseline signs upon initial presentation, including otoscopy, audiometry, and occupational fitness (determined solely based on objective findings) are summarised in the table below. All numbers except combat readiness describe ears, not patients. Combat readiness is calculated as a percentage of patients in each group. HTPA – high pure tone average; IQR – interquartile range

Characteristic	Overall *n* = 129	≤ 7 days *n* = 67	8–14 days *n* = 24	15–21 days *n* = 13	> 3 weeks *n* = 25
Findings on initial otoscopic evaluation, *n* (%)					
Bullous myringitis	1 (0.8)	0 (0)	0 (0)	1 (7.7)	0 (0)
Clouded	3 (2.3)	2 (3.0)	1 (4.2)	0 (0)	0 (0)
Haemotympanum	2 (1.6)	2 (3.0)	0 (0)	0 (0)	0 (0)
Mild redness	3 (2.3)	3 (4.5)	0 (0)	0 (0)	0 (0)
Myringosclerosis	5 (3.9)	1 (1.5)	0 (0)	1 (7.7)	3 (12)
Normal	109 (84)	55 (82)	21 (88)	11 (85)	22 (88)
Perforations	3 (2.3)	1 (1.5)	2 (8.3)	0 (0)	0 (0)
Small perforation	2 (1.6)	2 (3.0)	0 (0)	0 (0)	0 (0)
Serous otitis media	1 (0.8)	1 (1.5)	0 (0)	0 (0)	0 (0)
Fit for combat on initial evaluation, *n* (%)	20 (16)	11 (16)	1 (4.2)	3 (23)	5 (20)
HTPA on initial evaluation, Median (IQR)	45 (35–57)	43 (35–57)	46 (40–55)	48 (42–53)	45 (35–57)

Looking at the primary outcome, 59 of 67 patients (88%) treated within seven days met the criterion for minimal response of 10 dB improvement in at least one of 3–8 KHZ frequencies. Only 56% of patients who began treatment more than 21 days after exposure met this criterion (Table 3).

The absolute change in high pure tone summation (HPTS) was significantly greater in patients treated within seven days from exposure in comparison to later treatment (55 dB vs. 5, 15 and -5 dB, $P = 0.01$, 0.024 and < 0.001 compared to treatment initiation latency of 8–14 days, 15–21 days and more than three weeks after exposure, respectively). Similar

Figure 2
Pure tone threshold averages before treatment
Average pure tone thresholds (with the 95% confidence interval marked by error bars) are presented in (A) by the time passed from injury to initial HBO and in (B) by age group (younger half of the cohort versus older half)



trends were noted when looking at the relative change from audiometry upon presentation, with a significantly greater improvement of 55% in the rHPTS when HBO therapy was initiated within seven days from injury (compared with 10% for week two and three and only 3% when over three weeks have passed; $P = 0.011$, 0.033 and < 0.001 respectively).

Regarding combat readiness, 109 of 129 ears were deemed unfit for combat upon admission. Of those, 57% of ears treated within seven days restored combat readiness after treatment. This percentage decreased with prolonged treatment latency. This difference was significant when comparing treatment within seven days from injury (57%) to treatment after 14–21 days (10%) and more than 21 days (15%) from injury (Bonferroni adjusted $P = 0.012$ and 0.017, respectively).

Examining the whole study population, the average improvement following HBO treatment for each of the high pure tone frequencies (3,000–8,000 Hz) was not statistically significant (at $\alpha = 0.05$, Figure 3A). However, on a week-by-week analysis, as can be seen in Figure 3, there was a noticeable difference between groups regarding the improvement in each of the high pure tone frequencies. Patients treated within seven days of exposure improved more than patients treated later (Figure 3 B, C, D). Patients receiving HBO therapy within seven days of exposure were younger (mean age 24.7 vs 27.8, mean difference -3.1 years, 95% CI -0.4 to -5.8). Patients treated more than three weeks after noise exposure did not significantly improve in any of the high tone frequencies (Figure 4).

On univariate analysis, only age, time from injury to glucocorticoid initiation (steroid latency), and time from injury to HBO therapy initiation (HBO latency) were found to significantly predict either the primary or any of the secondary outcomes.

Adjusting for age, in a logistic regression model each additional day of steroid initiation delay significantly decreased the likelihood of the primary outcome of minimal response to therapy (RR -0.01, 95% CI -0.02 to 0.00) or the restoration of combat readiness (RR -0.01, 95% CI -0.02 to 0.00). In other words, each day of steroids delay decreased the likelihood of these outcomes by about 2% and 1%, respectively. Similarly, a linear regression model showed steroid latency to be inversely associated with the improvement in HPTS (RR -2.2, 95% CI -3.3 to -1.2) and rHPTS (RR -2%, 95% CI -3% to -1%).

Likewise, the age-adjusted relative risk predicted by a logistic regression model of any additional day from injury to HBO therapy initiation was -0.01 (95% CI -0.02 to -0.01) for minimal response and -0.01 (95% CI -0.02 to -0.01) for the restoration of combat readiness. Implementing a linear regression model the age-adjusted relative risk was -2.0 (95% CI -3.0 to -1.0) for HPTS, and -2% (95% CI -3% to -1%) for rHPTS. However, a mixed model accounting for both HBO latency and steroid latency (in addition to age), showed only HBO therapy latency to be a significant predictor of minimal response (RR -0.02, 95% CI -0.03 to 0.00), or of restoration of combat readiness (RR -0.02, 95% CI -0.04 to 0.00), or of rHPTS (linear regression predicted RR -1%, 95% CI -3% to -0.2%). These models are presented in Table 4.

Recorded adverse effects and treatment complications were minimal. Middle ear barotrauma was recorded in nine patients (one ear each), with minimal clinical significance (Teed's grade 1). In these cases, HBO therapy was paused for 1–3 treatments, with return to treatment and completion of a full HBO course once a repeat otoscopy showed improvement. There were no cases of central oxygen toxicity in our cohort. No other adverse effects of pressure changes or the administration of high partial pressure of oxygen were recorded.

Table 3

Primary and secondary outcomes; post hoc between-group comparisons is Bonferroni corrected for multiple comparisons. No comparisons between weeks 2, 3 and 4 or over showed any significant differences. [1]Fisher's exact test; Kruskal-Wallis rank sum test. [2] Bonferroni adjusted pairwise comparison; HPTS – high pure tone sum; IQR – interquartile range; rHPTS – relative high pure tone sum

Characteristic	Overall *n* = 129	≤ 7 days *n* = 67	8–14 days *n* = 24	15–21 days *n* = 13	> 3 weeks *n* = 25	*P*-value[1]	1 vs 2 weeks[2]	1 vs 3 weeks[2]	1 vs 4 weeks[2]
Minimal response, *n* (%)	102 (79)	59 (88)	18 (75)	11 (85)	14 (56)	**0.010**	0.184	0.662	**0.002**
Delta HPTS, Median (IQR)	25 (-10–70)	55 (23–85)	5 (-11– 3)	15 (0– 0)	-5 (-15–20)	< 0.001	**0.010**	**0.024**	**< 0.001**
rHPTS, Median (IQR)	25% (-3%–70%)	55% (23%–80%)	10% (-5%–46%)	10% (-2%– 8%)	3% (-13%–17%)	< 0.001	**0.011**	**0.033**	**< 0.001**
Cases not fit for combat at admission Combat readiness restored, *n* (%)	109 44 (40)	56 32 (57)	23 8 (35)	10 1 (10)	20 3 (15)	< 0.001	0.086	**0.012**	**0.017**

Discussion

Acute acoustic trauma is a leading cause of a high tone sensorineural hearing loss, damaging the cochlea and causing hearing loss both by mechanical and metabolic pathways. This is by far the largest cohort of acute acoustic trauma receiving HBO therapy thus far reported.[8,12] The small and centralised nature of military healthcare in the IDF ensured all acoustic trauma cases evaluated by any caregiver were referred to our consideration. Selection bias is thus primarily limited only to cases where patients sought absolutely no professional health care whatsoever, a scenario we deem to be diminishingly rare. Although theoretically patients with worse injuries could be biased towards seeking help earlier, in our cohort there was no major difference in the initial audiometry between the different presentation latency groups.

In this study, we sought to evaluate whether a delay in HBO is associated with a poorer response to HBO treatment after acute acoustic trauma. Our data show a clear association between the delay in HBO therapy initiation and a decreased improvement in high pure tone thresholds. This association is maintained across all our pre-specified outcome measures. Most importantly, this association is maintained even when adjusted to glucocorticoid therapy initiation time and patient's age. Our data indicates that HBO therapy initiated within seven days from injury is associated with the most significant improvement, when looking at higher (3–8 kHz) pure tone hearing thresholds, that are most commonly impaired by noise exposure. These findings are consistent with what was previously described by Holy et al.[12] In our study, when accounting for both HBO latency and steroid latency, steroid latency was not found to contribute significantly to hearing improvement. This can be accounted for by the fact that according to the IDF acoustic trauma treatment protocol – both treatments, corticosteroids and HBO, are initiated approximately at the same time. Therefore, we were limited in our ability to isolate the sole impact of steroid initiation time, and it can be assumed that the impact of HBO initiation time represents the efficacy of combined treatment, both HBO and steroids.

Acute acoustic trauma is associated with multifactorial changes, both mechanical and metabolic. Vasospasm of microcirculation and hypoxia of sensory cells occur, to prevent metabolic imbalance. These processes have been shown to be most significant in the first days after injury.[2,16] We propose that HBO therapy acts primarily by reversing these processes and increasing blood oxygen through an increase in the arterial partial pressure of oxygen, which results in better oxygen diffusion to compromised areas.[13,17] Hence, the association between its therapeutic benefits and time elapsed from injury are in line with our mechanistic understanding.

Age appears to be a significant predictor of HBO-associated hearing improvement in AAT. This could be, at least

Figure 3

Average pre- and post-HBO pure tone thresholds (with the 95% confidence interval shaded in gray); (A) for the entire study cohort; (B) in patients where HBO was initiated within seven days from injury; (C) in patients where HBO was delayed beyond seven days from injury; (D) shows mean before vs after HBO differences (with 95% confidence intervals) in pure tone thresholds by groups (within or later than seven days)

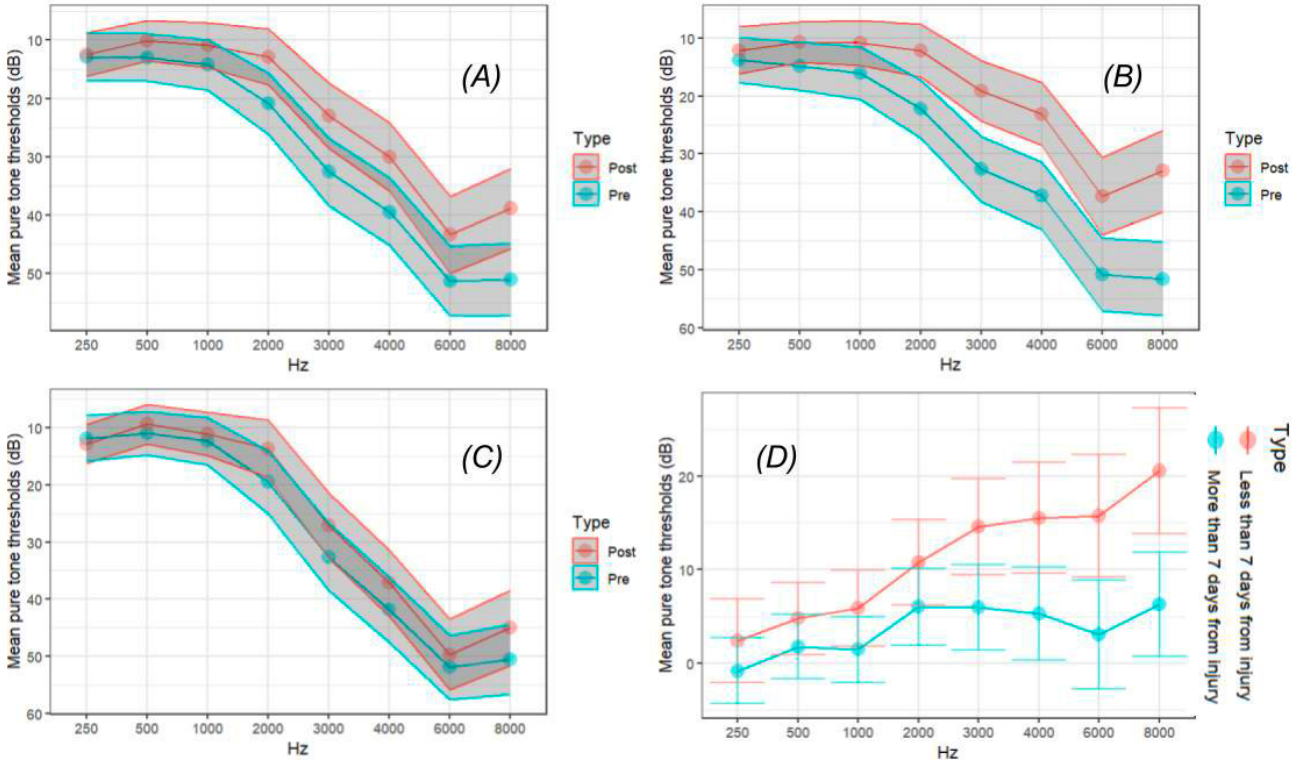
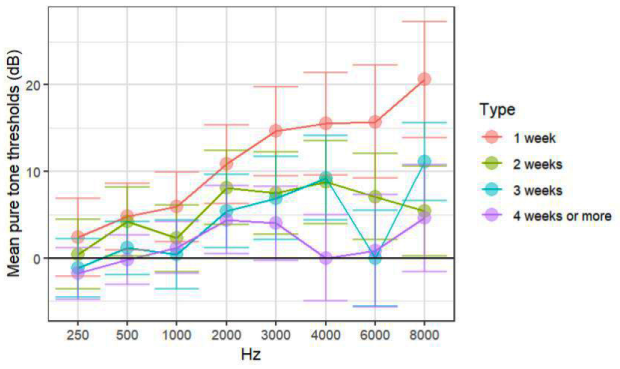


Figure 4

Average pure tone threshold changes (with error bars indicating a 95% confidence interval) by week of HBO initiation



in part, attributed to a higher incidence of underlying (chronic) sensorineural hearing loss in older individuals. The true magnitude of this potentially confounding effect is impossible to ascertain in our study population, since we had no recent baseline (pre-AAT) audiogram in the majority of cases. We acknowledge that this is a significant limitation in our study. Moreover, previous studies support the notion that age might mechanistically influence the degree of improvement under HBO therapy. Chen et al.[18] report a similar pattern of strong association between treatment outcomes and age (as well as treatment delay) in sensorineural hearing loss. This may be attributed to decreased inner ear oxygen supply due to microangiopathic changes that are not uncommon with older age.[18] Similar findings were reported by Wu et al. in a larger, more recent cohort.[19]

Patients referred for evaluation earlier after injury had a higher incidence of complaints of dizziness. However, no vestibular dysfunction was found on vestibular evaluation in any of the patients referred to HBO therapy following AAT. This presentation was not associated with decreased improvement under HBO therapy.

Despite the physiological plausibility of different injury mechanisms when looking at blast versus noise exposure, we deemed patient recollection not significantly reliable to discriminate between the mechanisms.[20] Additionally, most patients referred to our institute reported repeated loud noise exposure, as expected during war. Therefore, we could not discriminate reliably between noise and blast exposure types.

LIMITATIONS

The retrospective nature of this analysis limits our ability to infer causality/treatment efficacy. Since the chance of spontaneous hearing restoration might be decreased

Table 4

Multivariate regression model; multivariate regression models were constructed incorporating age with steroid latency, hyperbaric oxygen treatment (HBOT) latency or both for the primary (minimal response) and each of the secondary outcomes. For binary outcomes (minimal response and combat readiness) the relative risk (RR) describes a change of the probability of reaching this outcome with each year of age or additional day of delaying therapy. For Delta HPTS and rHPTS the RR describes the change in HPTS in dB (Delta HPTS) or percent from initial audiometry (rHPTS) with each additional year of age or day of delaying therapy. CI – confidence interval; Delta HPTS average – difference in the high pure tone sum average; rHPTS – relative high pure tone sum

Characteristic	Minimal response		Combat readiness restored		Delta HPTS		rHPTS	
	RR (95% CI)	*P*-value	RR (95% CI)	*P*-value	RR (95% CI)	*P*-value	RR (95% CI)	*P*-value
HBOT latency and age only								
Age	-0.01 (-0.02 to 0.00)	**0.033**	-0.02 (-0.03 to -0.01)	**< 0.001**	-2.4 (-3.5 to -1.3)	**< 0.001**	-2% (-3% to -1%)	**< 0.001**
Days from injury to HBOT initiation	-0.01 (-0.02 to -0.01)	**< 0.001**	-0.01 (-0.02 to -0.01)	**< 0.001**	-2.0 (-3.0 to -1.0)	**< 0.001**	-2% (-3% to -1%)	**< 0.001**
Steroid latency and age only								
Age	-0.01 (-0.02 to 0.00)	0.064	-0.02 (-0.03 to -0.01)	**< 0.001**	-2.2 (-3.3 to -1.0)	**< 0.001**	-2% (-3% to -1%)	**< 0.001**
Days from injury to steroid initiation	-0.01 (-0.02 to 0.00)	**0.004**	-0.01 (-0.02 to 0.00)	**0.004**	-2.2 (-3.3 to -1.2)	**< 0.001**	-2% (-3% to -1%)	**0.002**
HBO latency, Steroid latency, and age								
Age	-0.01 (-0.02 to 0.00)	**0.026**	-0.02 (-0.03 to -0.01)	**< 0.001**	-2.3 (-3.4 to -1.1)	**< 0.001**	-2% (-3% to -1%)	**< 0.001**
Days from injury to steroid initiation	0.01 (-0.02 to 0.03)	0.51	-0.01 (-0.04 to 0.02)	0.44	-1.3 (-4.3 to 1.6)	0.37	-2% (-3% to 1%)	0.46
Days from injury to HBOT initiation	-0.02 (-0.03 to 0.00)	**0.033**	-0.02 (-0.04 to 0.00)	**0.028**	-1.1 (-3.2 to 0.98)	0.29	-1% (-3% to -0.2%)	**0.015**

with time, patients evaluated later might have inherently less chances of improvement, with or without treatment. However, in view of the mounting evidence of diminished effect when treatment is delayed, a prospective comparison of early versus delayed HBO therapy for acute acoustic trauma of any etiology seems unethical. Moreover, a retrospective approach can still yield important clinical guidance as to the success rates, and resultant justification of the cost and potential side effects of HBO, once patient presentation is delayed.

Conclusions

Early initiation of HBO therapy is associated with improved response to therapy in AAT. The rate of improvement when therapy is delayed beyond three weeks seems to be particularly low, raising the question of overall justification in view of the cost of HBO therapy. Larger cohorts are needed to fully elucidate the temporal limits of HBO therapy latency in AAT.

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Acknowledgments

We wish to express our deepest gratitude to Eng. Guy Wiener for his invaluable help in procuring the data for this study.

Conflicts of interest and funding: nil

Submitted: 7 October 2024
Accepted after revision: 22 February 2025

An unblinded training exposure to hypoxia enhances subsequent hypoxia awareness

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Keywords
Aviation; Diving research; Diving Medicine; Rebreathers – closed circuit; Technical diving

Abstract
(Allocco A, van Waart H, Connell CJW, Wong NYE, Charukonda A, Gant N, Vrijdag XCE, Mitchell SJ. An unblinded training exposure to hypoxia enhances subsequent hypoxia awareness. Diving and Hyperbaric Medicine. 2025 30 June;55(2):136–144. doi: 10.28920/dhm55.2.136-144. PMID: 40544141.)
Introduction: Malfunctions and human errors in diving rebreathers can cause hypoxia, hyperoxia, and/or hypercapnia. We evaluated whether a prior unblinded hypoxia experience enhances a diver's ability to recognise hypoxia and initiate self-rescue.
Methods: Forty participants were randomised to receive either an information leaflet describing hypoxia symptoms or an unblinded hypoxia experience, prior to a blinded hypoxia testing exposure during a virtual reality dive over one month later. The primary outcome was the comparison of the proportion of participants in these two groups who initiated self-rescue before reaching a peripheral oxygen saturation of 70% in the blinded exposure. An individual's 'symptom profile' was assessed by comparing symptoms during the unblinded hypoxia experience and blinded testing exposures.
Results: During the blinded hypoxia testing exposure, 18/20 (90%) participants in the hypoxia experience group performed a self-initiated rescue compared to 6/18 (33%) in the information leaflet group ($P < 0.001$). Participants in the information leaflet group had lower mean SpO_2 (73.4% vs 81.4%, mean difference 8% [95% CI = 2.5–13.5%, $P = 0.005$]) and lower inhaled oxygen fraction (7.6% vs 9.4%, mean difference 1.8% [95% CI = 0.6–3.1%, $P = 0.005$]) at self-rescue. The most frequent and severe symptoms were light-headedness and shortness of breath. Of the 20 participants completing both hypoxia exposures, 14 (70%) had a consistent hypoxia symptom profile, which was not related to the ability to recognise hypoxia.
Conclusions: Self-rescue was approximately three times more likely for participants who had previously experienced hypoxia compared to simply receiving information on relevant symptoms. Most participants exhibited a consistent pattern of individual symptoms, which did not result in earlier or improved detection of hypoxia.

Introduction

Rebreathers are used in scientific, military, and recreational diving. Closed circuit rebreathers have numerous advantages over traditional open circuit scuba equipment, such as extending the duration of a gas supply, preserving expensive gases (e.g., helium), minimising exhaled bubbles, and providing warm, humidified breathing gas. Breathing gas is recycled in a rebreather by removing carbon dioxide and adding oxygen. Failure to perform these functions can lead to hypercapnia, hypoxia, or hyperoxia (referred to as 'the 3-H's'), which may, in turn, cause incapacitation, unconsciousness, and drowning. Two-thirds of military rebreather accidents[1] and more than a third of the recreational rebreather fatalities have been attributed to the 3-Hs.[2]

To combat these hazards, rebreather divers typically carry an independent supply of open-circuit bailout gas. However, bailout gas is only useful if the diver can recognise the need and maintain sufficient cognitive and motor functions to transfer gas supply during the 'bailout' process. Hypoxia is challenging to detect and manage because it can quickly impair cognitive abilities before a diver can initiate self-rescue using their bailout gas.[3,4] Hypoxic people underestimated their degree of impairment despite making errors or becoming unresponsive.[5]

Many aviators undergo a controlled exposure to hypoxia by breathing air at a simulated high altitude in a hypobaric chamber.[6–8] Studies of this training practice have established that there are commonalities of hypoxic symptom experiences at group level.[6–8] It has been assumed that knowledge of one's 'hypoxic symptom signature' could facilitate early recognition and self-rescue in a future hypoxic event. There has been advocacy for such training in divers. However, no study to date has explicitly evaluated the effect of these periodic hypoxia 'training' exposures on the ability to self-rescue in a subsequent hypoxia exposure. This study investigated whether an unblinded hypoxia experience enhances a diver's ability to recognise hypoxia symptoms and initiate self-rescue in a subsequent blinded hypoxia exposure.

Methods

The study protocol was approved by the Health and Disability Ethics Committee, Auckland, New Zealand (reference 21/NTB/102), and was registered with the Australian New Zealand Clinical Trial Registry (U1111-1266-1320, http://www.anzctr.org.au/, RRID:SCR_002967).

PARTICIPANTS

This single-blind randomised study was conducted at the Exercise Physiology Laboratory at the University of Auckland between May and December 2023. Forty healthy participants aged 18 to 55 years old were recruited. Eligible participants were certified divers and deemed medically fit by the Recreational Scuba Training Council screening questionnaire. People currently using psychoactive drugs, tobacco, more than 21 alcoholic drinks per week or five caffeinated drinks per day, having a mental illness or prior hypoxia experience were excluded. At each visit, a physician confirmed medical fitness. All participants provided written informed consent.

STUDY DESIGN

Participants were block-randomised in REDCap[9] into 'hypoxia information leaflet' and 'hypoxia experience' groups. Participants in the hypoxia information leaflet group received a leaflet explaining the basic physiology of hypoxia and the most common symptoms presented in a manner consistent with commonly available diver educational material (*Appendix 1). Participants in the hypoxia experience group received the information leaflet plus an unblinded / open-label hypoxia experience as described below (Figure 1).

The blinded 'hypoxia testing exposure' undertaken by both groups was scheduled no sooner than four weeks after the hypoxia experience. In this testing exposure participants were told that they may be exposed to hypoxia or normoxia on a randomised basis but that we would not tell them which exposure they were receiving. However, since our primary outcome was a comparison of the recognition and self-rescue performance of the two groups when exposed to hypoxia, and to increase the power of the study, with ethics approval, all participants were exposed to hypoxia. After the study was complete, participants were debriefed on the fact that they were all exposed to hypoxia in the testing exposure, and they provided additional informed consent for the use of their data.

EQUIPMENT CONFIGURATION

A closed-loop breathing circuit was built from an O_2ptima closed-circuit rebreather (Dive Rite, Lake City, USA), Inspiration and Sentinel bailout valves (AP diving, Helston, UK and VR Technology, Poole, UK) and AD Instrument parts (Dunedin, New Zealand) (Figure 2). Participants breathed through a mouthpiece with a disposable filter attached to a bailout valve. The bailout valve was connected with respiratory tubing (MLA1011A, AD Instruments) to the counter lungs via a 3-way manual stopcock (SP0143, AD Instruments). Both stopcocks could be opened to room air via a respiratory tube with a filter to simulate the breathing resistance of an intact rebreather circuit. The rebreather incorporated a canister containing Sofnolime® 797 (Molecular Products, Harlow, UK) to remove carbon dioxide. The automatic diluent valve was connected to an air cylinder. To produce hypoxia, normal oxygen additions were discontinued, resulting in a gradual decline in inspired oxygen levels similar to a real-world diving scenario with oxygen delivery failure. Oxygen was added at the mouthpiece to 'rescue' participants at the end of their exposures. In the hypoxia testing exposure, the Sentinel bailout valve was connected to 100% oxygen, which participants breathed if they self-rescued by turning the lever a quarter-turn.

A sampling line ported in the mouthpiece continuously measured inspired oxygen with a respiratory gas analyser (ML206, AD Instruments). Participants wore a 5-lead electrocardiogram and a finger peripheral oxygen saturation (SpO_2) sensor (Masimo Radical 7 Oximeter, CA, USA), known for its accuracy at low SpO_2 values.[10] All audible signals were silenced. All data were sampled continuously at 1 kHz using Powerlab 16/35 and acquired via LabChart Pro 8.1.24 (AD Instruments, Dunedin, New Zealand).

EXPERIMENTAL PROCEDURE

In both the experience and testing exposures participants were comfortably seated and wore a nose clip whilst breathing on the experimental set-up. Prior to each exposure, the breathing circuit was flushed with air to a near approximation of a standard volume. Each exposure

***Footnote:** Supplementary Appendix 1 is available to download from: https://www.dhmjournal.com/index.php/journals?id=358

Figure 1
Flow diagram of study design; note that numbers represent the plan, whereas due to technical issues, two participants were lost for analysis from the hypoxia information leaflet group. All participants were blinded to the intervention (hypoxia) during testing visits

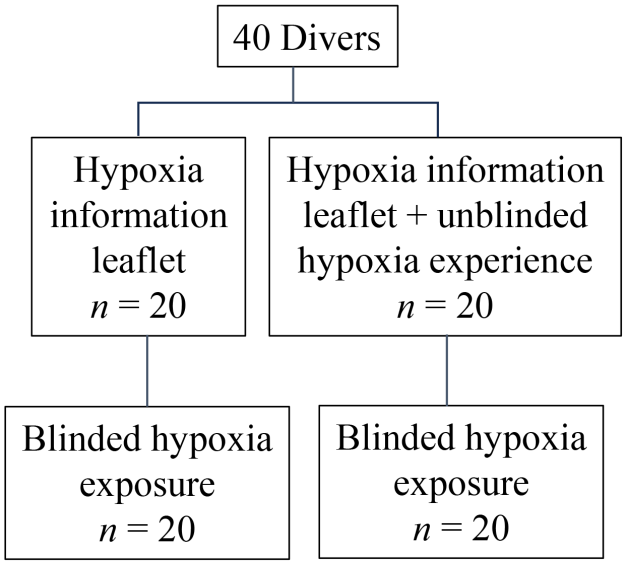
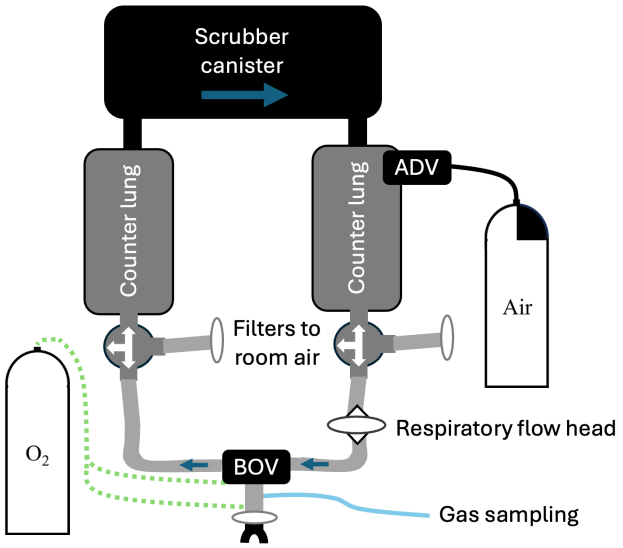


Figure 2
Experimental hypoxia rebreathing circuit set-up; the three headed arrows represent the 3-way manual stopcocks that allowed the switch between rebreathing circuit (depicted) and breathing room air (turn counter clockwise); ADV – automatic diluent addition valve; BOV – bailout valve



began with the participant breathing room air (circuit open to air) for two minutes, after which the circuit would be closed without the participants' knowledge, and the inspired fraction of oxygen and peripheral oxygen saturation would gradually decline. An anaesthetist was present during all hypoxia experience and testing exposures. At exposure termination, the breathing circuit was flushed with 100% oxygen until the participant's SpO_2 stably read > 99%.

Unblinded (open-label) hypoxia experience exposure

Cognitive functioning was monitored via a card recognition task adapted from our prior hypoxia study.[5] Playing cards between four and 10 (inclusive) of all four suits with the numbers removed were presented to the participant on a computer monitor, with one card appearing every six seconds. Participants identified the card by pointing to the corresponding card on an answer board depicting the number and suit. Participants were familiarised with the task, and their ability to achieve 100% task reliability was confirmed prior to the hypoxia experience training. Incorrect cards or failure to answer within 6 seconds were scored as errors. Based on previous work,[5] the termination criteria for the hypoxia experience were: (1) three errors made at any SpO_2, (2) two errors at SpO_2 < 60%, or (3) termination at the discretion of the physician (whichever occurred first).

Blinded hypoxia testing exposure

Participants were shown a standardised briefing video explaining the hypoxia testing exposure. Participants were 'immersed' in a virtual reality (VR) diving environment (HTC Vive Pro Eye, Taoyuan, Taiwan) and performed a distracting task of pushing a button every time an orca was sighted. They were instructed to bail out if they perceived hypoxia symptoms. The VR environment included a heads-up display with a green light at the bottom right of the visual field. If the participant's SpO_2 dropped below 70% without them attempting to bailout, the heads-up display would switch to red, to signal them to perform a bailout. If the participant failed to respond to the red signal, the rescue procedure was performed by the researchers.

OUTCOME MEASURES

The primary outcome measure was the proportion of participants who performed a self-initiated bailout during the blinded hypoxia testing exposure either prior to activation of the heads-up display or in response to it. Secondary outcome measures included SpO_2, inspired oxygen, elapsed time, and self-reported symptoms. Five minutes after each hypoxia exposure, participants were asked to recall the total number of errors they made and to rate the severity of these symptoms on a visual analogue scale (VAS) from 0 to 100. In an open-ended question, participants were asked what their first recognised symptom was.

STATISTICAL ANALYSIS

Descriptive statistics were reported as mean and standard deviation (SD) or median (range) where appropriate. Normality of outcome measures was established with the

Shapiro-Wilk test. Difference in proportion of participants in the information leaflet versus the hypoxia experience group who performed a self-initiated bailout was analysed with a Chi-square test. Differences between the information leaflet and hypoxia experience groups were analysed with independent *t*-tests and reported as mean difference with 95% confidence intervals (95% CI). For participants in the hypoxia experience group, consistency in all combined experienced symptoms was checked for each individual participant with Pearson correlation between the hypoxia experience and hypoxia testing exposure. All data were analysed with MATLAB version 2023b (Mathworks, Natick, MA, USA) and SPSS Statistics version 27.0 (IBM, Armonk, NY, USA), with α set at 5%.

Results

Forty participants completed the study, two participants were excluded from analysis due to technical malfunctions, leaving 38 participants for analysis. Participant characteristics are reported in Table 1. For the participants who underwent the unblinded hypoxia experience, the mean time interval between the hypoxia experience and the blinded hypoxia testing exposure was 60 days (range 28–107 days).

During the unblinded hypoxia experiences, many participants experienced very low SpO_2 levels before meeting the functional stopping criteria. The most hypoxic participant reached a SpO_2 of 38%, and the mean SpO_2 when reaching termination criteria was 60% (range 38 to 82%, Figure 3). On average the inspired fraction of oxygen at termination of the hypoxia experience was 5.2% (SD 0.8%). Hypoxia experiences lasted, on average, 7.3 minutes (SD 1 minute). All sessions were stopped because participants met the termination criteria; 6/20 by making mistakes, and 14/20 (70%) by no longer responding to the task. Unresponsiveness started at oxygen saturations as high as 85% and as low as 43%. Six participants correctly identified their number of mistakes, eight participants did not recall making any mistakes, three participants only recalled making one, and three participants recalled making more than five mistakes.

In the blinded hypoxia testing exposures, when compared to the hypoxia experiences, participants had higher SpO_2, inspired oxygen percentages, and shorter hypoxia durations at termination, likely because they were performing bailout procedures based on perceived symptoms. All participants achieved 'self-rescue' by operating the bailout valve on the rebreather mouthpiece. Six out of 18 participants (33%) in the information leaflet group, and 18 out of 20 divers (90%) in the unblinded hypoxia experience group, self-initiated bailout prior to the SpO_2 falling to 70% ($P < 0.001$, Figure 4). All other participants required (but appropriately responded to) the heads-up display prompt when SpO_2 fell

Table 1
Characteristics of the study participants. Note that the participants could identify as having more than one ethnicity

Parameter	Hypoxia experience *n* = 20	Information leaflet *n* = 18	Total *n* = 38
Age (mean years, range)	33 (18–53)	25 (21–33)	33.6 (18–53)
Female *n* (%)	8 (40)	6 (33)	14 (37)
Ethnicity *n* (%)			
European	9 (45)	12 (67)	21 (55)
Māori	2 (10)	1 (6)	3 (8)
Pacific peoples	1 (5)	0	1 (3)
Asian	2 (10)	0	2 (5)
Other	6 (30)	5 (28)	11 (29)
Education *n* (%)			
Secondary School	6 (30)	7 (39)	13 (34)
Bachelors	5 (25)	6 (33)	11 (29)
Masters	6 (30)	4 (22)	10 (26)
PhD or other doctorate	3 (15)	1 (6)	4 (11)
Diving history			
Years diving experience (median, range)	7 (< 1–19)	11 (< 1–34)	7 (< 1–34)
Number of dives (median, range)	86 (5–1,675)	225 (7–1,500)	104 (5–1,675)
Diving certification *n* (%)			
Open-circuit recreational	16 (80)	14 (78)	30 (79)
Open-circuit technical	2 (10)	2 (11)	4 (11)
Closed-circuit rebreather	2 (10)	2 (11)	4 (11)

Figure 3
Peripheral oxygen saturation (SpO_2) at bailout; yellow triangles denote participants in the hypoxia experience; blue circles represent participants who performed a bailout in the blinded testing exposure; purple squares represent participants who required a head-up display warning to perform the bailout

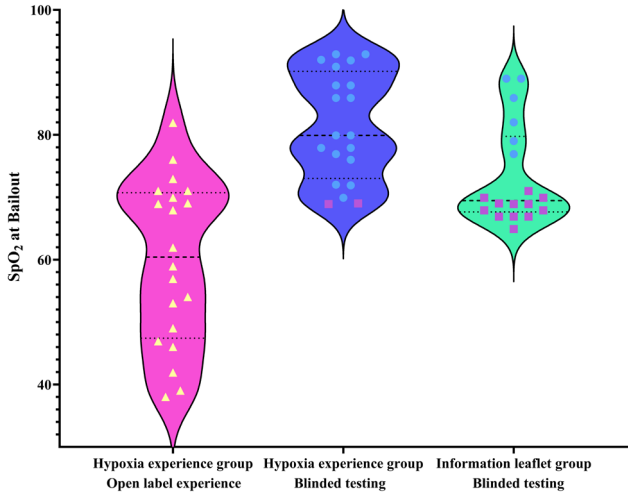
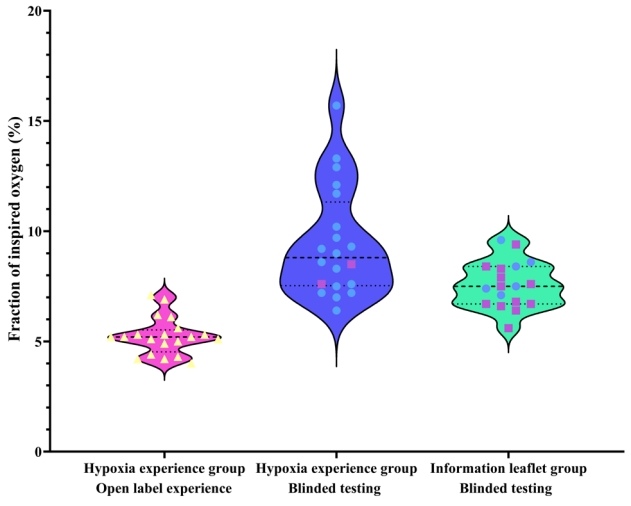
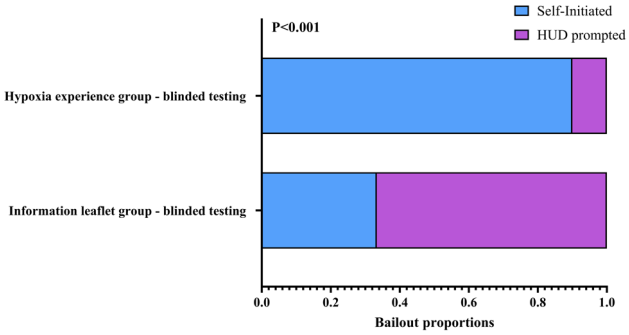


Figure 5
Fraction of inspired oxygen at bailout; yellow triangles denote participants in the hypoxia experience; blue circles represent participants who performed a bailout in the blinded testing exposure; purple squares represent participants who required a head-up display warning to perform the bailout



to 70%. When receiving a heads-up display prompt, it took participants, on average, 5.7 seconds to bail out (range 3.6 to 10.1 seconds). Time between the hypoxia experience and testing for the two HUD-prompted participants was 52 and 56 days. Divers in the information leaflet group had lower SpO_2 values (73.4% vs 81.4%, mean difference 8% (95% CI = 2.5 to 13.5%, $P = 0.005$, Figure 3) and lower inspired oxygen fractions (7.6% vs 9.4%, mean difference 1.8% (95% CI = 0.6 to 3.1%, $P = 0.005$, Figure 5) at bailout. The mean desaturation rate was 2.16%·min^{-1} (range 1.04–3.48) in the training and 2.49%·min^{-1} (range 1.14–3.38) in the

Figure 4
The proportion of self-initiated and heads-up display (HUD) prompted bailout in the hypoxia experience and information leaflet group during the blinded hypoxia testing exposure



information leaflet group ($P = 0.10$) during the blinded test exposure. For those who initiated self-rescue, there was no difference in SpO_2, inspired oxygen fraction, or time to bailout, regardless of receiving an information leaflet or an unblinded hypoxia experience.

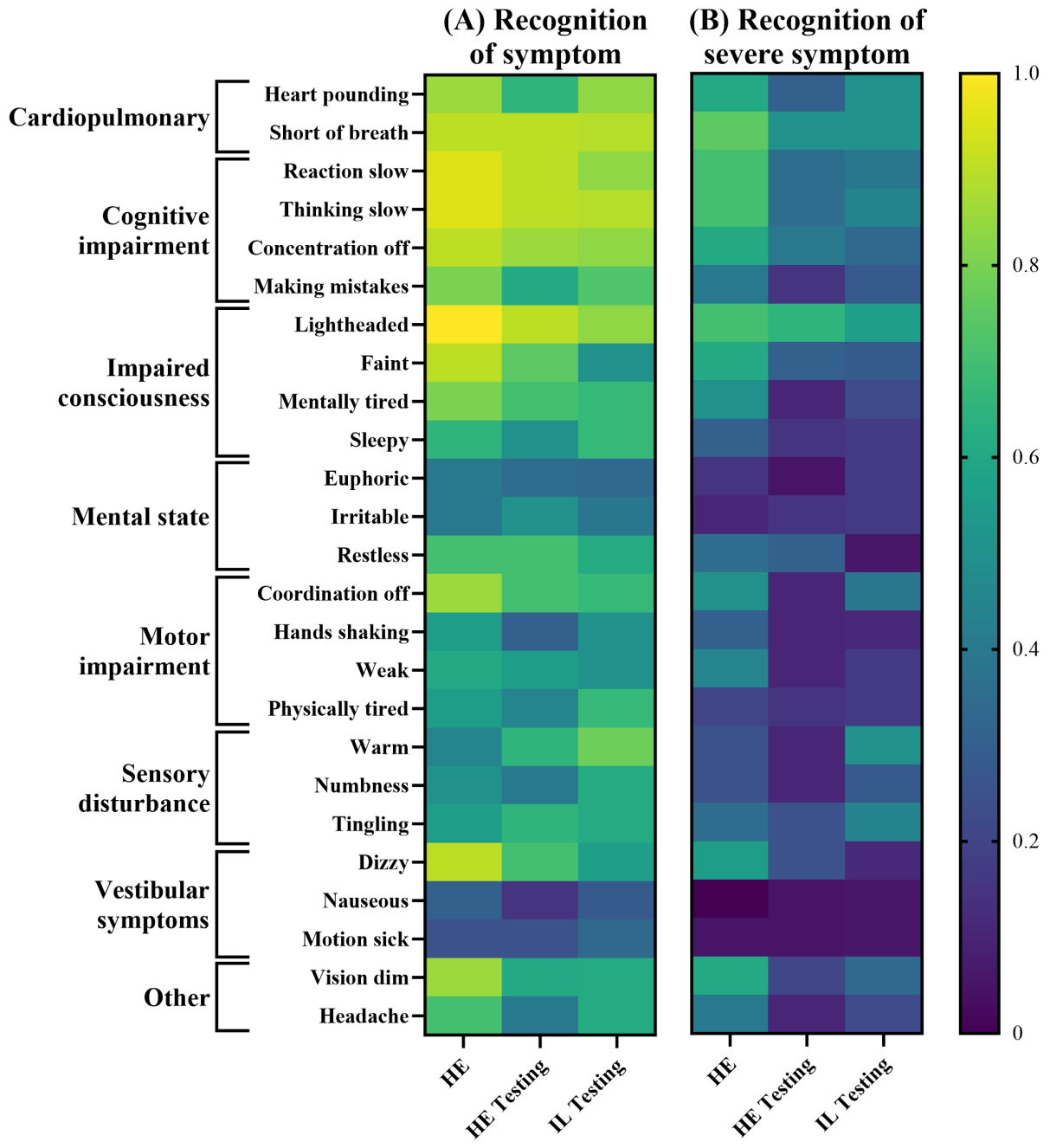
In both the unblinded hypoxia experience and the subsequent blinded hypoxia testing exposures, the two most frequently reported and most severely perceived symptoms were light-headedness and shortness of breath. During the unblinded hypoxia experiences, participants reported more numerous and intense symptoms compared to the hypoxia testing exposure accompanied by lower SpO_2 values. Reported symptoms were similar during the hypoxia testing exposure in both the information leaflet and hypoxia training groups (Figure 6). The first reported symptoms were shortness of breath (7/38, 18.4%), light-headedness (5/38, 13.2%), paraesthesia (5/38, 13.2%), feeling warm (4/38, 10.5%), impaired concentration (3/38, 7.9%), slow thinking (3/38, 7.9%), heart pounding (3/38, 7.9%), tunnel vision (3/38, 7.9%), increased blinking (2/38, 5.3%), slower reaction (1/38, 2.6%), feeling euphoric (1/38, 2.6%), and feeling tired (1/38, 2.6%). Of the 20 participants who underwent both an unblinded hypoxia experience and a subsequent hypoxia testing exposure, 14 (70%) had a correlated symptom signature (consistent symptoms between exposures), while six (30%) did not. Despite this, all six with an inconsistent hypoxia symptom profile performed a self-initiated bailout in the hypoxia testing exposure, while the participant requiring a heads-up display prompt had a consistent hypoxia symptom profile.

Discussion

We investigated the effect of a prior unblinded / open label hypoxia experience on the ability to self-rescue in a subsequent blinded hypoxia 'testing' exposure. Divers in the hypoxia experience group were approximately three times more likely to self-rescue (18/20, 90%) without prompting compared to those in the information leaflet group (6/18, 33%) before the SpO_2 fell below 70%. All participants

Figure 6

Self-reported symptom heatmap; heatmap A shows the recognition of a symptom (visual analogue scale score ≥ 5/100), and heatmap B shows the recognition of severe symptoms (visual analogue scale score ≥ 50/100). Yellow indicates all participants recognised this symptom (heatmap A) or recognised it as severe (heatmap B), while dark blue indicates no participant recognised this symptom (heatmap A) or recognised it as severe (heatmap B). HE – unblinded / open label hypoxia experience; HE Testing – hypoxia experience group during blinded hypoxia testing event; IL Testing – information leaflet group during blinded hypoxia testing event



in both groups were able to self-rescue if they received a heads-up display prompt. Hypoxia symptoms varied across participants; however, most participants who completed both the open label hypoxia experience and testing exposures exhibited a consistent within-individual symptom pattern. This consistency did not seem crucial to the participants' ability to self-rescue.

In 2022, Popa and colleagues conducted a study in which 20 divers underwent an unblinded hypoxia exposure using a similar approach to inducing hypoxia as reported here.[4] The experience was terminated when SpO_2 fell to 75%. Then, on the same day and often with very short intervening periods (as short as 10 minutes), participants underwent three blinded exposures, two normoxic and one hypoxic, in randomised order. During the hypoxia exposure, only

9/20 (45%) participants bailed out with no prompt. On this basis, the authors concluded that unblinded hypoxia training provided little benefit. Popa's findings differ from the present study in which 18/20 (90%) of participants who had a prior unblinded hypoxia experience self-rescued during the hypoxia testing exposure. Possible reasons for this difference include our allowing SpO_2 to fall to 70% before prompting participants to bailout which arguably provided a greater hypoxic stimulus to act, and the use of very mild exercise in the Popa study which may have caused a greater level of participant distraction and a faster decline in oxygen levels thus reducing useful cognitive function time to initiate self-rescue.

Interpretation of the Popa study requires cognisance of several other issues. First and most importantly, there was no comparator group that had not undergone hypoxia training experience. It is, therefore, possible that such a comparator group would have performed even more poorly than their universally trained cohort in relation to self-rescue. Second, it is also possible that participants had not fully cognitively recovered after the initial hypoxia exposure, even though SpO_2 had returned to normal. Full cognitive recovery, or disappearance of the 'hypoxia-hangover' takes at least 2–4 hours.[11] This may also explain the difference in responsiveness to a prompt to bailout between the Popa study (85%)[4] versus our study (100%).

Our laboratory-based finding of apparent training benefit after an open label hypoxia experience, while seemingly relevant to an aviation cockpit scenario (sedentary, cognitively distracted participants), cannot be extrapolated to the diving environment with strong confidence. Participants in our study self-initiated bailout at SpO_2 levels between 81.4 and 73.4%. These represent values near the top of the steep downward slope of the oxygen-haemoglobin dissociation curve and a further decline will result in a precipitous reduction in arterial oxygen content and a rapidly progressive risk of impairment and unconsciousness. Being immersed and exercising increases oxygen demand, resulting in faster depletion of oxygen levels in the body thus reducing useful cognitive function time to recognise a problem and self-rescue. Gas narcosis might further hamper the ability to perceive symptoms of hypoxia and to act on experienced symptoms. It is also notable that in the diving setting, hyperoxia and hypercapnia may also occur, and these may have some symptoms in common with hypoxia. Our study did not address a diver's ability to distinguish between these conditions. Nevertheless, the endpoint tested (bailout to a breathable gas) is a recommended intervention for all three conditions. If a diver incorrectly perceived symptoms of hypoxia produced by hypercapnia or hyperoxia and bailed out, it would still be the correct intervention in the vast majority of scenarios.

Hypoxia training research has mainly focused on consistency in the experienced symptoms of hypoxia between exposures.[4–8,12] All studies agree with our findings that light-headedness and shortness of breath, closely followed by cognitive impairment are the most frequently and severely reported symptoms.[4,6–8] This does not mean that all people, who become hypoxic, experience these symptoms. Many have tried to identify a 'hypoxia symptom signature'. Studies to date have analysed similarity of symptoms at group level,[6–8] or looked at within-individual consistency per one individual symptom.[12] We evaluated the individual symptom signature by correlating all symptoms of one individual between the open label experience and blinded testing exposures. The majority of people (70%) showed a consistent symptom signature. However, this consistent signature did not appear to result in better recognition of hypoxia in the blinded test exposure of our study.

There has been advocacy within the diving community for hypoxia training experiences in private or diver training facilities, particularly for rebreather divers. We strongly discourage the practice of intentionally inducing hypoxia outside of a purposive controlled environment with medically trained staff immediately available. Although none of our participants became unconscious, 70% became unresponsive to the card recognition stimulus. It is highly unlikely that these participants would have been able to rescue themselves. The level of preparation, organisation and attention required to prevent problems (and treat them if they occur) would not likely be replicated outside a highly supervised medical environment.

There are several limitations to this study which need to be acknowledged. First, the participants were healthy young divers. While this may be representative of military divers or aviators, recreational divers could be older and/or have undiagnosed (cardiovascular) health issues, which would negatively impact the safety of hypoxia experiences. The utility (and safety) of such experiences apparent from our highly selected study population cannot be extrapolated across the entire population of recreational divers. Second, although participants undertaking the blinded hypoxia testing exposures were told they could receive hypoxia or normoxia, all received a hypoxia exposure. This had the benefit of increasing the power of the study for the primary outcome, but limited our ability to identify 'false positives', i.e., participants bailing out during normoxic exposures. In the Popa study, 5/40 normoxic exposures were falsely identified as hypoxia.[4] This demonstrates that participants in such trials may be hypervigilant for hypoxia symptoms and illustrates the importance of an ecologically valid distracting task. In our case, we used a VR diving environment with an orca counting task as the distractor. Third, the desaturation rates were dependent on the individual oxygen consumption rate, and it would be extremely difficult to dynamically vary the fraction of inspired oxygen for each participants to ensure desaturation rates were identical in each individual. If desaturation rates were systematically different between the information leaflet and training experience groups during the test exposure, that could introduce a bias in relation to symptom perception, for example, earlier onset of hypoxia-

induced dyspnoea in a group becoming hypoxic more quickly. However, the desaturation rates were very similar between the two groups so we do not consider this a factor that may have influenced our results. Last, the time interval between the open-label hypoxia experience and the blinded hypoxia testing event was, on average, two months in this study. Aviators typically undergo hypoxia refresher training every three years.[8] It is unclear whether the improvement in recognition of hypoxia symptoms exhibited by the hypoxia experience group will persist after a much longer interval.

This study also had a number of strengths, including a head-to-head comparison of the effect of an unblinded hypoxia experience to an information leaflet on hypoxic symptom recognition, participant blinding, participant distraction, and the mimicking of real-life hypoxia onset in a failing closed-circuit rebreather. During this study, a suite of physiological data was recorded. We intend to present these additional data in a separate publication that focuses on the cardiovascular and respiratory physiological responses to severe hypoxia in humans.

These results support the use of hypoxia experiences to enhance symptom recognition in real-world emergencies as currently practised in aviation. It is interesting that such training became widespread in the absence of convincing evidence that it works. The existence of a 'hypoxic symptom signature' has been assumed to enhance recognition of a hypoxic event in real-world scenarios, but until recently, no studies designed to explicitly test the assumption have been conducted. Besides symptom recognition training, two technological methods for hypoxia detection in divers are proposed in the literature, including a wearable pulse oximeter,[13–15] and an oxygen monitor in the rebreather mouthpiece.[16] However, neither has been incorporated into commercial products because of signal reliability. It is known that due to the distance and blood flow, there is variability in pulse oximetry measurement depending on where the probe is placed, such as a 20 second delay at the finger and only a 5 second delay at the earlobe relative to the brain.[17,18] Furthermore, hypothermia can increase this delay at the extremities. Hence, pulse oximeter proximity to the brain should be considered in future to reduce delay and improve accuracy of results. Based on our study results, the detection limits need to be at least equivalent to a SpO_2 of 70% to be in time for an adequate response to bail-out. Ideally, the technology can recognise hypoxia before symptom onset.

Conclusions

In a controlled laboratory environment, divers who underwent an unblinded hypoxia experience were three times more likely to self-rescue in a subsequent blinded hypoxia testing exposure compared to those who only received a hypoxia symptom information leaflet. The majority of participants have a consistent individual symptom signature, which does not lead to earlier or better recognition of hypoxia. Being immersed, exercising and affected by gas narcosis could all negatively influence the ability to recognise and act on hypoxia symptoms. Future studies should examine if hypoxia training helps in symptom recognition after years, and whether such training decreases rebreather accidents.

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Acknowledgements

The authors are grateful to all participants in this study. Furthermore, we would like to thank the rebreather manufacturers (Dive Rite, Ambient Pressure Diving) for kindly donating parts to construct the breathing circuit. Additionally, we would like to thank Axel Busch for creating the VR orca counting environment.

Conflicts of interest and funding

Professor Simon J Mitchell is the Editor of *Diving and Hyperbaric Medicine*. He took no part in the peer-review and decision-making processes for this paper, which were managed entirely by the Deputy Editor, Dr Lesley Blogg. There were no other conflicts of interest.

This work was supported by funding from the Office of Naval Research Global (ONRG), United States Navy (N62909-22-1-2003), the ANZCA Foundation, Australian and New Zealand College of Anaesthetists (AEG22/002), and the James G. Hirsch Endowed Medical Student Research Fellowship.

Submitted: 29 January 2025
Accepted after revision: 27 May 2025

Technical report

Comparison of three infusion pumps as an option for intensive care treatments in monoplace hyperbaric chambers

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Keywords
Drug administration; Fluid administration; Hyperbaric chambers; Hyperbaric oxygen therapy; Intravenous infusions

Abstract
(Schmitz G. Comparison of three infusion pumps as an option for intensive care treatments in monoplace hyperbaric chambers. Diving and Hyperbaric Medicine. 2025 30 June;55(2):145–153. doi: 10.28920/dhm55.2.145-153. PMID: 40544142.)
Introduction: Hyperbaric oxygen therapy (HBOT) is used in critical care for managing certain severe conditions. However, the reliability of infusion pumps under hyperbaric conditions remains a critical concern. This study evaluated the performance of three infusion pump models – the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space – under hyperbaric conditions.
Methods: Infusion pumps were modified to deliver flow into an environment pressurised up to 284 kPa. Accuracy of flow delivered into a pressurised monoplace chamber were tested across a range of infusion rates (1–100 mL·h^{-1}), with different absolute chamber pressures during the iso-pressure phase (243–284 kPa) and a range of different pressurisation/decompression rates (6.9–34.5 kPa·min^{-1}).
Results: More than 3.6 million measurements were obtained. At iso-pressure the Mindray BeneFusion VP5 and the Baxter Flo-Gard 6201 under-performed at low infusion rates (< 20 mL·h^{-1}) and over-performed at high infusion rates (> 20 mL·h^{-1}). Both models exhibited significant under-delivery during pressurisation and over-delivery during decompression. For all conditions the Mindray BeneFusion VP5 demonstrated superior performance. The Braun Infusomat Space was unsuitable for hyperbaric use, failing to maintain performance at pressures above 90 kPa.
Conclusions: The Mindray BeneFusion VP5 outperformed the Baxter Flo-Gard 6201 and Braun Infusomat Space under hyperbaric conditions, offering enhanced reliability for critical care HBOT using monoplace chambers. Clinical protocols should prioritise pumps capable of maintaining flow accuracy during pressure fluctuations. These findings inform best practices for infusion pump use in hyperbaric intensive care, addressing a critical gap in HBOT safety and efficacy.

Introduction

Hyperbaric oxygen therapy (HBOT) is defined as the exposure of the entire body to medical-grade oxygen at pressures of no less than 202.7 kPa (2 atmospheres absolute[atm abs]).[1] Over the past decade, HBOT has been increasingly integrated into intensive care units (ICUs), playing a role in managing certain life-threatening conditions.[2] Evidence suggests that HBOT significantly reduces ICU admissions and improves patient outcomes in conditions such as carbon monoxide poisoning and necrotising fasciitis.[3–5]

Monoplace hyperbaric chambers are currently more widely used than multiplace chambers, accounting for approximately 76.8% of the HBOT device market in 2022.[6] The use of monoplace chambers for ICU patients has been extensively documented and is widely accepted clinical practice,[7,8] despite some concerns regarding their limitations.[9]

A typical ICU setup for HBOT involves mechanical ventilation, invasive monitoring, and multiple infusion pumps. However, a critical challenge is the limited availability of infusion pumps capable of delivering accurate flows into pressurised chambers. These pumps must function under these conditions without triggering downstream obstruction alarms or causing flow inaccuracies.

The issue of infusion pump performance in this setting has been previously recognised, though earlier studies were limited by small sample sizes, isolated condition settings, outdated pump models, and reliance on indirect flow measurements.[10] This study addresses these limitations by evaluating two newer infusion pump models and comparing them to the established Baxter Flo-Gard 6201, which was

previously considered the gold standard.[11] The goal was to provide a comprehensive analysis of infusion pump performance in the monoplace chamber setting and assess the viability of modern pumps in critical care settings, given that the Baxter Flo-Gard 6201 is no longer available for new purchase.

Methods

PUMP MODIFICATION

To deliver flow into a pressurised vessel with a chamber gauge pressure of up to 206 kPa, the infusion pumps were modified to prevent downstream obstruction alarms caused by increased chamber pressure.

- Baxter Flo-Gard 6201: This pump has been extensively used for ICU patients undergoing HBOT and is considered the most reliable option.[11] Modifications were performed as previously described.[12]
- Mindray BeneFusion VP5: According to the manufacturer, this pump tolerates downstream gauge pressures up to 112 kPa (900 mmHg). To extend its tolerance, the downstream pressure sensor spring was removed, and its spring constant (k) was measured. A replacement spring, with a constant reduced to 55–65% of the original, was installed. This adjustment allows for downstream pressures up to 183 kPa, plus an additional tolerance for partial flow obstructions up to 30 kPa (approximately 225 mmHg), achieving a total occlusion gauge pressure of 213 kPa.
- Braun Infusomat Space: Similarly, the downstream occlusion sensor springs were replaced to match the required pressure tolerance.

PUMP SELECTION

The accuracy of the actual flow compared to the programmed flow was tested for each pump using a Sensirion LD20-2600B Liquid Flow Sensor (Ref. 1-101564-02, Sensirion AG, Stäfa, Switzerland) both before and after modification.

A pump was accepted if the average deviation in flow with respect to the set infusion rate remained within ± 0.1 $mL \cdot h^{-1}$ for rates between 1–10 $mL \cdot h^{-1}$ and ± 0.2 $mL \cdot h^{-1}$ for rates between 20–100 $mL \cdot h^{-1}$.

To obtain three pumps of each model meeting these criteria, five Baxter Flo-Gard 6201 pumps were tested, while the first three models of both the Mindray BeneFusion VP5 and Braun Infusomat Space passed on the initial test.

TEST DEFINITION AND SET UP

A 1-litre normal saline bag was used for infusion testing, connected to manufacturer-recommended infusion sets:

- ANDE Healthcare disposable auto-exhaust infusion set (Model ZPQ, Ref. X-IS-002K), Shandong Ande Healthcare Apparatus Co., Ltd., Shandong, China for the Mindray BeneFusion VP5.
- Infusomat SpaceLine (Ref. 8700110SP), Braun Melsungen AG, Melsungen, Germany for the Braun Infusomat Space.
- Baxter Clearlink System continu-flo solution set (Ref. 2C8519s) for the Baxter Flo-Gard 6201 pump.

The infusion set was connected to a Sensirion LD20-2600B liquid flow sensor (Ref. 1-101564-02) outside the chamber, obtaining a flow measurement every 0.1 second. The line passed through a Sechrist H3300 hyperbaric monoplace chamber via a pass-through (041600503A, Argon Medical Devices), where it connected to an extension tubing and a collection manifold inside the chamber. The manifold consisted of three three-way stopcocks (VMG, Ref 14020101, China) attached to 3-, 10-, and 50-mL syringes with the plungers removed (Hospimedica HK Holding Group Limited, China), similar to previously described setups.[6] Before each test run, all air was purged from the system. A new infusion set and extension was used for each run.

Each test included:
1. Fifteen minutes at ambient pressure.
2. Pressurisation to test pressures at rates of: 6.9 $kPa \cdot min^{-1}$ (1 $psi \cdot min^{-1}$), 20.7 $kPa \cdot min^{-1}$ (3 $psi \cdot min^{-1}$), or 34.5 $kPa \cdot min^{-1}$ (5 $psi \cdot min^{-1}$).
3. Fifteen minutes at iso-pressure at absolute chamber pressure of: 243 kPa (2.4 atm abs) or 284 kPa (2.8 atm abs).
4. Decompression at the same rates as pressurisation.

For each condition, two test runs were performed. Each pump model was tested simultaneously within the same chamber to ensure comparability.

The theoretical infusion volume was calculated using the Riemann sum method from flow sensor measurements. Measured volumes were compared to the theoretical values, and deviations exceeding 5% were considered significant.

The hyperbaric experiments were done using two Sechrist H 3300 monoplace chambers (Sechrist Industries, Anaheim – USA). Each pump's performance was measured at flow rates of 1, 2, 5,10, 20, 50 and 100 $mL \cdot h^{-1}$ under three conditions: pressurisation, iso-pressure, and depressurisation (as above).

STATISTICAL ANALYSIS

A Kolmogorov-Smirnov test was applied to confirm the non-normal distribution of the flow measurements. Comparisons between test conditions were performed using the Mann-Whitney test, with statistical significance set at $P < 0.05$.

Performance during ambient pressure tests was considered baseline (control), while relative flow changes during pressurisation, iso-pressure, and decompression were calculated as fractions of the baseline flow.

Results

More than 3.6 million flow measurements were analysed across all experimental conditions. Importantly, no significant differences were observed between the two monoplace hyperbaric chambers or between the pumps of the same model. This ensured the consistency and robustness of the experimental setup. For all tests the calculated Riemann sum based on the flow measurements was within 5% of the measured fluid volume, which demonstrates the consistency and reliability of the flow sensor.

PERFORMANCE OF THE BRAUN INFUSOMAT SPACE PUMP

The Braun Infusomat Space infusion pump was unable to maintain adequate performance under hyperbaric conditions. Detailed analysis revealed a sharp decline in performance as relative pressure increased, with flow rates dropping below 50% of baseline at pressures as low as 90 kPa. These results are presented in Figure 1a. Given its inability to deliver adequate flow into a hyperbaric environment, the Braun pump was excluded from further testing.

PERFORMANCE AT AMBIENT PRESSURE

At ambient pressure, all three pumps (Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space) demonstrated performance that was consistent with the selection criteria adopted prior to the experimental phase. Specifically, the flow deviations remained within the defined thresholds.

A closer analysis revealed that the Mindray BeneFusion VP5 exhibited less variability compared to the Baxter Flo-Gard 6201, particularly at higher infusion rates. This trend suggests that the Mindray pump offers more stable performance during steady-state conditions, potentially due to improved flow regulation mechanisms.

Interestingly, the variability in relative flow change increased with higher infusion rates for both pumps, a phenomenon observed across multiple trials. This increase may be attributed to limitations in peristaltic pump mechanics, where higher flow rates can exacerbate small inaccuracies in flow delivery (Figure 1b).

PERFORMANCE UNDER ISO-PRESSURE CONDITIONS

The infusion rates were significantly affected under the tested conditions, with notable deviations from baseline performance observed for both pumps.

- At low infusion rates (below 10–20 $mL \cdot h^{-1}$), the actual flow delivered was consistently lower than the programmed rate, resulting in negative relative flow changes.
- In contrast, at higher infusion rates (above 20 $mL \cdot h^{-1}$), both pumps tended to over-deliver fluid, producing positive relative flow changes.

Between the two pumps, the Mindray BeneFusion VP5 again outperformed the Baxter Flo-Gard 6201, demonstrating smaller deviations and greater consistency across all flow rates. A linear correlation was observed between the set infusion rate and the actual measured flow (Figures 1c and 1d.), allowing prediction based on multiple regression analysis confirming excellent agreement for the Mindray pump ($R^2 = 0.999$) and slightly lower precision for the Baxter pump ($R^2 = 0.975$) (see Table 1).

PERFORMANCE DURING PRESSURISATION

During the pressurisation phase, both pumps exhibited significant reductions in effective infusion rates, particularly at low infusion rates. This effect was influenced by three key variables: the pump model being tested; the set infusion rate; and the rate of pressurisation.

For all combinations of infusion rates and pressurisation speeds, the Mindray BeneFusion VP5 consistently outperformed the Baxter Flo-Gard 6201 (Figures 2a and 2b).

Regression analysis further confirmed strong linear correlations between the set and actual flow rates for both pumps, with R^2 values of 0.996 for the Mindray pump and similar values for the Baxter pump (see Table).

PERFORMANCE DURING DEPRESSURISATION

The depressurisation phase produced the opposite effect, with infusion rates increasing significantly compared to baseline performance, particularly at low infusion rates (Figures 3a and 3b). As with pressurisation, the degree of deviation was influenced by the pump model, set infusion rate, and depressurisation rate. The Mindray BeneFusion VP5 once again demonstrated superior consistency, with smaller deviations and less variability compared to the Baxter Flo-Gard 6201. For both pumps, higher flow rates were less affected, while lower flow rates exhibited the largest deviations.

Regression analysis confirmed that both pumps maintained a strong linear correlation between set and measured flow rates under dynamic pressure changes ($R^2 \geq 0.995$) (see Table 1).

The performance differences between pressurisation and depressurisation phases suggest that the pumps' mechanical components, including compliance of the tubing and internal pressure regulation systems, respond asymmetrically to changes in chamber pressure.

Figure 1

Performance of infusion pumps at ambient pressure and iso-pressure conditions; (a) flow performance of the Braun Infusomat Space under increasing chamber gauge pressure; shaded area represents 95% confidence interval; (b) comparative flow performance of the Mindray BeneFusion VP5 and Baxter Flo-Gard 6201 at ambient pressure, with variability across infusion rates (shaded areas); (c) linear correlation of set infusion rates and measured flow rates at 243 kPa and 284 kPa absolute chamber pressure for the Mindray BeneFusion VP5, dashed line is the line of equality. (d) Linear correlation of set infusion rates and measured flow rates at 243 kPa and 284 kPa absolute chamber pressure for the Baxter Flo-Gard 6201; dashed line is the line of equality

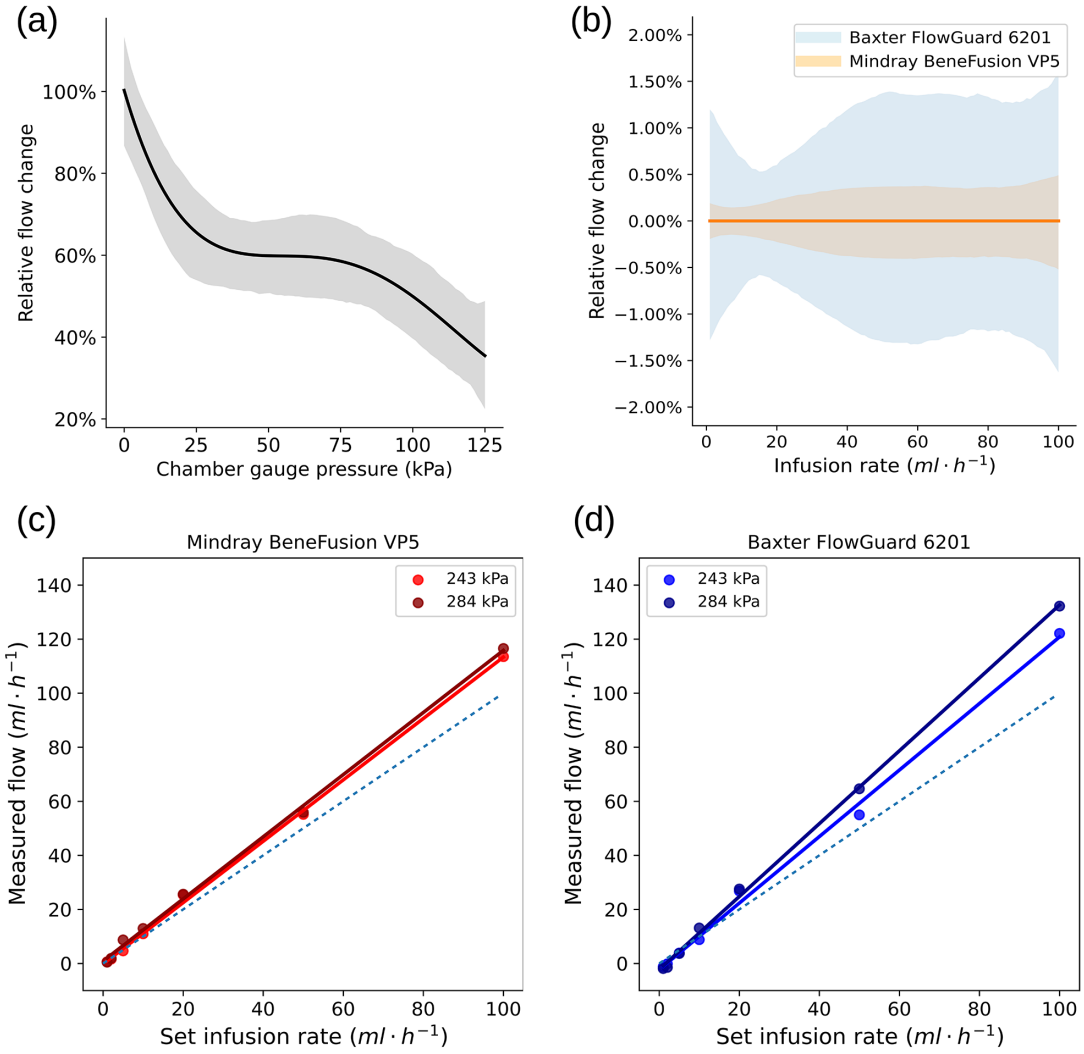


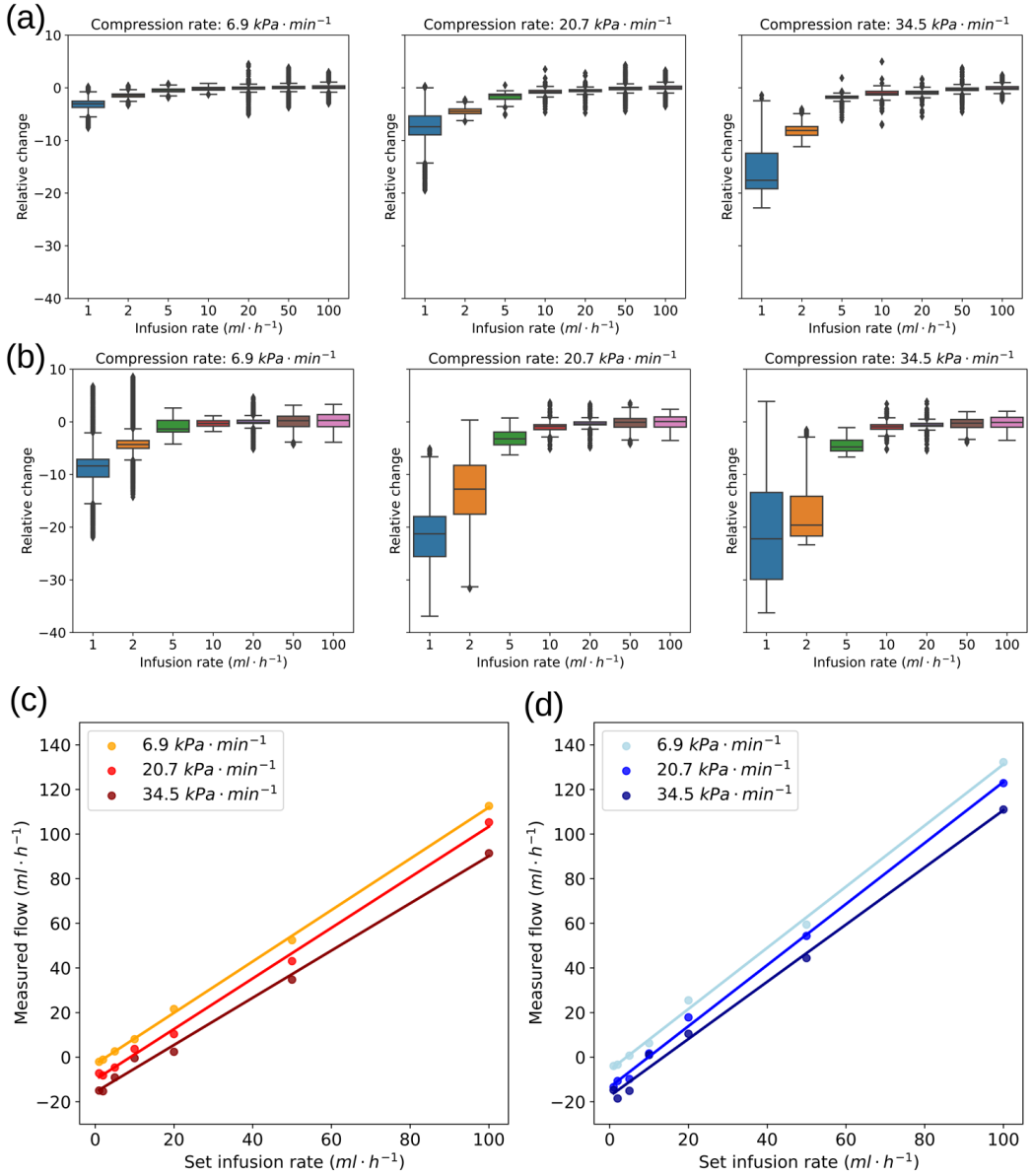
Table 1

Regression model coefficients describing the relationship between set and delivered infusion rates under different hyperbaric conditions. Values represent the intercept, chamber pressure factor, and programmed infusion rate factor for each pump (Mindray BeneFusion VP5 and Baxter Flo-Gard 6201) during compression, iso-pressure, and decompression phases. These coefficients were derived from multiple linear regression analysis and indicate the degree to which chamber pressure and programmed rate influenced actual flow delivery. Positive infusion factors reflect strong linearity with the programmed rate, while negative chamber factors indicate inverse relationships with increasing pressure

Condition	Pump	Intercepts	Chamber factor	Infusion factor
Compression	Mindray BeneFusion VP5	1.6051	-0.5453	1.1147
	Baxter FlowGuard 6201	-1.7363	-0.5087	1.3400
Iso-pressure	Mindray BeneFusion VP5	-9.0908	0.0358	1.1423
	Baxter FlowGuard 6201	-23.0449	0.0789	1.2894
Decompression	Mindray BeneFusion VP5	0.0538	0.5214	1.2977
	Baxter FlowGuard 6201	-2.3222	0.4187	1.4605

Figure 2

Infusion pump performance during pressurisation; (a) box plot of relative flow changes for the Mindray BeneFusion VP5 at different infusion and pressurisation rates; the box represents the interquartile range (IQR), with the lower and upper edges corresponding to the first (Q1) and third quartiles (Q3), respectively. The line inside the box indicates the median (Q2). Whiskers extend to the smallest and largest values within 1.5 times the IQR, while individual points beyond this range are considered outliers. (b) Box plot of relative flow changes for the Baxter Flo-Gard 6201 at different infusion and pressurisation rates. Box and whiskers represent data as described for Figure 2(a). (c) Correlation between set infusion rates and measured flow during pressurisation for the Mindray BeneFusion VP5. (d) Correlation between set infusion rates and measured flow during pressurisation for the Baxter Flo-Gard 6201



Discussion

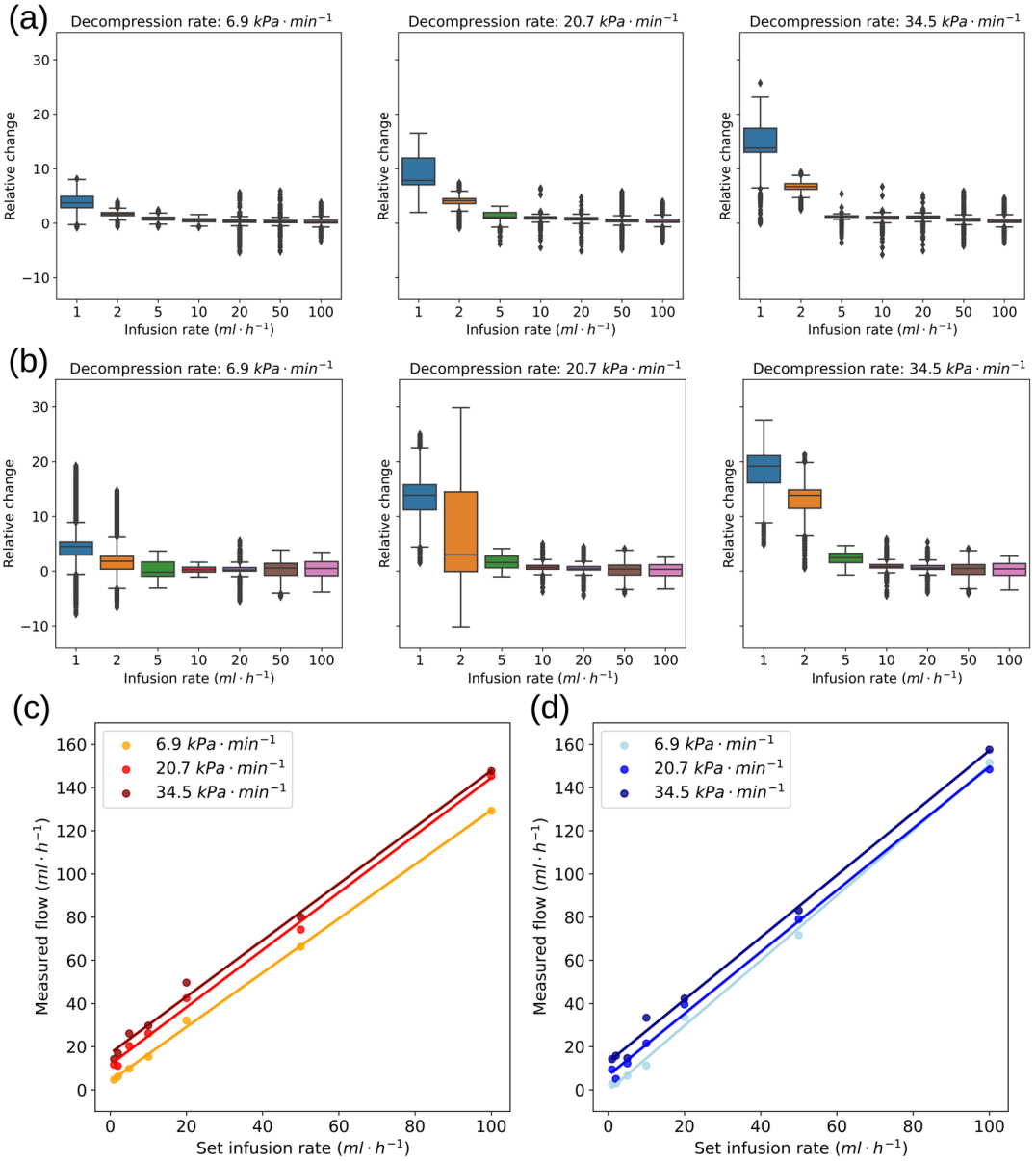
The performance of infusion pumps during HBOT has been a concern in both monoplace and multiplace chambers. Previous studies showed that changing environmental pressure in hyperbaric chambers can significantly influence fluid delivery.[10,11,14] This study provides an updated evaluation of three infusion pumps under such conditions, focusing on the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space using direct flow measurements.

IMPACT OF PRESSURE CHANGES ON INFUSION PUMP PERFORMANCE

During HBOT, pressure fluctuations impose unique challenges on infusion systems. As the chamber is pressurised, the environment exerts increasing resistance on the infusion tubing and pump mechanisms, reducing fluid flow. Conversely, during decompression, decreasing chamber pressure facilitates over-delivery, as the pressure differential between the pump and environment increases. This asymmetry in pump behaviour aligns with the Bernoulli

Figure 3

Infusion pump performance during decompression; (a) Box plot of relative flow changes for the Mindray BeneFusion VP5 at varying infusion and decompression rates. (b) Box plot of relative flow changes for the Baxter Flo-Gard 6201 at varying infusion and decompression rates. In Figures 3(a) and (b) the box and whiskers represent data as described for Figure 2(a). (c) Correlation between set infusion rates and measured flow during decompression for the Mindray BeneFusion VP5; (d) correlation between set infusion rates and measured flow during decompression for the Baxter Flo-Gard 6201

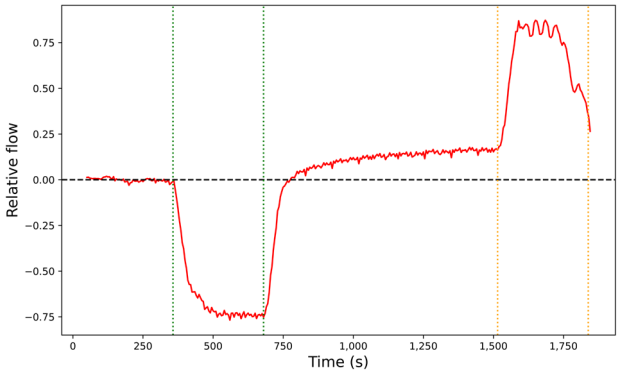


principle, which dictates that pressure differences influence fluid velocity and flow rate. Other explanations, like potential air spaces in the infusion system and tubing compliance, have been mentioned.[12,14] Compliance may affect tube diameter and resistance, influencing flow, but it should be symmetric during compression and decompression and cannot explain negative flow in certain conditions. To fully explain the observed results, infusion set compliance and each pump's flow regulation should be considered alongside the Bernoulli principle.

Performance problems of infusion pumps during hyperbaric treatment have been identified in multiplace[10,14–16] and monoplace chambers.[11–13,18] Figure 4 shows an example of flow problems with reduced effective flow rate during compression and increased rate during decompression.

In the present study, pressurisation mostly resulted in significantly reduced flow rates, particularly at low infusion settings and high pressurisation rates. Decompression induced a reverse effect, with flow rates increasing significantly compared to baseline values. This over-delivery

Figure 4
Typical flow performance of the Mindray BeneFusion VP5 during a complete hyperbaric oxygen therapy cycle with pressurisation / depressurisation rate = 20.7 kPa·min^{-1} and flow rate = 10 mL·h^{-1}; the graph illustrates a reduction in flow rates during pressurisation (between green dotted lines), stabilisation during iso-pressure, and an increase in flow rates during decompression (between orange dotted lines)



was more evident at higher decompression rates and can be explained by the Bernoulli principle.

THE ROLE OF INFUSION RATE IN PERFORMANCE VARIABILITY

An important observation in this study was the relationship between infusion rate and pump accuracy under hyperbaric conditions. At low flow rates (below 10–20 mL·h^{-1}), both pumps exhibited significant deviations, particularly during pressurisation and decompression. The under-delivery during pressurisation and over-delivery during decompression is concerning for critically ill patients requiring precise administration of drugs at low infusion settings, such as vasopressors or sedatives. This limitation may expose patients to risks of inadequate dosing during hyperbaric treatment.

At higher flow rates (above 20 mL·h^{-1}), deviations were less severe, with most values within clinically acceptable ranges. Flow rates above 40 mL·h^{-1} showed minimal performance variability, even during pressurisation or decompression phases. These findings suggest that infusion rates above 40 mL·h^{-1} should be prioritised during hyperbaric treatments to minimise inaccuracies. For patients requiring lower infusion rates, slower pressurisation and decompression protocols should be implemented to mitigate flow disruptions.

PUMP-SPECIFIC INSIGHTS

The performance of the three pumps tested underscores significant variability in their suitability for HBOT environments, likely attributed to their mechanical design.

The Mindray BeneFusion VP5 emerged as the most reliable option, exhibiting minimal variability across all phases of the hyperbaric protocol. At both iso-pressure conditions (243 kPa and 284 kPa), the Mindray pump maintained an almost perfect correlation between programmed and measured flow rates, with a squared Pearson correlation coefficient of R^2 = 0.999. During dynamic pressure changes, it consistently outperformed the Baxter Flo-Gard 6201, showing smaller deviations and better adaptation to pressurisation and decompression. This makes the Mindray pump more suitable to be adjusted based on multiple regression formulas.

CLINICAL IMPLICATIONS

Pump selection: The choice of infusion pump is critical for ensuring accurate fluid delivery during HBOT delivered in a monoplace chamber. Newer pump models should be thoroughly tested for their suitability in hyperbaric medicine. Infusion rates: clinicians should aim to use infusion rates above 20–40 mL·h^{-1} whenever possible. If lower infusion rates are required, additional precautions such as slower pressurisation and decompression should be implemented. Monitoring and adjustment: continuous monitoring of infusion rates using flow sensors can help detect deviations in real time, allowing for timely adjustments to maintain accurate drug delivery. This may be important for critically ill patients who are sensitive to volume overload.

Calibration and testing: Infusion pumps intended for hyperbaric environments should undergo rigorous testing and calibration to account for performance variability under pressure. Regression models, such as those developed in this study, provide a useful tool for predicting flow deviations and optimising pump performance in clinical settings.

Clinical awareness: The clinical team must be aware of infusion rate changes during HBOT. Failure to do so may lead to setting higher infusion rates during compression and maintaining them throughout treatment, risking over-medication. Conversely, lowering the infusion rate after treatment may result in under-medication following HBO exposure.

Safety: Built-in reverse pressure protection, such as a check valve, may prevent fluid from flowing in the opposite direction. For pumps used in hyperbaric medicine, at least a basic risk assessment should be conducted to mitigate potential harm to the patient.[19,20]

Conclusions

The performance of infusion pumps under HBOT conditions presents notable challenges, particularly during pressure changes. This study comprehensively evaluated the behavior of three infusion pump models – the Mindray BeneFusion VP5, Baxter Flo-Gard 6201, and Braun Infusomat Space – under conditions simulating real-world monoplace chamber treatments. Through direct flow measurements and rigorous

testing across various pressures, flow rates, and compression/decompression rates, critical insights into pump reliability, limitations, and clinical implications were gained.

The Mindray BeneFusion VP5 emerged as the most consistent and reliable option, demonstrating superior stability across all tested conditions. At both iso-pressure and during dynamic pressure phases (pressurisation and decompression), it maintained excellent linearity between the set and actual infusion rates, particularly at rates above 10–20 $mL \cdot h^{-1}$. Its ability to adapt to changing environmental pressures, coupled with lower variability, positions it as the most suitable choice for clinical use in hyperbaric intensive care.

The Baxter Flo-Gard 6201, while historically recognised as a 'gold standard' for HBOT applications, exhibited greater variability, particularly at lower infusion rates and during faster pressurisation. Although it remains a viable option for higher infusion rates (above 40 $mL \cdot h^{-1}$), its inconsistencies at low rates necessitate caution when precision is critical. These findings align with previous studies but highlight the need for updated testing protocols to better reflect the demands of modern hyperbaric therapy.

The insights gained here contribute to the development of safer and more reliable HBOT treatment protocols in intensive care units. Moreover, they underscore the importance of ongoing evaluation and innovation in medical device design to meet the unique challenges of hyperbaric medicine.[21]

Further research is needed to explore real-time compensation systems. Developing pumps with real-time pressure compensation or integrated flow sensors could enhance precision under dynamic hyperbaric conditions.

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Conflicts of interest and funding: nil

Submitted: 16 January 2025
Accepted after revision: 30 March 2025

Review articles

Electroencephalographic (EEG) changes accompanying normal breathing of concentrated oxygen (hyperoxic ventilation) by healthy adults: a systematic review

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Keywords
Hyperoxia; Electroencephalography; Central nervous system; Hyperbaric oxygen; Diving; Toxicity

Abstract
(Barnes LD, Hallum LE, Vrijdag XCE. Electroencephalographic (EEG) changes accompanying normal breathing of concentrated oxygen (hyperoxic ventilation) by healthy adults: a systematic review. Diving and Hyperbaric Medicine. 2025 30 June;55(2):154–163. doi: 10.28920/dhm55.2.154-163. PMID: 40544143.)
Introduction: Divers often increase their fraction of inspired oxygen (FIO_2) to decrease their risk of decompression sickness. However, breathing elevated pressures of oxygen can cause central nervous system oxygen toxicity (CNS-OT). This study aimed to review the literature describing the effect of hyperoxia on the electroencephalogram (EEG), thus exploring the potential for real-time detection of an impending CNS-OT seizure.
Methods: We searched Medline, Embase, Scopus, and Web of Science for articles that reported EEG measures accompanying hyperoxic ventilation ($FIO_2 = 1.0 \pm$ hyperbaric pressure) in healthy participants. We included peer-reviewed journal articles, books, and government reports with no language or date restrictions. Randomised controlled trials and cross-over studies were included; case reports were excluded. We used the Newcastle-Ottawa scale to evaluate evidence quality.
Results: Our search strategy returned 1,025 unique abstracts; we analysed the full text of 46 articles; 22 articles (16 studies) were included for review. Study cohorts were typically small and comprised of male non-divers. We discovered a variety of EEG analysis methods: studies performed spectral analysis ($n = 12$), the analysis of sensory-evoked potentials ($n = 4$), connectivity/complexity analysis ($n = 3$), source localisation ($n = 1$), and expert qualitative analyses ($n = 4$). Studies of severe exposures (long duration at hyperbaric pressure) typically reported qualitative measures, and studies of mild exposures typically reported quantitative measures.
Conclusions: There is a need for a large randomised controlled trial reporting quantitative measures to better understand the effect of hyperoxia on the EEG, thus enabling the development of real-time monitoring of CNS-OT risk.

Introduction

Diver performance and safety is affected by the physical and chemical properties of the gas mixtures breathed.[1] For example, technical divers working in shallow water (< 30 metres) will often breathe oxygen-enriched (nitrox) gas mixtures;[2] this, as compared to breathing normal air, can reduce the likelihood of diving-related medical conditions such as decompression sickness.[3] However, breathing elevated fractions of oxygen ('hyperoxic ventilation') at increased pressure produces hyperoxia, the physiological state wherein oxygen levels in blood and tissue are abnormally high. This, in turn, increases the risk of central nervous system oxygen toxicity (CNS-OT), that is, a toxicity that occurs due to exposure to elevated partial pressures of inspired oxygen.[4] Several factors (some potentially interlinked) can promote toxicity, including the oxygen concentration of the breathed gas, the duration of exposure to this gas, barometric pressure, water immersion, hypercapnia, and physical exertion.[5–7] Importantly, several of these factors (e.g., water immersion, physical exercise) necessarily accompany diving. At present, the accepted way for divers to prevent CNS-OT is to choose conservative oxygen exposures as defined by partial pressure and duration of exposure.

CNS-OT can be mild to severe.[8] Signs and symptoms of mild and moderate toxicity include tunnel vision, tinnitus, nausea, lip twitching, irritability, and dizziness.[9] Severe toxicity manifests as seizures and unconsciousness;[10] an unconscious diver is at high risk of losing their mouthpiece, and drowning. CNS-OT symptomatology is highly variable

both between divers, and within a diver between dives.[7] Often, a diver has no warning of impending seizure.[5]

CNS-OT seizures have been shown to alter electroencephalogram (EEG) recordings.[11–13] Additionally, EEG correlates with regional cerebral blood flow,[14] which is to linked to CNS-OT.[15] However, the precise nature of these EEG alterations is unclear. It is also unclear whether related EEG alterations occur abruptly or, rather, emerge gradually. The gradual emergence of EEG alterations could be used to predict an impending seizure and therefore be useful in real-time monitoring of seizure risk during dives, or in clinical decision support in a hyperbaric medicine setting. The aim of this study is to review EEG alterations known to be associated with hyperoxic ventilation and, therefore, identify those alterations potentially useful in predicting CNS-OT onset.

Methods

SEARCH STRATEGY

We conducted a systematic search using Medline, Embase, Scopus, and Web of Science (date of last search: 16 February 2024). We searched for entries labelled with the MeSH Headings "*Electroencephalography*" or "*Electroencephalography phase synchronization*", or entries containing "*electroencephalogram*", or synonyms thereof, anywhere in the title, abstract, or keywords. We limited these results to those with the MeSH Headings "*Oxygen*", "*Hyperbaric Oxygenation*", or "*Hyperoxia*", or those containing the terms "*hyperoxia*", "*hyperoxemia*", or those with "*oxygen*" within two words of "*hyperbaric*" or "*pressure*". Next, these results were limited to those labelled with the MeSH Heading "*Diving*", or containing the terms "*diving*", "*diver*", "*divers*", "*hyperbaric*", or "*normobaric*". Finally, we restricted these results to human studies. We imposed no restrictions on language or publication date; we translated non-English articles for screening and review. Our search strategy is fully specified in *Appendix A . We drafted the search strategy with assistance from the University of Auckland librarian, and validated the strategy against five articles identified as matching the review protocol.[12,16–19] After developing the Medline search strategy, we translated it into formats compatible with the other three databases (*Appendix A).

SELECTION PROCESS

We imported search results from Medline, Embase, Scopus, and Web of Science into Covidence reference management software (Veritas Health Innovation Ltd., Melbourne, Australia; available at https://www.covidence.org) for deduplication, review, and data extraction. To guide our methods, we used the PRISMA statement.[20] The authors (LB, LH, XV) screened titles and abstracts of articles discovered by the search; every title and abstract was screened independently by at least two authors. We excluded articles involving paediatric subjects, animals, chronic exposure scenarios, or patient cohorts (i.e., studies of participants with pre-existing medical conditions). We resolved any disputes regarding inclusion or exclusion through discussion.

We obtained full-text versions of all articles deemed relevant. After reviewing the full text, we excluded articles that either lacked primary data, used exposures other than pure oxygen (i.e., $FIO_2 < 1.0$), or failed to report EEG outcomes. We then screened the citations within the included articles, adding relevant references to the full-text review. Next, we conducted citation searches on these articles using two tools: ResearchRabbit (ResearchRabbit, USA; available at https://www.researchrabbit.ai), and PaperFetcher.[21] Both tools used the list of included references to identify additional relevant papers. ResearchRabbit generates a list of articles related to the supplied articles (they do not specify their methodology). PaperFetcher employs both forward and backward citation searches to compile a list of relevant articles. Forward citation searches find all articles that have cited the references, while backward citation searches find all articles cited by any of the articles in the reference list. All discoveries from this citation search underwent title and abstract screening before any full-text review.

DATA EXTRACTION

Authors LB and LH extracted data using a custom data extraction form (*Appendix B). The data extracted included study design, hyperoxic ventilation exposure, participant demographics, and quantitative and qualitative EEG results. Qualitative results were defined as expert evaluation of EEG recordings, typically summarised with observations such as "*no abnormalities detected*". Given the diversity in quantitative data and experimental designs, a formal meta-analysis was not feasible.

Reviewers LB and LH employed the Newcastle-Ottawa scale (NOS) for assessing the quality of studies[22] (*Appendix B). This scale ranges from zero to nine, where zero (nine) indicates the worst (best) possible quality. The NOS evaluates three aspects of studies: (1) cohort selection, scoring up to 4 points for representativeness; (2) comparability between study groups, scoring up to 2 points for effective control of confounding variables (e.g., age and gender); and, (3) integrity of outcome assessments, scoring up to 3 points based on blind evaluation, sufficient outcome manifestation time, and thorough follow-up. The overall score is converted to a measure of quality using the Agency for Healthcare Research Quality guidelines[23] as follows:

- Good quality: Requires 3 to 4 points in selection, and 1 to 2 points in comparability, and 2 to 3 points in outcome assessment.

***Footnote:** Appendix A and B are available to download from https://www.dhmjournal.com/index.php/journals?id=357

- Fair quality: Requires 2 points in selection, and 1 to 2 points in comparability, and 2 to 3 points in outcome assessment.
- Poor quality: 0 or 1 points in selection, 0 in comparability, 0 or 1 in outcome assessment.

Results

INCLUDED STUDIES

Our search across the four databases (Medline: 1966-present, Embase: 1947–present, Scopus: 1823–present, and Web of Science: 1900–present) yielded 1,115 articles. Additionally, automated citation searching contributed 403 articles, and manual citation searching added seven more. After deduplication, we screened the titles and abstracts of 1,025 articles. We read the full text of 46 articles; we included 22 of these articles in this review. These 22 articles reported 16 studies (i.e., several articles reported the same primary data). We illustrate the article selection process in Figure 1.

Our process selected one randomised control trial;[24] the remaining studies were non-randomised and/or non-controlled. Most studies used a cross-over design. Of the 16 studies included in this review, we graded 13 as good quality, none as fair, and three as poor. All poor studies used visual analysis and therefore failed to score comparability points on the NOS (Table 1).

STUDY PARTICIPANTS

In most of the studies included in our review, the cohort size was less than 15. The study with the largest cohort included 39 participants, however, this study used normobaric, not hyperbaric, exposure, meaning its results are less relevant to the prevention of CNS-OT which only occurs in hyperbaric conditions.[25] The largest hyperbaric study involved 34 participants across five separate exposures.[13] Typically, experimental participants were male; overall, 80% of participants were male; only two studies used majority-female cohorts.[26,27] Most participants were between 30 and 39 years old; the youngest participant was 18 years,[26] while the oldest was 81 years.[28] Cohort demographics are tabulated in Table 2.

Participants were healthy adult volunteers, and most had no reported diving experience (10 out of 16 studies). Four studies involved individuals with some diving experience (either unspecified or less than one year),[11,12,18,29] while two studies recruited participants with significant diving experience (three or more years).[16, 30] Most studies failed to report if participants had prior hyperoxic ventilation exposures. In two studies, some participants had undergone oxygen tolerance tests,[12,16] and in one study, four individuals had prior hyperoxic episodes.[16]

Figure 1
Flow diagram of article selection

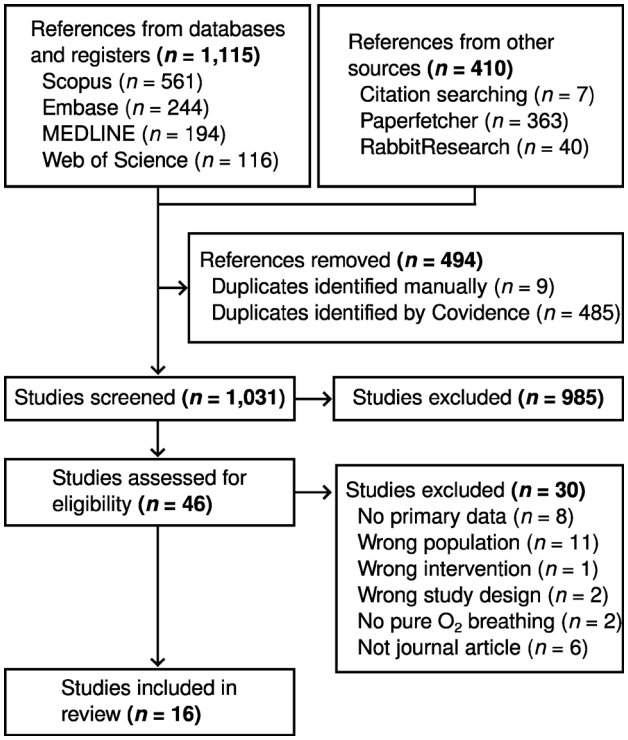


Table 1
We used the Newcastle-Ottawa scale to assess the quality of the 16 studies included in our review. The table shows the count of studies that received each score for each aspect of the Newcastle-Ottawa scale

Score	Selection (max. 4 points)	Comparability (max. 2 points)	Assessed outcome (max. 3 points)
≥ 3 points	15	Not applicable	16
2 points	1	0	0
1 point	0	13	0
0 points	0	3	0

INTERVENTION

Among the 16 studies included, four included multiple oxygen exposures (all were $FIO_2 = 1.0$) at different durations and/or hyperbaric pressures.[13,18,30 31] One study featured five exposures,[13] two studies each included three exposures,[18,30] and one study included two exposures.[31] Of these 25 exposures, we classified seven as mild, four as moderate, and 14 as severe. We defined mild exposures as those that occurred at normobaric pressure. Moderate exposures were

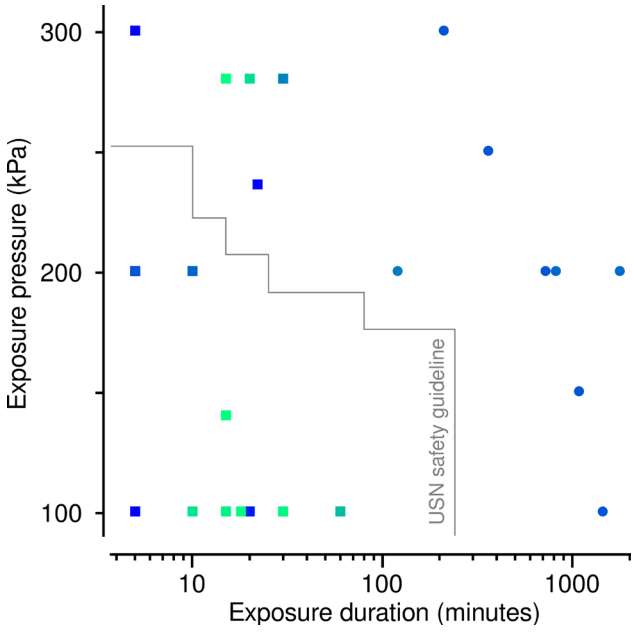
Table 2
Study participant characteristics; 'diving' – refers to years of diving experience; HAV – healthy adult volunteers

Parameter	*n* studies (*n* = 16)
Number of participants	
< 10	2
10–15	6
16–20	1
> 20	5
Not specified	2
Male percentage	
100%	7
50–99%	3
< 50%	2
Not specified	4
Average age (years)	
18–19	0
20–29	3
30–39	5
40–49	1
50–59	0
Not specified	7
Characteristic	
HAV	10
HAV, diving < 1 year	4
HAV, diving 1–3 years	0
HAV, diving > 3 years	2
Participants who had conducted an oxygen tolerance test	
100%	1
50–99%	0
> 50%	1
Not specified	14
Publication date	
1940–1960	1
1961–1980	3
1981–2000	6
2000–2025	6

hyperbaric, but did not exceed the safety guidelines set by the US Navy Dive Manual Rev. 7A for single-depth oxygen dives.[25] Severe exposures were hyperbaric exposures that surpassed these guidelines.

There were three studies reporting 'outlier' exposures which far exceeded the US Navy Diving Manual guidelines.[11,13,31] Of these three studies, the data collection for two occurred during wartime (World War II).[11,13] The greatest hyperbaric exposure was at 472.2 kPa (duration not specified),[11] and the greatest exposure duration was 24 hours (at 101.3 kPa).[13] Figure 2 illustrates the range of interventions described by the studies included in our review.

Figure 2
Hyperoxic ventilation exposures described by studies included in our review; the grey line shows the US Navy (USN) Diving Manual guidelines.[25] Each symbol represents a studied exposure. Squares represent studies reporting quantitative measures, whereas circles represent studies reporting only qualitative measures. Green symbols show recent studies (up to 2022), and blue symbols show earlier studies (starting from 1947)



INDUCTION OF HYPEROXIA

In the 16 studies reviewed, all exposures used either normobaric conditions or used a hyperbaric chamber to create hyperbaric conditions. Most of these studies delivered oxygen via a face mask.[12,13,16,24,26,27,30–35] However, there were exceptions: a Siebe Gorman 'salvus' apparatus;[11] a clear plastic tent;[28] a mouthpiece with a two-way valve,[17] and a mouthpiece with an on-demand valve.[18]

EEG FREQUENCY ANALYSIS

Of the 16 studies reviewed, 12 reported using quantitative spectral analysis of EEG. Of the 12 studies, eight reported changes in EEG spectra, summarised in Table 3. Few studies reported detailed information on their EEG recording methodology, instead reporting only the montage (usually the international 10–20 system) and the number of electrodes. We found no systematic relationship between the documented recording parameters and the EEG outcomes.

Alpha waves

Studies relating alpha-band power to hyperoxic ventilation produced mixed results. At normobaric pressure, four

Table 3

Overview of EEG frequency-band power alterations with hyperoxic ventilation; we do not show studies that reported no relationship between power alterations and exposures. Increases in power are indicated by ↑, decreases by ↓, and no change by ↔. Statistically significant results are indicated by *, while results without any reported statistical testing are underlined

Study	Exposure	Duration (minutes)	Exposure (kPa)	Alpha	Beta	Delta	Theta
Pastena[16]	Severe	20	283.7	↑*	↑*	↓*	↓*
Visser[12]	Severe	30	283.7	↥ (upper alpha) ↧ (lower alpha)	↔	↔	↔
Donald[11]	Severe	Not specified	472.2	↧	↥	↔	↥
Litscher[35]	Moderate	10	202.7	↥	↔	↧	↔
Kaskinoro[32]	Mild	60	101.3	↓	↔	↑	↔
Damato[24]	Mild	30	101.3	↑	↔	↔	↔
Kizuk[26]	Mild	15	101.3	↓*	↓*	↑*	↑*
Sheng[17]	Mild	10	101.3	↓*	↓*	↔	↔

studies (mild exposures) reported change in alpha-band power.[17,24,26,32] Sheng et al. reported a 15.6% reduction in alpha-band power during rest (hyperoxic ventilation versus normoxic ventilation) and a 7.7% reduction in alpha-band power while measuring visual evoked responses.[17] Similarly, Kizuk et al.[26] observed a reliable decrease in alpha-band power, but only when participants' eyes were open. Kaskinoro et al. also reported a decrease in alpha-band power, but this finding was a trend only.[32] In contrast, Damato et al. reported increased alpha-band power at normobaric pressure.[24]

At hyperbaric pressure, several studies reported change in alpha-band power, likewise with mixed results.[11,12,16,35] Litscher et al. (moderate exposure), reported an increase in alpha-band power (hyperoxic ventilation versus normoxic ventilation), however, this change was not statistically significant.[35] Similarly, Pastena et al. (severe exposure) reported an increase in alpha-band power at posterior recording sites.[16] In contrast, some studies have reported decreased alpha-band power.[11] However, this conclusion was made using visual analysis (i.e., qualitative analysis) of the recorded EEG, and no statistical analysis was provided. Visser et al. (moderate exposure), observed an increase in upper-frequency alpha-band power and a decrease in lower-frequency alpha-band power during hyperoxic ventilation (compared to normoxic).[12] They also observed a statistically significant increase in alpha peak frequency at hyperbaric pressure, but this increase did not persist when participants switched from breathing air to pure oxygen.

Beta waves

Studies relating beta-band power to hyperoxic ventilation also produced mixed results. For normobaric exposure, four studies (mild exposures) concluded an association between hyperoxic ventilation and beta-wave activity.[11,16,17,26] Two of these studies reported decreased beta-band power (hyperoxic ventilation versus normoxic ventilation).[17,26] In one case, this decrease was only observed when participants' eyes were open.[26] Sheng et al. observed this change only during the measurement of visual evoked responses.[17] For hyperbaric exposure, two studies reported an increase in beta-band power linked to hyperoxia.[11,16] Pastena et al. (severe exposure) found that this decrease was limited to the upper beta band (13 to 30 Hz) and primarily observed over temporal cortex.[16] A similar result was reported by Donald et al. (severe exposure), but this change in the beta-band power was observed only in the 25 to 32 Hz range.[11]

Theta waves

Studies relating theta-band power to hyperoxic ventilation, again, produced mixed results. For normobaric exposure, Kizuk et al. (mild exposure) reported an increase in theta-band power (hyperoxic ventilation versus normoxic ventilation) during their eyes-closed condition – a change which was focused around the right-frontal region.[26] For hyperbaric exposure, Pastena et al. (severe exposure), observed a decrease in theta-band power; this change persisted throughout hyperoxic ventilation, and was focused over the parietal region.[16] In contrast, Donald et al. (severe exposure) reported an increase in theta-band power.[11]

Delta waves

Results relating delta-band power to hyperoxic ventilation were, too, mixed. For normobaric exposure, two studies (mild exposures) identified effects of hyperoxic ventilation on delta waves.[26,32] Kizuk and colleagues reported an increase at the right-posterior electrode sites while participants' eyes were closed.[26] Kaskinoro and colleagues

reported an increase over frontal and temporal cortical regions.[32] For hyperbaric exposure, two studies reported a decrease in delta-band power.[16,35] Pastena et al. (severe exposure) reported statistically significant decreases at posterior electrodes;[16] this decrease in delta-band power was accompanied by a simultaneous increase in alpha-band power at the same site. Litscher et al. (moderate exposure) described a decrease in delta-band power activity, however, this change was not statistically significant.[35]

OTHER EEG ANALYSIS TECHNIQUES

Among the 16 studies included in our review, spectral analysis was not the only technique used. Additional techniques fell into three broad categories: evoked potentials (reported by four studies),[17,29,30,35] connectivity/complexity analysis (reported by three),[18,36,37] source localisation (reported by one),[36,37] and qualitative analysis (reported by four).[11,13,31,34]

Evoked potentials

Four studies measured evoked potentials during hyperoxic ventilation: one employed visual stimuli,[17] another used auditory and somatosensory stimuli,[35] a third applied auditory and visual stimuli,[29] and the fourth used auditory stimuli.[30] Two of these studies reported significant changes in evoked potential responses (hyperoxic versus normoxic ventilation).[17,30] Sheng et al. (mild exposure) reported a delay in N1 and P2 components of the visual evoked potential (VEP), but found no change in VEP amplitude.[17] In contrast, Bennett et al. (mild-severe exposures) reported a reduction in the amplitude of auditory evoked potentials (AEPs) (hyperoxic versus normoxic ventilation); the magnitude of this reduction increased with hyperbaric pressure.[30] Litscher et al. (moderate exposure), noted a small change in brainstem evoked potentials, but this change was not statistically significant.[35]

Connectivity/complexity analysis

Two studies employed connectivity/complexity analysis techniques to understand the impact of hyperoxic ventilation on the brain.[18,36] Vrijdag and colleagues (mild-severe exposures), found no significant change in connectivity (hyperoxic versus normoxic ventilation).[18] However, a significant reduction in temporal complexity was reported. These researchers quantified temporal complexity by the entropy of the diagonal line-length probability distribution of the binarized cross-correlation matrices of consecutive time samples, indicating how variable the signal was over the medium time range (2–10 seconds).[18] Storti et al. (severe exposure) used multivariate autoregression to estimate the direction of information flow between cortical sites.[36] They found an increase in connectivity from frontal to posterior cortical regions (hyperoxic versus normoxic ventilation), particularly within the alpha- and beta-band frequencies.

Source localisation

Pastena et al. (severe exposure) used the source localisation technique to estimate the origin of EEG alterations associated with hyperoxic ventilation;[36,37] to do so they used sLORETA (standardised low-resolution brain electromagnetic tomography).[38] They found when participants breathed pure oxygen at 283.7 kPa, there was a rapid and statistically significant reduction in delta- and theta-band sources in the posterior region of the brain. Simultaneously, there was an apparent increase in power in the alpha and lower-beta (12 to 18 Hz) bands which was localised to the posterior region.

Qualitative analysis

Four studies conducted qualitative analysis of EEG recordings.[11,13,31,34] In all cases, experts reviewed the electroencephalogram, but found no EEG patterns consistently associated with hyperoxic ventilation, nor any preceding CNS-OT seizure. In work by Donald et al. (severe exposure),[11] fifteen participants from the Admiralty Experimental Diving Unit were ranked on oxygen tolerance. This ranking was based on multiple dives at 286.6, 379.3, and 471.9 kPa in dry conditions, and 255.7 kPa in wet conditions. Dry EEG recordings were then classified as normal, abnormal or doubtful based on two independent opinions (the criteria used for these classifications was not reported). Of these, five participants had normal EEGs, seven had doubtful EEGs, and three had abnormal recordings. Notably, the three participants with the highest oxygen tolerance exhibited normal EEGs; however, all participants who experienced convulsions during, or after, the intervention had either abnormal or doubtful EEGs. However, the third most oxygen tolerant participant, who initially had a normal EEG, convulsed after intervention.

EEG changes accompanying CNS-OT seizures

Among the 16 studies included in our review, three documented EEG changes during CNS-OT seizures.[11–13] Donald et al. (severe exposure)[11] observed that, in some cases, there were bursts of theta-band activity, with increasing voltage just before seizure. However, in other cases, they reported no observable change in cortical activity preceding seizure. In a study by Visser et al. (severe exposure),[12] an experienced diver, who had passed an oxygen-tolerance test three years earlier, experienced a seizure at the end of his 30-minute exposure to hyperbaric hyperoxic ventilation (283.7 kPa). This diver's breathing became irregular 135 seconds before seizure onset due to abdominal myoclonic jerks. Throughout the seizure, no lateralising signs or epileptiform activities were visually detected. However, there was a noticeable increase in theta-wave activity, both isolated and in short bursts, alongside a slowing of the alpha rhythm. The power spectrum showed a mild increase, particularly in the theta and delta bands,

about three to four minutes before the seizure onset. This change coincided with the initial clinical respiratory signs. The EEG patterns during the seizure were consistent with those typical of a tonic-clonic seizure.

In work by Lambertsen et al. (mild-severe exposures), two participants were exposed to hyperoxic ventilation at 304.0 kPa.[13] The first participant experienced a seizure after three hours of exposure, showing typical tonic-clonic EEG patterns; this study reported no change in EEG prior to seizure onset.[13] The second participant, after 2.5 hours, exhibited a 10-second flat (i.e., isoelectric) EEG period, accompanied by 20 seconds of hypotensive unconsciousness. Recovery was marked by a mild tonic-clonic seizure and 30 seconds of disorganised EEG activity, after which normal EEG activity resumed.

Discussion

Our systematic search of the literature discovered 16 studies (22 articles) reporting EEG alterations (or a lack thereof) that accompany hyperoxic ventilation (FIO_2 = 1.0) in healthy adults. We were surprised by the paucity of data on this topic; most studies were observational, designs were heterogeneous, and results were inconsistent. There appears to be a need for a large randomised, controlled trial on the cortical effects of hyperoxic ventilation on normal participants. Across studies, we found no consistent association between hyperoxic ventilation and alterations in the power spectrum of recorded EEG. Quantitative analyses of EEG recordings other than the spectral analysis show promise, but are limited: connectivity/complexity analysis may signal hyperoxia, but these results need independent replication; visual- and auditory-evoked potentials may also signal hyperoxia, but the analysis of evoked potentials is not applicable to real-time monitoring, which is our primary motivation for conducting this review.

The studies discovered by our search all involved small cohorts, typically comprised of male non-divers. Using the Newcastle-Ottawa scale, we judged most studies to be of good quality, usually because they used a cross-over study design. Most studies did not produce results that achieved statistical significance; some studies reported statistical significance, but only for a subset of experimental conditions (e.g., only when analysing EEG recordings using a subset of EEG electrodes). Studies typically involved either quantitative analysis of EEG recordings during mild/moderate hyperoxic ventilation exposures (i.e., short-duration exposure at normo- or hyperbaric pressure), or qualitative analysis of EEG recordings during more severe exposures (i.e., long durations at hyperbaric pressure).

Our systematic searches discovered only studies conducted in dry experimental conditions during which participants were not exercising. No studies in wet experimental conditions would be expected due to the difficulties of measuring EEG underwater. Therefore, the results of these studies may have only limited applicability to diving. Donald et al. have previously reported that oxygen tolerance is diminished when participants are in wet, as opposed to dry, conditions.[7] The current understanding is that immersion in water redistributes the body's circulation, leading to increased regional cerebral blood flow (rCBF), which in turn reduces seizure onset latency.[40,41] Donald and colleagues confirmed earlier animal studies,[42] finding that exercising participants show markedly diminished resistance to CNS-OT.[7,39,43] Exercise appears to cause a build-up in carbon dioxide which interacts with nitric oxide production, thus resulting in increased CNS-OT susceptibility.[15] Superoxide oxygen radicals produced by hyperoxic-ventilation are known to impact sensitivity to CNS-OT.[44] Despite this, none of the included studies reported the background antioxidant state of their participants.

Although we found no clearcut association between EEG and CNS-OT, it is not unreasonable to suppose that seizures can be predicted using EEG which correlates with other pathophysiological states, such as oxygen hyperexcitability,[18] hypoxia,[45] and nitrogen narcosis.[46] While these states differ from CNS-OT, they suggest that EEG activity might serve as a predictive signal for CNS-OT. Additionally, studies demonstrate that other physiological measures, such as electrodermal activity,[47,48] can be used to predict CNS-OT. These studies employed advanced signal processing techniques, which could similarly facilitate EEG's predictive capability for CNS-OT.

Our systematic review discovered three studies that reported EEG alterations specifically associated with a CNS-OT seizure.[11–13] Results across these three studies were consistent in that EEG changes during an oxygen toxicity seizure appear indistinguishable from tonic-clonic seizures from other causes. Two of these studies reported that seizure onset was preceded by a broadband power increase in general, and a theta-band power increase in particular.[11–13] However, by contrast, Visser et al. reported no EEG alterations preceding seizure onset.[12] Indeed, relevant reports of CNS-OT seizure in the literature are few, and none of the studies reporting seizure is recent. It remains an open question whether there exist reliable EEG signs of impending seizure.[49] We note that some animal studies indicate a relationship between rCBF, nitric oxide production and CNS oxygen toxicity. Demchenko et al.[50] found hyperoxia leads to an increase in nitric oxide production, increased rCBF, causing surplus oxygen to be delivered to the neuropil. This rise in rCBF preceded an increase in bursts of EEG activity,[50] possibly originating from the brainstem,[33] followed by seizure.

We employed a 'target trial' framework[51] to assess the risk of bias in the studies identified in our review. This framework also serves as a guide for designing future studies on the effects of CNS-OT on the EEG. Here, we outline an ideal study: it recruits healthy adult volunteers and exposes them to hyperoxic ventilation using pure oxygen in a hyperbaric environment. To simulate diving without compromising

safety, participants are head-out immersed (i.e., in water to the neck) and engaged in physical activity. We propose a cross-over design, wherein participants act as their own controls. Participants are monitored for the signs and symptoms of CNS-OT;[9] the experiment is terminated when any of these signs or symptoms are observed, or a predetermined time limit is reached. Simultaneous recording of EEG and other physiological markers – such as electrodermal activity, brainstem auditory evoked responses, and functional near-infrared spectroscopy – is conducted during both normobaric air-breathing and hyperbaric hyperoxic ventilation. Additional physiological variables, such as baseline antioxidant status, are also measured on the day of recording. This proposed design is similar to a study presently ongoing at Duke University.[52]

Conclusions

Can EEG be used to detect an impending CNS-OT seizure in real time? Our review revealed several shortcomings of the literature which, taken together, obviate a straightforward answer to that question. First, the 16 studies included in our review were small-cohort studies; cohort size likely contributed to the heterogeneous results we discovered. Second, none of these studies used an experimental set-up representative of diving. Water immersion and exercise necessarily accompany diving, and both are known to affect susceptibility to CNS-OT.[7] However, none of the reviewed studies incorporated these factors into experimental design. Finally, most reviewed studies used either mild hyperoxic-ventilation exposures with quantitative EEG analysis, or moderate/severe exposures with qualitative analysis. Thus, these EEG findings have limited translational potential for real-time monitoring; mild exposure is unlikely to cause CNS-OT seizure, and qualitative expert analysis is difficult to implement by way of real-time software. We conclude that there is a need for further research into hyperoxic ventilation's effect on the EEG to help answer this open question.

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Acknowledgements

We thank Rayna Dewar, a librarian at the University of Auckland, for her expert guidance and support in creating the Medline search strategy. We also thank The National Archives for their assistance in conducting this research.

Conflicts of interest and funding

This work was supported by funding from the Office of Naval Research (ONR), United States Navy (N00014-23-1-2467). No conflicts of interest were declared.

Submitted: 24 September 2024
Accepted after revision: 8 February 2025

Safety and efficacy of continuous glucose monitoring devices in individuals with diabetes undergoing hyperbaric oxygen therapy: a scoping review

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Keywords
Hyperbaric medicine; Hyperbaric research; Implantable devices

Abstract
(Katsnelson G, Salvatori M, Djaiani G, Greer E, Tarshis J, Katznelson R. Safety and efficacy of continuous glucose monitoring devices in individuals with diabetes undergoing hyperbaric oxygen therapy: a scoping review. Diving and Hyperbaric Medicine. 2025 30 June;55(2):164–172. doi: 10.28920/dhm55.2.164-172. PMID: 40544144.)
Introduction: Continuous glucose monitoring devices (CGMs) have emerged as an effective approach to optimise glycaemic control for individuals living with diabetes mellitus. Despite CGMs offering improved patient satisfaction and quality of life, they have been primarily validated for outpatient and home use. This has posed a challenge for patients and providers who wish to incorporate CGMs into clinical settings such as hyperbaric oxygen therapy (HBOT). Those with advanced diabetes mellitus who have diabetic foot ulcers that are refractory to treatment are among the most prevalent users of HBOT. However, those who prefer to use their CGM during HBOT face uncertainty regarding the accuracy and safety of their device under hyperbaric conditions.
Methods: The product specifications of commonly used CGMs were collated. In addition, a scoping review of the literature was conducted where Medline, Embase, and Scopus were searched for reports that assess the accuracy or safety of CGMs in hyperbaric conditions.
Results: The product specifications of commonly used CGMs by Dexcom, Abbott, Medtronic, and Senseonics demonstrate a maximum validated pressure of approximately 106 kPa (1.06 atmospheres absolute). Our literature search identified five reports, of which four focused on accuracy and one focused on safety of CGMs in hyperbaric conditions. Treatments were conducted in multiplace chambers and cumulatively described 39 participants, of whom 12 have diabetes. Although heterogeneous in nature, the reports generally supported the safety and accuracy of CGMs in hyperbaric conditions.
Conclusions: The safety and accuracy of using CGMs during HBOT warrants further investigation. CGMs have not been validated for repeated exposure to hyperbaric conditions and should not be used in oxygen pressurised monoplace chambers until further safety data is available. We provide practical recommendations for use of CGMs in multiplace chambers.

Introduction

Diabetes mellitus (DM) and its related complications represent one of the most significant global health crises. In North America, there are currently 50.5 million people living with DM, reflecting an approximate prevalence of 14%.[1] Glucose monitoring is an essential management tool and has traditionally been accomplished with self-monitoring blood glucose (SMBG). However, advancements in diabetes care have made continuous glucose monitoring devices (CGMs) increasingly effective for both short- and long-term use. CGMs offer a user-friendly alternative to SMBG that provides real-time glucose tracking and reliable reduction in glycated haemoglobin (HbA1c) levels and hypoglycaemic episodes. Indeed, the American Diabetes Association has issued clinical practice recommendations and guidelines ascribing benefits to CGM use for managing diabetes in individuals on daily insulin therapy.[2]

The peripheral neuropathy, small vessel vasculopathy, and impaired immune response that is characteristic of advanced DM often results in complex diabetic foot ulcers (DFUs).[3,4] When unresponsive to conventional approaches, hyperbaric oxygen therapy (HBOT) has been shown to accelerate the

healing of DFUs and improve quality of life.[5–11] CGMs are playing a growing role in managing DM, including among those referred for HBOT. However, little is known regarding how to best integrate CGMs in the hyperbaric oxygen environment.

CGM DEVICES

The advent of CGMs represents a significant advancement in the field of diabetes, enhancing glycemic control and overall quality of life.[12,13] A CGM typically consists of a wearable sensor inserted into the subcutaneous tissue which automatically measures glucose levels in the interstitial fluid and transmits this information to a nearby receiver every 1–5 minutes for user interpretation. CGMs aid in glycemic control by tracking glucose fluctuations and providing alerts for rapidly changing glucose levels and hypo- and hyperglycaemic thresholds. These alerts not only help maintain glucose levels within a safe range but also encourage lifestyle modifications by highlighting deviations from individual glucose targets.[14,15] Glucose measurement methods vary depending on the sensor, with electrochemical methods being the most commonly used. Furthermore, one optical approach is currently in clinical use.[16] Presently available CGMs are developed by medical technology companies such as Dexcom, Abbott, Medtronic, and Senseonics.

Most modern CGM electrochemical sensors (Dexcom, Abbott, and Medtronic) work through a glucose oxidase enzymatic reaction.[17] Oxidation of glucose leads to a transfer of electrons to the sensor's electrode, producing an electrical current proportional to the glucose concentration in the interstitial fluid.[17] The electrical current is then converted to a glucose concentration that is displayed for the user. Current Dexcom, Abbott, and Medtronic CGM devices are factory calibrated, eliminating the need for daily calibration with SMBG.[18] However, electrochemical sensors have lifespans of 1–2 weeks beyond which their accuracy significantly deteriorates.[18]

Optical sensing is a novel means of glucose detection first brought to market by Senseonics. Their Eversense® E3 CGM device uses a fluorescence-based optical sensor to measure glucose concentrations. This surgically-implanted device consists of a microfluorometer within a capsule coated with proprietary material that produces fluorescence proportional to the glucose concentration in the interstitial fluid.[19] The degree of fluorescence is converted into a glucose concentration that is displayed for user interpretation. The Eversense E3 CGM is the only device that can be left in place for six months; however, it also requires calibration with a SMBG every 12 hours.

It is important to note that interstitial electrochemical and optical sensors indirectly measure blood glucose, which makes them accurate only under steady state conditions.[20] Capillary glucose is shuttled into the interstitial fluid through simple diffusion which creates a physiological lag time of 5.5 minutes between plasma and interstitial compartments in healthy individuals at rest.[21] This can lead to differences in glucose values between the two compartments which can be exacerbated during times of rapid glucose change, such as in postprandial, exercise, or certain disease states.[22] For instance, although there is significant inter-individual and exercise specific variability, individuals with type 1 diabetes have been reported to have a lag time of 12–35 minutes during moderate to vigorous aerobic exercise.[22–25] The lag time may potentially impact the CGM's analytical performance, typically measured as the mean absolute relative difference (MARD) which represents the difference in measurement between the device and a reference standard. Several studies have reported an increased CGM MARD during various forms of activity, indicating a potential decline in accuracy.[22,26–29] Others have shown conflicting evidence regarding CGM performance during exercise.[30,31] As a result, guidelines and position statements have been developed to clarify how CGMs can be used safely and effectively during physical activity.[25,32] Importantly, stimuli that promote rapid glucose fluctuation can potentially have a similar deleterious impact on CGM accuracy, predispose patients to hypoglycaemia, and complicate carbohydrate replacement and insulin dosing decisions.

USE OF CGMS IN HYPERBARIC OXYGEN CONDITIONS

Diabetic foot ulcers refractory to conventional therapy represent significant cohorts commonly referred for HBOT. However, HBOT presents a unique set of conditions that may impact the accuracy and safety of CGM devices. It is unknown whether increases in pressure or oxygen affect the function, reliability, and safety of CGMs. There are currently no technical or clinical guidelines outlining the appropriate use of CGMs among those undergoing HBOT. As a result, we reviewed the product specifications of commonly used CGMs and have conducted a scoping review of the literature to explore the accuracy and safety of CGMs for individuals undergoing HBOT. We have also provided practical considerations which was informed by a recently published expert consensus guideline regarding the adaptation of CGMs to the hospital setting.[33]

Methods

PRODUCT SPECIFICATIONS

As part of a comprehensive review, we collated information with respect to the product specification of commonly used CGMs currently on the market. This data was obtained from publicly available records from product monographs of respective manufacturers' websites. We have reviewed the available information on Dexcom, Abbott, Medtronic, and Senseonics websites.[34–38]

PROTOCOL AND SEARCH STRATEGY

To supplement the product specifications of current CGMs, we mapped the available evidence regarding CGM use in HBOT through a scoping review that conforms to the PRISMA guidelines. The paucity of available literature that explores CGM use in the context of HBOT guided our decision to implement a scoping review approach. We have reviewed the available literature from MEDLINE (Ovid), Embase (Ovid), and Scopus (Elsevier) databases from inception to 19 October 2024. Our search strategy consisted of Medical Subject Headings (MeSH) and keywords related to hyperbaric oxygen therapy and glucose monitoring, with a complete version of the search strategy available in *Supplementary File 1 (GK). We have also performed a supplementary search of the literature by reviewing the bibliographies of all included studies and searching Google Scholar for any additional reports.

INCLUSION CRITERIA

The inclusion criteria consisted of peer-reviewed original studies that reported on the safety or accuracy of CGMs under hyperbaric conditions. Only full length randomised controlled trials, cohort, cross-sectional, case-control, case reports, case-series, and technical reports were included, while commentaries, letters to the editor, editorials, abstracts, and reviews were excluded from this study. Studies that described at least one primary outcome were included in this review: (1) CGM accuracy in hyperbaric conditions or (2) safety of CGMs in hyperbaric conditions.

SCREENING AND DATA EXTRACTION

The studies were initially screened through title and abstract by two independent reviewers (GK and RK). Thereafter, full texts were screened by two independent reviewers (GK and RK). Conflicts that arose were resolved by mutual agreement. Data extraction was similarly performed by two independent reviewers (GK and RK). The screening and data extraction for this study was conducted through the Covidence Systematic Review Tool (https://www.covidence.org/). Data extracted included study details (primary author and year of publication), patient characteristics (number of participants, presence of diabetes, CGM model), HBOT characteristics (treatment pressure, duration of treatment, type of chamber used), as well as variables related to the primary outcomes. A narrative data synthesis was done using a qualitative approach due to the limited number and heterogeneous nature of the reports identified.

Results

The product specifications of commonly used CGMs are available in Table 1. The operational temperatures for CGMs were from approximately 0°C to 45°C. The maximum approved pressure is approximately 106.4 kPa (1.05 atmospheres absolute [atm abs]) across all devices. The lifespan of the Metronic Guardian Connect is seven days, Dexcom G6 and G7 are 10 days, Freestyle Libre 2 and 3 are 14 days, and the Senseonics Eversense E3 is six months. The MARD of all devices ranged from 7.6% to 10.55%. The measurement frequency for Dexcom G6, Dexcom G7, Medtronic Guardian Connect, and Senseonics Eversense E3 CGMs is every five minutes, while the Abbott FreeStyle Libre 2 and 3 measure every minute.

After deduplication, our scoping review of the literature identified 378 total number of reports (Figure 1). After title and abstract screening, there were 15 studies remaining. Once full text screening had concluded, six reports were excluded because no CGM was used, one was excluded because of incorrect study design, and four were excluded because the full text was not accessible. One study was identified in the secondary search of the literature. Five studies ultimately underwent data extraction and are found in Table 2.

STUDY CHARACTERISTICS

The five studies were published between 2012 and 2021 and involved a total of 39 participants. Twelve of the participants had a diagnosis of DM, while the remainder did not. The devices analysed include the Dexcom G4, Dexcom G6, Minimed Medtronic Guardian Connect, and the iPro Medtronic (with an Enlite sensor) CGMs. The treatment conditions of included studies had significant variability with respect to the pressure and duration of hyperbaric exposure. Four of the studies explored multiplace chambers, while one study did not report which chamber was used. Four studies discussed CGM accuracy, while only one study addressed the safety of CGMs during HBOT.

ACCURACY

In an unblinded study of 10 participants with DM undergoing HBOT for two hours in a multiplace chamber (at unspecified pressures), Baines et al.[39] found that venous serum samples, capillary samples drawn with finger pricking, and the glucose oxidase-based Minimed™ Medtronic Guardian™ CGM sensor demonstrated average glucose readings within 1 $mmol \cdot L^{-1}$ of one another. This accuracy was maintained throughout the two hours which enabled real-time glucose trends. In another study, Huang et al.[40] assessed 26 participants without DM who were undergoing HBOT at 243 kPa (2.4 atm abs) in a multiplace chamber for 90 minutes with five-minute air breaks every 30 minutes. They found that the glucose oxidase-based Dexcom G6™ CGM device slightly overestimated glucose readings when compared to both glucose oxidase and dehydrogenase-based self-monitoring devices. While the dehydrogenase-based glucometer had

***Footnote:** Supplementary File 1 is available to download from https://www.dhmjournal.com/index.php/journals?id=356

Table 1

Product specifications of commonly used continuous glucose monitors; [a]mean absolute relative difference (MARD) values for CGMs were determined based on heterogeneous studies with dissimilar populations. In order to maximise consistency, where multiple MARD values were provided by manufacturers, we reported the one corresponding to the population of adults aged 18 and older. Where unique MARD values were provided based on sensor site (arm, abdomen, buttocks, etc.), we reported the overall MARD provided by the manufacturer. If no overall MARD was documented, we provided the MARD corresponding to each sensor site. [b]Maximum pressure was converted from meters below sea level minimum altitude, where temperature = 21°C and sea level = 101.3 kPa (1 atm abs). [c]Information not found in user manual, instead obtained from study by Bliss et al.[45] [d]MARD values provided corresponds with calibration every 12 hours. Calibration 3–4 times per day yields a MARD of 9.64% for the abdomen site and 8.68% for the arm site. atm abs – atmospheres absolute; NR – not reported

Sensor/transmitter	Temperature range	Humidity range	Maximum pressure	Maximum altitude	Power source	Duration	Accuracy (MARD)[a]	Measurement frequency
Dexcom G6	10–42°C	10%–95%	106.1 kPa 1.047 atm abs[b]	4,206 meters	Lithium-ion[c] battery	10 days	9.8%	5 min
Dexcom G7	10–42°C	10%–90%	105.9 kPa 1.045 atm abs[b]	5,000 meters	NR	10 days	8.7%	5 min
Abbott FreeStyle Libre 3	10–45°C	10%–90%	105.9 kPa 1.045 atm abs[b]	3,048 meters	Silver oxide battery	14 days	7.6%	1 min
Abbott FreeStyle Libre 2	10–45°C	10%–90%	105.9 kPa 1.045 atm abs[b]	3,048 meters	Silver oxide battery	14 days	9.2%	1 min
Medtronic Guardian Connect	0–45°C	10%–95%	105.9 kPa 1.048 atm abs	NR	NR	7 days	Abdomen–10.55% Arm–9.09%[d]	5 min
Senseonics Eversense E3	5–40°C	15%–90%	106 kPa 1.046 atm abs	3,048 meters	Lithium polymer	6 months	8.5%	5 min

Figure 1

PRISMA flow diagram illustrating the identification, screening, and inclusion of reports

no significant difference in glucose values when comparing normobaric conditions and hyperbaric oxygen conditions (5.05 mmol·L^{-1} to 4.98 mmol·L^{-1}, P = 0.841), glucose values measured by CGMs significantly increased from 5.607 mmol·L^{-1} in normobaric conditions to 5.816 mmol·L^{-1} ($P < 0.001$) in hyperbaric oxygen conditions. Although there was statistical significance, 0.2 mmol·L^{-1} is not clinically significant. As part of their study, Huang et al.[40] reproduced findings that are consistent with previous studies involving SMBG devices that show glucose oxidase-based test strips underestimating glucose values when exposed to HBOT, whereas glucose dehydrogenase-based strips do not.[41,42]

The effect of ambient pressure on the accuracy of CMGs is described by Adolfsson et al.[43] They showed that the Medtronic Enlite™ sensor performed adequately under both hypobaric and hyperbaric conditions in a healthy individual who was exposed to a variety of pressures in a multiplace chamber pressurised with room air (21% O_2). The hypobaric test consisted of exposure to 101.3 kPa (1.0 atm abs) for 30 minutes, followed by 50.5 kPa (0.5 atm abs) for 20 minutes, 76 kPa (0.75 atm abs) for 10 minutes, and 101.3 kPa (1.0 atm abs) again for 30 minutes. On the subsequent day, with a new set of sensors, the hyperbaric conditions consisted of 30 minutes at 101.3 kPa (1.0 atm abs), 20 minutes at 405 kPa (4.0 atm abs), 10 minutes at 132 kPa (1.3 atm abs), and 30 minutes at 101.3 kPa (1.0 atm abs). Interestingly, the sensor sensitivity was slightly diminished in hypobaric conditions, but remained unchanged in hyperbaric

Table 2

Characteristics of included studies; [a]ISO guideline 15197: at least 95% of the values compared must have a maximum difference of 20% for glucose levels > 75 mg·dL^{-1} (4.2 mmol·L^{-1}) and within 15 mg·dL^{-1} (0.83 mmol·L^{-1}) for values that are < 75 mg·dL^{-1} (4.2 mmol·L^{-1}); HBO_2 – Hyperbaric oxygen; MARD – Mean absolute relative difference; NA – Not applicable; NFPA – National Fire Protection Association; NR – Not reported; T1D – Type 1 diabetes; T2D – Type 2 diabetes

Ref	*n*	Diabetes Status	CGM Model	Treatment Pressure	Chamber	Treatment duration	Safety	Accuracy
43	1	Healthy	iPro Medtronic (Enlite sensor)	50.5–405 kPa 0.5–4.0 atm abs	Multiplace	105 minutes	NR	-Hypobaric: accuracy reduced (MARD 14.9 ± 9.1%) -Hyperbaric: accuracy maintained (MARD 6.7 ± 7.9%)
44	2	T1D	Dexcom G4	NR	NR	45 minutes	NR	2/26 measurements inaccurate, thereby narrowly failing ISO guideline 15197[a]
45	0	NA	Dexcom G6	138 kPa 1.36 atm abs	Multiplace	11 cycles of 120 minutes	Met NFPA 99 code	NR
40	26	Healthy	Dexcom G6	243 kPa 2.4 atm abs	Multiplace	90 minutes	NR	-CGM slightly overestimated glucose relative to glucometers 0.2 mmol·L^{-1} glucose change in HBO_2 vs. normobaric air with CGM ($P < 0.001$)
39	10	3 T1D 7 T2D	Minimed Medtronic Guardian Connect	NR	Multiplace	120 minutes	NR	-CGM within 1 mmol·L^{-1} of capillary and venous samples

conditions. Lastly, although not explicitly stated in their report, Pieri et al's[44] study was likely similarly conducted in a multiplace chamber with hyperbaric air since the purpose of the exposure was to validate the CGM device prior to scuba diving. They found that in two participants with DM, the Dexcom G4™ CGM was largely accurate with the exception of two of 26 measurements which significantly deviated from the reference standard. Besides having a treatment exposure of 45 minutes, there was otherwise limited information provided regarding the specific hyperbaric conditions.

SAFETY

One study explored the safety of CGM use in the hyperbaric environment.[45] They found that the lithium-ion batteries in the Dexcom G6 CGM device met the standards of section 14.2.9.3.17.5 of the 2018 National Fire Protection Association 99, and were deemed safe to use. However, this safety assessment was done primarily through an evaluation of the manufacturer's design specifications, while formal testing of this device was limited to a multiplace chamber with maximum oxygen concentrations of 23.5%.[45]

Discussion

Evidently, the safety and accuracy of CGM use in the context of HBOT warrants further investigation. The reports identified in this review were heterogeneous with respect to the sensor used, treatment conditions, and reported outcomes. None of the studies explored CGM use in monoplace chambers, nor did they consider repeated daily exposures consistent with accepted HBOT clinical protocols. However, the studies that assessed CGM accuracy generally supported their use in the hyperbaric environment. The only study assessing CGM safety in hyperbaric conditions deemed it safe, but testing was limited to a multiplace chamber pressurised with air. CGMs are only approved by manufacturers for clinical use at pressures of approximately 106 kPa (1.05 atm abs), far below typical pressures during HBOT. Furthermore, CGM safety and efficacy studies have conventionally been conducted at room air (21% oxygen).

The questionable accuracy of CGM during HBOT may be partially explained by the physiological changes that occur during treatment. HBOT is known to acutely decrease blood glucose concentrations, particularly in those with DM.[46–48] Although the exact mechanism is poorly understood, the implications are significant considering the decreased accuracy of CGM devices under conditions of rapid glucose flux. However, some studies have reported inconsistencies regarding the effect of HBOT on glycaemia likely owing to methodological differences. For instance, the type of chamber, the pressure and duration of exposure, the glucose detection approach, and the health status of participants were variable across studies, which potentially confounded the results.[49–51] Nonetheless, concerns about intra-chamber hypoglycaemic crises have rightfully prompted many

hyperbaric units to require minimum plasma glucose levels for HBOT users.

Several studies have explored the accuracy of CGMs in the context of recreational diving, a hyperbaric environment in which a hypoglycaemic event could be life-threatening. These results are limited to pre/post dive analytical performance due to a lack of a feasible reference standard during the dive itself.[52–56] Despite this limitation, there is a general consensus that CGMs provide potentially valuable information for risk reduction pre and post dive. However, CGMs are only water resistant to a depth of around 2.5–3.5 meters which precludes their use during deeper dives.[57]

The primary safety concern associated with using CGMs during HBOT is the risk of fire. This risk is particularly salient in monoplace hyperbaric chambers which are pressurised with 100% oxygen. Battery powered devices, especially those that are lithium-based, may present a source of ignition in the chamber. In monoplace chambers, a fire would have catastrophic consequences, endangering the life of any occupant within the chamber and any medical personnel in the area. Although a CGM was not used, Tsouras[58] conducted a study where the lithium battery-powered Abbott Optium FreeStyle glucometer was found to be safe in hyperbaric conditions at 23.5% oxygen or less. Despite both Tsouras[58] and Bliss et al.[45] supporting the safety of lithium batteries in hyperbaric conditions, it is critical to conduct appropriate testing in monoplace chambers due to the increased risk that pressurised high fraction oxygen may pose. Furthermore, patients may require up to 60 hyperbaric treatments, which is why it is also necessary to test the effects of repeated pressure cycling on the structural integrity and safety of CGMs.[59] This assessment is of particular importance for devices that are of longer lifespan, such as the implantable Senseonics Eversense E3, which has a lifespan of six months.

PRACTICAL CONSIDERATIONS

As CGMs continue to become more prevalent, hyperbaric units should consider establishing clear guidelines that communicate their policies on these devices. Many patients are hesitant to revert to SMBG using finger pricking, underscoring the need for detailed explanations. These guidelines should highlight that none of the current CGMs have been appropriately tested at clinically relevant pressures during repeated hyperbaric sessions, and the accuracy of these devices has not been appropriately validated after single or serial exposures to pressure. CGMs contain batteries that should not be allowed in the enriched oxygen environment of monoplace chambers due to the increased fire hazard they pose. Furthermore, surgically implanted CGMs which have extended lifespans may pose greater safety risks due to the unknown effects of pressure cycling on the device structure and performance. As a result, their use in hyperbaric conditions should be discouraged until more data on their accuracy and safety becomes available. If patients wish to use their self-administered CGM in a multiplace chamber pressurised with air, then a detailed risk-benefit discussion should be documented both verbally and in writing. A sample written consent form, provided as a template, is shown in Figure 2.

Figure 2
Sample informed consent agreement form for clinical HBOT use of CGM devices

I _____ currently have a continuous glucose monitor (CGM) in place and wish to maintain this device during my hyperbaric oxygen therapy (HBOT) sessions. I understand and agree to the following:

1. My CGM device will only be permitted to be used in a multiplace chamber (not monoplace).
2. I have a self administered CGM (not a surgically implanted CGM).
3. I may continue to wear my CGM during my HBOT session, but my blood glucose will also be monitored using a hospital-approved blood glucose meter and treatment decisions will be based on these results.
4. I will keep a back-up supply of all CGM supplies including sensors and dressings in the event a change is required.
5. I will change the CGM sensor in keeping with the device instructions, making sure that the sensor is replaced prior to the maximum lifespan is reached.
6. I will notify a hyperbaric provider immediately if my CGM indicates my glucose reading is trending out of target (too high or low) so that my blood glucose can be tested to confirm the trend and appropriate treatment can be initiated according to the prescriber's order.
7. I will allow my hyperbaric provider to assess the sensor during every appointment, including before and after the HBOT session.
8. Any of my CGM supplies stored by hyperbaric staff will be returned to me prior to my discharge from the clinic.

By signing below, I acknowledge that I have read, understood, and agreed to the above and that all of my questions have been answered.

Patient signature: _____

Health care provider name: _____

Health care provider signature: _____

Unit/service: _____

Date: _____

Time: _____

Care must be taken to avoid inadvertent wearing of CGMs during monoplace treatment. Patients may sometimes forget they are wearing one particularly if it is surgically implanted or if it is a skin colored self-administered CGM. Adding a CGM assessment as part of a pre-treatment checklist is recommended. The hyperbaric team may want to review the history of the CGM readings to determine the glucose control of each patient, including daily variations, and carefully monitor higher risk patients for early hypoglycaemic symptoms during treatment.

Device manufacturers should be encouraged to perform tests of their devices in hyperbaric environments, similar to what has been done by some manufacturers for implantable pacemakers.[60] These tests are relevant for both hyperbaric oxygen therapy and for recreational diving, with the latter requiring additional evaluation of water resistance.

Conclusions

This report highlights the need for more high-quality studies and consensus guidelines to define the reliability, safety, and logistics of CGM use during HBOT. Based on current data, the accuracy of CGMs has not been validated under hyperbaric conditions during repeated HBOT sessions. Furthermore, CGMs should not be allowed in monoplace

chambers pressurised with oxygen due to potential fire hazard. The risks and benefits of CGMs in multiplace chambers should be discussed with patients who have an interest in using their CGM during HBOT. Regardless, CGMs should complement but not replace routine glucose monitoring applied for individuals with DM undergoing HBOT.

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Conflicts of interest and funding: nil

Submitted: 15 October 2024
Accepted after revision: 8 March 2025

Psychosis and diving

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Keywords
Fitness-to-dive; Mental health; Psychiatry; Schizophrenia; Scuba

Abstract

(Querido AL, Wingelaar TT. Psychosis and scuba diving. Diving and Hyperbaric Medicine. 2025 30 June;55(2):173–179. doi: 10.28920/dhm55.2.173-179. PMID: 40544145.)
Psychotic disorders, characterised by impaired reality testing and a spectrum of symptoms, present significant challenges in assessing fitness for diving. While diving can be a safe and rewarding activity, the unique physiological and environmental stresses of hyperbaric conditions can exacerbate psychotic vulnerability or mimic psychotic symptoms. This article reviews the literature on psychosis and diving, exploring the implications of psychotic disorders, psychotropic medications, and hyperbaric effects. It highlights the critical importance of illness insight, the absence of comorbid conditions, and complete remission in determining diving fitness. Key recommendations include avoiding deep dives, careful evaluation of medication use, and a nuanced differentiation between chronic and transient psychoses. By synthesizing existing evidence, this article aims to guide diving medicine professionals in making informed decisions about psychosis and diving suitability.

Introduction

Scuba diving combines physical endurance and mental resilience with unique environmental challenges, such as hyperbaric conditions and exposure to high-pressure gases. For individuals with psychotic disorders, these challenges may be compounded by the risks posed by altered cognition, impaired decision-making, and potential interactions between psychotropic medications and diving physiology.[1]

According to the Diagnostic and Statistical Manual of Mental Disorders, Fifth Edition, psychotic disorders are defined by abnormalities in one or more of the following domains: delusions, hallucinations, disorganised thought, disorganized behavior, and negative symptoms.[2] Rather than providing a rigid definition of psychosis itself, the DSM-5 emphasizes these key symptom domains, which can manifest in various psychiatric and medical conditions.

Psychosis is characterised by a loss of contact with reality, where reality testing is severely impaired, leading to a distorted perception of the external world. It involves a profound disruption in the processing of information, including perception and thought, resulting in erroneous conclusions about reality. While the presentation of psychosis varies between individuals, it may include positive symptoms such as delusions, hallucinations, and disorganized behavior, thought, and speech – and/or negative symptoms, including emotional flattening, apathy, loss of pleasure and interest, and social withdrawal.

This review strives to assess the available evidence on psychosis and diving, addressing both clinical and practical considerations. It explores the interplay between psychotic vulnerability, medication, and hyperbaric conditions while providing a framework for assessing diving fitness. By offering evidence-based recommendations, this review aims to bridge the gap between psychiatric care and diving medicine, ensuring both safety and inclusivity for individuals with a history of psychosis.

Methods

The protocol for literature search strategies was prepared according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA).[3] A structured search of the literature was performed using PubMed up to 30 November 2024 to identify studies and case reports regarding diving and psychosis. A query involving diving and psychosis resulted in very few results, therefore, the keywords were expanded to include aviation and transportation by car. The search query was: ((diving[Mesh] OR dive[tw] OR diving[tw] OR divers[tw] OR hyperbaric[tw] OR scuba[tw]) OR (aviation[mesh] OR flying[tw] OR altitude[tw]) OR (driving[mesh] OR driv*[tw] OR traffic[tw])) AND ((psychosis[Mesh] OR psychosis[tw])). Additionally, several

handbooks on diving medicine that discussed psychiatry or psychology were screened for additional information.

Of the 1,314 potentially relevant studies, which were assessed by title and abstract, only nineteen deemed eligible for inclusion. The reference lists of these studies were also used to identify additional studies. After carefully reading these studies, a total of nine papers were included in the present review. More details can be found in Figure 1.

What is a psychosis?

Psychosis is the core symptom of a group of psychiatric disorders classified under the term schizophrenia spectrum disorders in the DSM-5.[2] Rather than a clearly defined condition, this represents a spectrum of disorders in which psychotic symptoms vary in severity, duration, and number. These symptoms can be viewed on a continuum ranging from 'normal functioning' to severe psychotic states.

The primary difference lies in the underlying cause and progression: while chronic psychosis often involves a persistent vulnerability to relapse, psychoses with a clear, identifiable cause may have a more favorable prognosis when the underlying issue is effectively addressed. However, future vulnerability cannot be ruled out entirely, as individual risk factors and recurrence patterns vary.

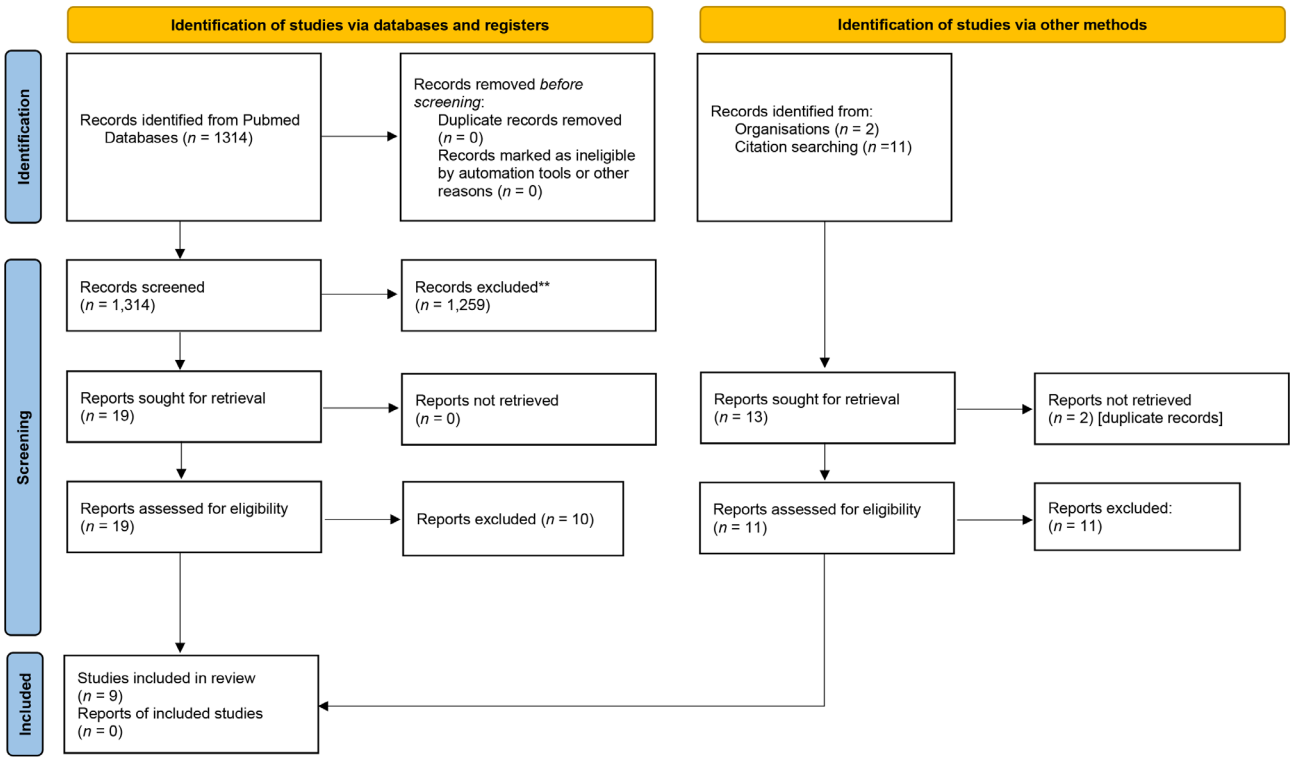
Several studies illustrate that psychoses with clear, identifiable causes, such as substance-induced psychosis, may have different trajectories compared to chronic psychotic disorders like schizophrenia.[4,5] While some individuals may develop persistent symptoms, others may experience remission, especially when the underlying cause is addressed. This supports the notion that psychoses with identifiable causes can have a more favorable prognosis, though individual outcomes can vary.

Psychotic disorders arise from a complex interplay between genetic predisposition and environmental factors, such as childhood traumatic experiences. Overall, early childhood trauma appears to be a critical factor in the vulnerability to psychotic disorders, they can result in a heightened sensitivity of the stress response system, increasing vulnerability to stressors in later life.[6]

The underlying mechanism by which prior stress experiences lead to enduring psychotic vulnerability and heightened stress reactivity is referred to as sensitisation.[7]

Lifetime prevalence of psychotic disorders varies widely across studies. Across studies that use household-based survey samples, clinical diagnostic interviews, and medical records, estimates of the prevalence of schizophrenia and related psychotic disorders in the U.S. range between 0.25% and 0.64%.[8–10] Estimates of the international prevalence of

Figure 1
PRISMA 2020 flow diagram for new systematic reviews which included searches of databases, registers and other sources



schizophrenia among non-institutionalised persons is 0.33% to 0.75%.[11,12]

Fitness for driving and aviation

It is evident that naval aviators who have experienced psychiatric issues require thorough evaluation before being deemed fit to resume flight duties, in order to mitigate the risk of recurrence.[13] In a review of five cases of naval aviators who developed psychiatric symptoms due to severe psychosocial stress, two individuals (without a definitive psychiatric diagnosis) were subsequently returned to unrestricted flight duties. The remaining three aviators discontinued aviation duties, with two diagnosed with brief reactive psychosis and one with bipolar disorder.

The literature on psychosis and driving reveals a nuanced picture. Collectively, the findings indicate that while individual evaluations are necessary, schizophrenia does not inherently make patients unfit to drive or pose a substantial risk to public safety.[14–18]

Research consistently highlights that limitations such as medication dosage, age, and cognitive or psychomotor impairments must be considered when evaluating the driving capabilities of individuals with schizophrenia.[15,16,19] Psychomotor impairments related to driving skills are prevalent in a significant subset of patients, and these deficits cannot always be attributed to psychopharmacological side effects.[18]

Even with stabilisation achieved through antipsychotic medication, a significant subset of individuals with schizophrenia may remain unfit to drive.[20]

The influence of hyperbaric conditions

Nitrogen narcosis, a reversible alteration in consciousness caused by the anesthetic effects of gases at high partial pressures, typically occurs at depths greater than 30 metres (100 ft) or around 4 bar of ambient pressure. In rare cases, symptoms may emerge at shallower depths, such as 10 metres (33 ft). These effects resolve quickly upon ascending to a shallower depth and have no long-term consequences. When breathing air at depths of 90 metres (300 ft) – an ambient pressure of about 10 bar – narcosis in most divers leads to hallucinations, loss of memory, and unconsciousness.[21]

High-pressure nervous syndrome (HPNS) is a still not entirely understood neurological condition that affects divers exposed to extremely high pressures, typically during very deep dives below 150 metres (492 ft) while using mixed gases like helium-oxygen (heliox). HPNS results from the rapid compression of the nervous system under high pressures and is marked by symptoms that can range from mild to severe. It is characterised by neurological symptoms (tremors, dizziness, and problems with coordination and balance), cognitive impairment, anxiety, confusion and hallucinations.

These hyperbaric effects illustrate how high pressure and gas interactions can significantly alter perception, mood, and cognition, sometimes mimicking features of psychosis. Just as nitrogen narcosis and HPNS can induce hallucinations, memory disturbances, and loss of control in divers, these conditions create profound disruptions in reality perception, similar to those seen in psychosis.

Experimental deep dives using various breathing mixtures have documented psychotic-like symptoms such as hallucinations, mood disturbances, agitation, and paranoia.[22] These episodes are likely caused by a combination of factors, including increased partial pressures of inert gases (e.g., nitrogen or helium), hydrostatic pressure, psychological stress, and individual susceptibility. Such findings emphasise the complexity of hyperbaric environments and their potential to induce symptoms resembling psychosis.

While nitrogen narcosis and HPNS can induce transient alterations in perception and cognition in otherwise healthy individuals, it remains uncertain whether these conditions could precipitate or exacerbate psychosis in those with a predisposition. The combination of altered neurochemical states, high-pressure gas effects, and environmental stressors could theoretically increase the risk of psychotic decompensation in susceptible individuals. Additionally, a history of psychosis may heighten sensitivity to these hyperbaric stressors, potentially leading to more severe or prolonged psychiatric symptoms. However, direct evidence on this relationship is limited, and further research is needed to determine whether individuals with a history of psychosis are at increased risk for more severe forms of hyperbaric-related cognitive and perceptual disturbances.

We found only one case report in the period 1968–2024 that discusses two cases where divers presented with psychosis after diving.[23] The two cases were determined to be unrelated to decompression sickness (DCS) or other hyperbaric effects of diving. However, they may have been influenced by psychological stress associated with the diving experience itself. Both patients denied a history of psychiatric or neurologic illness. Based on the case description of the first patient and the psychiatric evaluation, a diagnosis of dissociative disorder due to a traumatic underwater event is more likely. The second patient was admitted to psychiatry due to 'auditory hallucinations and abnormal behavior,' and the discharge diagnosis was psychosis of uncertain cause.

Considerations in assessing fitness-to-dive

When assessing suitability for diving in individuals with psychotic vulnerability, we propose a model that evaluates functioning across the following domains.

1. SYMPTOMATIC STABILITY

Active psychosis, defined as a loss of contact with reality, is a contraindication for diving due to the significant risks it poses. A psychotic disorder is characterised by the presence of at least one psychotic symptom (delusions, hallucinations, disorganised speech, disorganised behavior, or catatonia), often accompanied by negative, cognitive symptoms or affective symptoms.

Individuals with psychosis often struggle to accurately assess their surroundings, respond effectively to emergencies, and make rational decisions – skills essential for safe diving. In the underwater environment, where clear and immediate judgment can mean the difference between life and death, these impairments pose significant risks.

Moreover, the effects of hyperbaric conditions and potential risks of narcosis may exacerbate symptoms, endangering both the diver and their buddy.

Studies estimate that 50–80% of individuals with schizophrenia lack insight into their illness.[24] Developing insight – a fundamental prerequisite for recognising illness – requires awareness of personal changes and acknowledgment of the disorder's presence. Understanding the nature of their condition and its impact on their life is crucial for effective treatment and prognosis. Limited illness insight can lead to poor treatment adherence, increased risk of relapse due to neglecting early warning signs, and impaired recovery by reducing engagement in rehabilitation and support programs.

We define symptomatic stability as the absence of relevant symptoms, intact reality testing, and, at most, mild residual symptoms. Additionally, it includes a history of only brief episodes, the ability to reliably predict relapse, good illness insight, awareness of the condition, and strong adherence to treatment. For individuals with a history of psychosis, achieving and maintaining symptomatic stability is a fundamental requirement for being considered fit to dive.

2. CHRONIC PSYCHOSIS OR PSYCHOSES WITH A SPECIFIC CAUSE

Psychosis often involves recurrent relapses, with up to 80% of first-episode patients relapsing within five years, and each episode heightening the risk of chronicity.[25,26] When assessing fitness for diving, it is essential to differentiate between chronic psychosis, which typically involves prolonged vulnerability, defined as an increased risk for the development of psychosis later in life,[27] and psychoses with an identifiable underlying cause. If the cause of an affective or organic psychosis has been successfully treated and the individual is in complete remission for over one year, diving suitability may be considered. However, chronic psychosis, or psychotic vulnerability, often includes ongoing symptoms and impaired social or occupational functioning, rendering diving unsuitable in these instances. It refers to an individual's predisposition to developing psychotic symptoms due to a combination of genetic, neurobiological, and environmental factors. Individuals with psychotic vulnerability may not necessarily experience psychosis under normal circumstances but could be at increased risk of an episode when exposed to certain triggers, such as psychological distress, sleep deprivation, substance use, or extreme environmental conditions including those encountered during diving. Given that fitness-to-dive assessments aim to predict and mitigate risks, understanding an individual's psychotic vulnerability is essential in evaluating their ability to safely participate in diving activities.

In the chronic stage, patients have experienced multiple relapses or have developed persistent psychosis. This stage is characterised by prolonged functional decline or severe, enduring illness with chronic symptoms and significant functional disabilities.[28]

A chronic psychotic condition is a contraindication for diving. Recovery following a first-episode of psychosis, relapse, or recurrence requires a thorough psychiatric evaluation in conjunction with dive medical expertise to ensure safety and suitability for diving activities.

3. COGNITIVE AND PSYCHOMOTOR FUNCTIONING

Approximately 80% of individuals with primary psychotic disorders, including schizophrenia, schizophreniform disorder, schizoaffective disorder, and affective psychoses, experience clinically significant cognitive impairments.[1] These deficits often interfere with their capacity to carry out daily activities, sustain employment, and maintain social relationships. Key domains affected include attention, memory, and executive functioning, which are critical for adaptive functioning in everyday life. Neurocognitive impairments, particularly deficits in attention, processing speed, verbal memory, and executive functioning, may persist in a subset of patients with bipolar disorder.[29]

Psychomotor slowing affecting up to 50% of individuals with schizophrenia, is characterised by reduced gait speed, decreased activity levels, and slower finger movements.[30] The assessment of cognitive and psychomotor functioning is based on observation, patient history, and, if applicable, supplemented by the adult self-report version of the World Health Organization Disability Assessment Schedule 2.0 (WHODAS 2.0),[31] as well as recent neuropsychological and/or occupational therapy evaluations.

It is important to consider the phenomenon of sensitisation, whereby prior stress experiences may result in enduring psychotic vulnerability and heightened stress reactivity, emphasising the need for careful evaluation of an individual's stress tolerance and coping mechanisms.

Our expert recommendation is that individuals considered fit for diving should have no cognitive or psychomotor impairments, or at most, only mild limitations in these domains. Additionally, given the phenomenon of sensitization where prior stress experiences may lead to enduring psychotic vulnerability and heightened stress reactivity – it is crucial to carefully evaluate an individual's stress tolerance, coping mechanisms, and overall stability to ensure their safety and suitability for diving. As mentioned before in the section regarding daily functioning, adherence to the treatment plan is paramount.

4. COMORBIDITY

There is a high rate of comorbidity between post-traumatic stress disorder (PTSD), substance abuse, depression and psychosis, but also anxiety disorders are also commonly found in individuals with psychosis.[32,33] The presence of comorbid conditions, such as PTSD, anxiety disorders, depression, or substance use disorders, significantly increases the risk of adverse outcomes in individuals with psychotic vulnerability.[32,34] These conditions not only heighten baseline stress and arousal levels but also exacerbate the individual's sensitivity to stressors, including those encountered in the challenging underwater environment. Pre-dive training focusing on stress recognition, breathing techniques, and relaxation exercises can improve resilience under pressure and reduce the risk of panic or cognitive overload.

Comorbid conditions should be fully resolved or effectively managed, with no active symptoms or functional impairments. Psychological evaluations should specifically assess the individual's stress tolerance, arousal regulation, and coping capacity under simulated or anticipated diving conditions.

5. MEDICATION

Medication for psychosis, primarily antipsychotics, are designed to manage symptoms such as hallucinations, delusions, and disorganised thinking. While severe adverse effects are possible, most individuals tolerate these medications well and experience only mild side effects, such as drowsiness, dry mouth, or weight gain.[35] Commonly reported side effects include weight gain, sedation, drowsiness, and dry mouth; however, movement disorders, seizures, orthostatic hypotension, and disrupted blood glucose levels may also occur. Because psychotropic medications may heighten the risk of nitrogen narcosis or oxygen toxicity, limiting diving depth such as to 18 metres (60 ft) – is recommended to help prevent these effects.[36,37] While narcosis symptoms typically become more pronounced at greater depths, Clarke notes that cognitive impairment can occur as shallow as 10–20 m (33–66 ft), with more severe symptoms emerging beyond 30m (99ft).[37] Given that narcosis symptoms may develop insidiously and compromise self-control at greater depths, a depth limit of 18 m (60 ft) serves as a precautionary measure to mitigate potential risks in individuals with psychotic vulnerability.

Diving on a low dose of antipsychotic medication, provided there are no side effects or additional cardiovascular risk factors, is generally considered safe.[38] While most individuals tolerate antipsychotics well, certain medications carry a higher risk of seizures, which can be fatal underwater. Clozapine, in particular, is incompatible with diving due to its significant seizure risk, and older antipsychotics such as chlorpromazine, promazine, thioridazine, and haloperidol may also increase seizure susceptibility.[38]

Patients with affective psychosis may require mood stabilisers, particularly lithium, which is commonly prescribed for bipolar disorder. Diving while taking lithium requires careful consideration due to its potential risks.[38] However, other mood stabilisers are generally well-tolerated and not contraindicated for diving, provided general factors such as potential side effects are carefully evaluated.

Although diving on a low dose of antipsychotic medication, in the absence of significant side effects or additional cardiovascular risk factors, is generally considered safe, we recommend complete remission for over one year, no polypharmacy, and stable medication use for a period of at least one year.

6. DAILY FUNCTIONING

To prevent a psychotic relapse, early recognition and intervention are crucial, these are achievable only with consistent adherence to medication and commitment to therapy, insight and awareness of the condition. Prognosis is closely tied to these factors, with individuals demonstrating better adherence and self-awareness typically achieving greater stability. There are essential factors that impact recovery in individuals with long-term psychosis across three areas: clinical recovery, societal recovery, and personal recovery.[39,40] Clinical recovery is linked to fewer negative symptoms, improved daily functioning, and enhanced societal and personal recovery. Societal recovery is supported by employment, a life partner, and better clinical outcomes, while personal recovery is associated with higher life satisfaction, fewer depressive symptoms, and clinical improvement.

Given the importance of adequate daily functioning, it is essential to consider that there should be no more than mild limitations in daily activities.

7. DEEP DIVING

Although the altered states caused by nitrogen narcosis and HPNS may mimic psychotic symptoms, narcosis is typically restricted to depths exceeding 30 metres (100 ft). For divers who avoid these depths, the likelihood of encountering such effects is minimal. Importantly, there's no evidence to suggest that a history of psychosis increases susceptibility to nitrogen narcosis. Narcosis results from physiological responses to high-pressure gases, independent of one's

psychological history, underscoring that while the effects may appear similar, the underlying causes are distinct.

Limitations and future research directions

While this article provides a comprehensive overview of psychosis and its implications for diving, it is important to acknowledge certain limitations:

- Many of the recommendations and assessments presented here are based on clinical expertise and professional judgment, rather than extensive empirical studies. This reflects the limited availability of robust data on psychosis in the context of diving medicine. Although expert guidelines offer valuable insights, they underscore the need for more evidence-based research to validate and refine these recommendations.
- While hyperbaric environments are known to influence cognition and mood, little research has explored whether repeated or prolonged exposure to high-pressure conditions could exacerbate psychotic vulnerability or trigger psychosis in predisposed individuals. Future longitudinal studies could investigate these potential risks.
- Modern antipsychotics and mood stabilisers are generally well-tolerated, but their interaction with hyperbaric conditions such as heightened risk of narcosis or oxygen toxicity remains under-researched. Investigating the pharmacological profiles of these medications in hyperbaric environments could refine guidelines for divers with psychiatric histories.
- Current assessments for diving fitness often generalise risk based on broad categories of psychotic disorders and medication use. However, individual factors such as genetic predisposition, stress resilience, and cognitive functioning may significantly influence outcomes. Research exploring these individualised risks could improve the precision of fitness evaluations.
- The rarity of documented cases linking psychosis and diving incidents limits the ability to draw definitive conclusions. Retrospective analyses and detailed case reports could shed light on patterns or triggers, helping to enhance safety protocols.

Conclusions

This article examines the relationship between psychosis and diving, providing an in-depth exploration of psychotic disorders, their implications under hyperbaric conditions, and guidelines for assessing diving fitness. This article serves as a guide for medical professionals to assess diving suitability in individuals with psychosis while highlighting the need for further research to refine and validate these recommendations.

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Conflicts of interest and funding: nil

Submitted: 16 December 2024
Accepted after revision: 30 March 2025

Shared decision-making when considering hyperbaric oxygen therapy: a systematic review

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Keywords
Evidence; Policy; Risk management; Theory-based advice; Treatment sequelae

Abstract
(Meijering JR, Risvanoglu N, Nederhoed JH, Hoencamp R, van Hulst RA, Ubbink DT. Shared decision-making when considering hyperbaric oxygen therapy: a systematic review. Diving and Hyperbaric Medicine. 2025 30 June;55(2):180–185. doi: 10.28920/dhm55.2.180-185. PMID: 40544146.)
Introduction: Hyperbaric oxygen therapy (HBOT) is a treatment modality used for various non-acute medical conditions, ranging from ischaemic diabetic ulcers to late post-radiation damage. Despite its wide application, HBOT is often time-consuming, requires multiple sessions, and can be physically and psychologically challenging for patients, contributing to high drop-out rates. In addition, treatment results can vary significantly. These challenges suggest the need for more patient-centred approaches, such as shared decision-making (SDM), to improve patient engagement, satisfaction, and adherence to treatment. SDM, which involves patients in the decision-making process, could potentially improve outcomes and reduce dropout rates. This systematic review presents currently available evidence on the extent of SDM in patients eligible for HBOT.
Methods: A comprehensive literature search was conducted in the Medline, Embase, TRIP and Cochrane Central databases, from inception up to 29 August 2024, to find all studies with original data on SDM when considering HBOT as a treatment option. Study selection was conducted by two reviewers independently. Desired study outcomes were the application and observed levels of SDM.
Results: The search yielded 988 articles of which 24 appeared eligible. After assessing the inclusion criteria and outcomes in the full text articles, zero remained for inclusion: none reported on patient involvement in the decision-making process regarding HBOT. However, six articles did mention that SDM should be an important element when developing clinical practice guidelines for HBOT.
Conclusions: Despite the obvious need for preference-sensitive decision-making in HBOT, there is no scientific evidence available on this topic. Possibly, physicians and patients consider HBOT as a last-resort or even the only treatment option. Consequently, involving the patient's preference regarding HBOT in the decision-making process is rarely documented. Hence, more awareness of the need for SDM is advocated when considering HBOT, which should be corroborated by research in this area.

Introduction

Hyperbaric Oxygen Therapy (HBOT) is a treatment modality used for various non-emergent medical conditions, ranging from ischaemic diabetic ulcers to late post-radiation damage.[1–4] HBOT is provided in a hyperbaric chamber where the air pressure is raised above normal atmospheric pressure (200–250 kPa) and in which patients breathe 100% oxygen administered through a mask.

For non-emergent conditions, the HBOT regimen typically consists of five sessions per week. Each session takes approximately two hours. The total number of HBOT sessions varies per indication, ranging between 10 and 60 sessions.[2]

This therapy implies that patients need to commute almost daily to the treatment centre. Therefore, HBOT is often perceived as time-consuming and exhausting, especially among patients who are elderly, have difficulty walking, or suffer from multiple comorbidities.

Shared decision-making (SDM) has been recognised as an essential method of care in modern healthcare and in some countries even legally required.[5] SDM can be defined as an interactive process in which healthcare professionals

and patients collaborate to make informed decisions about the patient's health that best fit the patient's situation and preferences.[6] SDM has been shown to increase patient satisfaction as well as treatment adherence.[7] SDM is particularly relevant when considering intensive treatment modalities where patient preferences and expectations are even more relevant. The application of SDM in other medical fields, such as surgery, cardiology and paediatrics, has highlighted its importance in improving both patient reported outcomes and treatment experiences.[8–10]

As HBOT is an intensive treatment that requires continuous patient commitment, SDM is particularly useful to ensure that patients understand the demands and benefits of the therapy. Through SDM, patients can assess whether the intensive schedule and potential health benefits align with their personal circumstances and expectations. Therefore, the goal of this systematic review was to give an overview of existing literature to appreciate whether and how SDM is applied in patients eligible for HBOT.

Methods

PROSPERO

Prior to performing this systematic review, the Prospero database was checked for similar studies, either past or current. The systematic review was then entered into the Prospero database on 8 January 2024 (CRD42024493698).

SEARCH STRATEGY

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement and checklist were used as reporting guideline aimed at improving the transparency and completeness of reporting this systematic review.[11] A comprehensive search strategy was developed with the aid of a medical librarian. The Medline, EMBASE, TRIP and Cochrane Central Register of Controlled Trials databases were searched using the primary keywords 'Shared Decision Making', 'patient participation', and 'Hyperbaric Oxygen Therapy' (see *Appendix A for the complete search strategy in each database). The literature search was performed on 14 February 2024, and repeated on 29 August 2024. No language restrictions were applied. Reference lists from relevant articles were also considered to further identify potentially relevant articles.

STUDY SELECTION

The systematic screening was conducted by two reviewers independently (JM and NR), using Rayyan, software for deduplication and review of articles for systematic reviews. Titles and abstracts of all articles were screened based on relevance. Full text articles were then retrieved and further assessed for eligibility based on the in- and exclusion criteria, again by two reviewers independently. If the two reviewers could not reach consensus, a third reviewer was consulted.

INCLUSION AND EXCLUSION CRITERIA

Articles were included when meeting all of the following, broadly formulated, criteria: investigating SDM or patient involvement in the decision-making surrounding HBOT; reporting qualitative or quantitative data on the SDM-process; involving human subjects. Articles with no original data such as opinion pieces were excluded.

QUALITY ASSESSMENT

Quality assessment of the included articles was to be carried out using the Cochrane Risk of Bias tool for randomised controlled trials (RCTs), the QUIPS for cohort and case-control studies, and the ROBINS-1 for cross-sectional studies. Each article was to be systematically evaluated for potential sources of bias including selection, performance, detection, attrition, and reporting bias.

DATA EXTRACTION

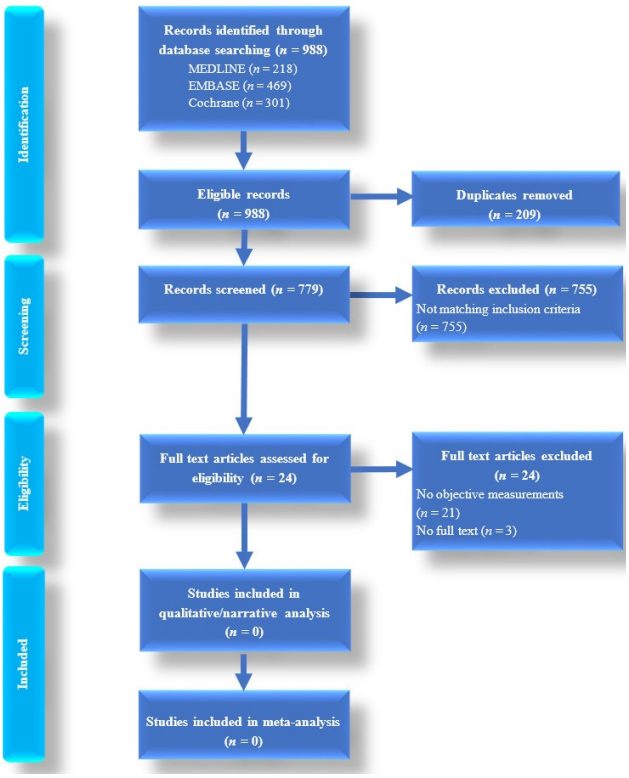
Data extraction was performed using a predefined standardised form to ensure consistency and comprehensiveness across all included studies and to avoid reporting bias. Extracted data included information on SDM observation tools and their corresponding scores, the number of HBOT sessions administered, the indication for HBOT, and patient-reported outcome measures (PROMs). Additionally, data on study characteristics such as sample size, study design, participant demographics, and the context in which SDM was implemented were also collected. This systematic extraction process aimed at capturing all relevant data necessary for a thorough analysis of the extent and impact of SDM in HBOT.

DATA ASSESSMENT

Extracted data were subjected to a detailed assessment in order to determine their suitability for inclusion in a meta-analysis. Studies were initially evaluated for qualitative soundness: considering factors such as study design, sample size, and the robustness of the findings, using the (Dutch version of the) Cochrane Collaboration's validity checklist for RCTs.[12] If the data from multiple studies were found to be methodologically sound and the data entries were homogeneous in terms of measurement tools, outcomes, and population characteristics, they were to be pooled in a meta-analysis. If meta-analysis would not be feasible due to clinical heterogeneity in the study designs, patient populations or outcomes, a narrative synthesis was to be conducted to summarise the findings.

***Footnote:** Appendix A is available on DHM Journal's website: https://www.dhmjournal.com/index.php/journals?id=355

Figure 1
Prisma flowchart of study selection



Results

The literature search, with update, yielded 988 articles: Medline (n = 218); Cochrane (n = 301) and EMBASE (n = 469). After deduplication, 779 were screened for eligibility. The flowchart of study inclusion is displayed in Figure 1.

After applying the inclusion criteria on title and abstract, 755 articles were excluded. Thus, 24 articles remained for full text screening. Full texts could not be retrieved for three articles (two were oral presentations and one could not be found). None of the remaining 21 articles were deemed eligible for inclusion as none of these quantified or compared SDM in any way. Hence, zero studies were found addressing SDM in HBOT according to our (broad) inclusion criteria. Due to the lack of articles suitable for inclusion, the full-texted reviewed articles were revisited with the intention to get more perspective on the current status of SDM in HBOT.

This reassessment yielded six articles that mentioned the importance of SDM in HBOT without further specification or quantification. An overview of these articles can be found in Table 1. De Ru et al.[13] described the importance of SDM in patients with sudden sensorineural hearing loss (SSNHL) for whom HBOT was found to be effective.[14] Also, both Chandrasekhar et al. and Fazel et al. underlined benefits of SDM, such as better patient adherence and outcomes, in SSNHL patients.[15,16] Various key action statements were provided regarding different treatment options for SSNHL, in which the importance of SDM was considered for each statement. These included the importance of providing good information as well as suggesting that SDM is especially useful in areas where evidence is weak or benefits are unclear, as became clear from the Cochrane review regarding SSNHL treatment.[14] The notion that SDM should be used when considering HBOT for Diabetic Foot Ulcer patients was supported by a systematic review by Lalieu et al. It was mentioned that this could reduce drop-out rates in this intensive treatment modality.[17] Huang et al. described a conversation with patients eligible for HBOT to ascertain the importance and impact of provided information in their clinical practice guidelines.[18] Lastly, Jefferson and Linder also pointed out the value of SDM in the process of treating haemorrhagic cystitis after radio- or chemotherapy without describing specific benefits of SDM.[19]

Discussion

This systematic review highlights the notable absence of literature regarding SDM in patients eligible for HBOT. This lack of evidence on SDM in HBOT suggests a possible neglect of prioritising patient involvement in treatment decision-making regarding HBOT when weighing its possible benefits against the possible harms.

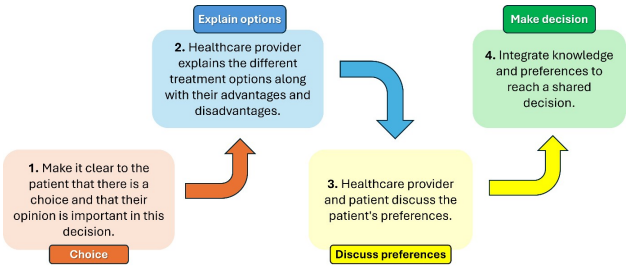
Although no studies were found that quantified the level of SDM when deciding about HBOT, some aspects of SDM may have occurred and been described that were not identified as part of SDM. Essential elements of SDM have been defined previously and are illustrated in Figure 2. When considering HBOT, this SDM-process would include the following steps: (1) Informing patients at the start of the consultation that a decision regarding possible HBOT treatment has to be made in which the patient has a decisive voice; (2) explaining to the patient the relevant and feasible treatment options, including standard care with or without HBOT, along with their pros and cons. For example, HBOT may increase the chance of wound healing, lower the risk of amputation, and reduce the patient's complaints. However, patients also face possible undesired effects, such as the burden of undergoing multiple HBOT sessions to achieve results, possible barotrauma, oxygen toxicity, or myopia; (3) explicitly asking the patients how they appreciate these options, including the possible benefits and harms, and what their personal preference would be; and (4) integrating the patients' preference into the eventual treatment decision.[20]

Some of these elements commonly occur in doctor-patient encounters, such as informing about the HBOT treatment, including the benefits and harms, but without presenting alternatives.[21] Also, informed consent is commonly asked, but may be done without any involvement of the patient in the decision-making process.[22] In addition, surgeons rarely ask patients how they would like to receive information, whether they have understood the information (for example with the teach-back method) and how they would like to be involved in SDM.[23,24] Practicing only a few of these essential

Table 1
Overview of excluded studies referring to shared decision making (SDM); HBOT – hyperbaric oxygen therapy

Title	Ref	Key points related to SDM
Sudden deafness: hyperbaric oxygen therapy should be discussed	13	Suggests that hyperbaric HBOT should be considered in sudden deafness cases, implying the need for SDM between clinicians and patients.
Clinical practice guideline: sudden hearing loss (update) executive summary	15	Discusses guidelines for sudden hearing loss treatment, including patient-centered approaches and informed discussions about treatment options.
Evaluation and treatment of acute and subacute hearing loss: a review of pharmacotherapy	16	Reviews pharmacological treatments and emphasises the importance of discussing risks and benefits with patients.
Hyperbaric oxygen treatment for University of Texas grade 3 diabetic foot ulcers: a retrospective cohort study	17	Examines HBOT for diabetic foot ulcers, noting that treatment selection should involve discussions with patients on expected outcomes.
A clinical practice guideline for the use of hyperbaric oxygen therapy in the treatment of diabetic foot ulcers	18	Provides guidelines for HBOT use and underscores the role of SDM in patient-centered care.
Haemorrhagic cystitis: making rapid and shrewd clinical and surgical decisions for improving patient outcomes	19	Discusses decision-making strategies for hemorrhagic cystitis, highlighting the need for rapid yet informed SDM processes.

Figure 2
Schematic representation of the four essential steps of shared decision-making process between healthcare providers and patients



elements is insufficient to achieve true SDM, in which the patient's preference is effectively evoked and integrated in the eventual treatment decision.

SDM seems the obvious approach, given HBOT's taxing character. Recent trials have revealed that patients eligible for HBOT often decline treatment or trial participation due to its intensity. For example, in the HONEY trial by Mink van der Molen et al.[25] conducted in patients with irradiated breast cancer, 94 patients out of 126 in the HBOT-group did not undergo HBOT. It was reported that 75 out of these 94 patients opted out or declined due to treatment-related reasons. In the HOT-2 trial, in patients with chronic bowel dysfunction after pelvic radiotherapy, significant drop-out rates were observed among patients who started HBOT (16.7%).[26] In the retrospective observational study by Ennis et al. drop-out rates were as high as 54.8%.[27] Similarly, in the DAMO$_2$CLES trial on HBOT for diabetic ischemic foot ulcers, 35% of the patients randomised for HBOT could not complete the full treatment of 40 sessions.[28]

While treatment intensity is a significant barrier to starting and continuing HBOT, Ennis et al. found that patients showed significant improvement of their diabetic foot ulcer wounds when completing their treatment versus not completing (75.2% vs 47.4%).[27] Also, patients in the DAMO$_2$CLES-trial who completed all HBOT sessions showed fewer amputations and had a higher amputation-free survival rate than those who did not.[28] This underscores the potential benefits of treatment as well as the importance of good pre-treatment counselling in order to enable patient participation in the decision-making process.

Additional barriers to applying SDM when discussing HBOT, perceived by both clinicians and patients, may include whether HBOT is covered by their health insurance or must be paid by patients themselves, and the vicinity of a HBOT facility. Other barriers may be local guidelines that may or may not recommend HBOT for the patient's affliction. Finally, clinicians' belief in HBOT as a useful therapeutic option plays a crucial role in whether it will be discussed with patients at all. Another key challenge is the perception that SDM is time-consuming, which may deter clinicians from fully engaging in the process. While SDM does require an initial investment in discussion and patient education, evidence suggests that it does not necessarily prolong consultations when integrated effectively.[29]

Furthermore, because many clinicians have not received formal training in SDM techniques, some feel uncertain about how to effectively incorporate it into their practice.

Although the search strategy was developed in collaboration with a medical librarian and repeated on a later date to capture newer publications, the possibility of missing relevant studies remains. The reliance on electronic databases and reference list screening means that unpublished studies, grey literature, or studies not indexed in the selected databases may not have been identified, despite their potential relevance.

Furthermore, three articles identified in the search could not be retrieved in full text, potentially impacting the review's comprehensiveness. Two were oral presentations, while the third was a published study that could not be located, possibly missing valuable insights into SDM in HBOT.

The use of broad search terms enhanced sensitivity but also increased the inclusion of irrelevant articles, adding to the screening burden and potentially diverting focus from highly relevant studies.

Finally, while this systematic review highlights a gap in the available research on SDM in HBOT, this does not necessarily indicate that SDM is absent in clinical practice.

Conclusions

This systematic review on SDM shows an apparent lack of patient involvement in the decision-making on HBOT. It also underscores the need to perform research in this area to explore the application of SDM in HBOT, as well as the potential benefits and challenges of integrating SDM into the decision-making process for patients undergoing HBOT for elective indications. Recommendations for future studies are to investigate the existing practice in referring patients for HBOT and the level of SDM present in these referrals, the patient perspectives on treatment intensity, the decision-making process, and perceived barriers to treatment with HBOT by both patients and healthcare workers.

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Acknowledgements

We would like to express our gratitude to Faridi Jamadulin, our medical librarian, whose expertise and dedication were instrumental in developing and executing the comprehensive search strategy for this systematic review.

Conflicts of interest and funding: nil

Submitted: 8 January 2025
Accepted after revision: 2 May 2025

Commentary

Advances in the delivery of cardiopulmonary resuscitation in a diving bell

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Keywords
Cardiac arrest; Decompression illness; Diving deaths; Diving incidents; Diving research; Saturation diving

Abstract

(Johnson G, Bryson P, Tabner A. Advances in the delivery of cardiopulmonary resuscitation in a diving bell. Diving and Hyperbaric Medicine. 2025 30 June;55(2):186–190. doi: 10.28920/dhm55.2.186-190. PMID: 40544147.)
This commentary discusses the provision of cardiopulmonary resuscitation to casualties in a diving bell. This single resource consolidates recent advances in the field, published in different medical journals, to support dissemination across the wider diving industry. It summarises the evaluation of techniques for the provision of manual cardiopulmonary resuscitation (CPR) to a seated casualty, including head-to-chest, knee-to-chest, and prone knee-to-chest compression delivery, and concludes that the only safe and potentially effective approach in a diving bell setting without room for a supine casualty is knee-to-chest CPR. The evaluation of a mechanical CPR device is discussed; it is found to be as effective as existing devices and manual CPR in terms of compression efficacy and is well-suited to the setting. The development of a bespoke resuscitation algorithm, together with deviations from accepted advanced life support algorithm principles, is presented. A novel 'upright CPR' technique for the provision of CPR to a seated casualty, developed during the algorithm evaluation process, is described. Finally, areas where evidence is still lacking, and research priorities for the future, are discussed; a key area for future work is the development and testing of a defibrillator suited to a diving bell setting, where space constraints, a heliox atmosphere, and the risk of both fire and rescuer injury are ever-present.

Introduction

The process by which cardiopulmonary resuscitation (CPR) is delivered within a diving bell has, until recently, received little attention from either the diving or medical communities, with no evidence-based algorithm to guide resuscitation efforts in this most challenging of environments.

The diving bell setting provides significant environmental and contextual barriers to the delivery of both chest compressions and ventilations. A typical diving bell has an internal diameter of only 2 metres; accommodating two to three divers plus the equipment required for a commercial dive within this space is a challenge at the best of times. This limitation, coupled with the hyperbaric environment and technical issues associated repeated pressurisation/depressurisation cycles, mean that standard mechanical chest compression devices are unsuitable. The floor of the bell has a hatch which may render laying a casualty on it impossible; standard approaches to CPR delivery require a recumbent casualty. Safe defibrillation in such a wet, confined space is not currently possible, and recovery of the bell to the surface and the living accommodation can take up to 40 minutes, delaying access to expertise, equipment and external intervention.

Recommendations for the delivery of chest compressions and ventilations have previously been based on standard CPR protocols with unevidenced modifications. Previously taught techniques included either head-to-chest or knee-to-chest compressions to be delivered to a casualty who is either seated or suspended in a harness.[1]

Technological advancements[2] and prominent cases of both diver death[3] and diver survival,[4] together with an ageing commercial diver population,[5] have led to increased interest in the topic of diver resuscitation. We delivered a multi-stage project with multiple industry partners, with the overall

aim of developing an evidence-based algorithm for diver recovery and resuscitation in a diving bell setting. The outputs of this work have been published in this and other medical journals. This commentary serves to consolidate the findings and recommendations of this work programme in a single article to support dissemination across the diving industry.

Manual chest compression techniques[6]

The key barrier to the delivery of effective chest compressions in a diving bell is the inability to lay a casualty flat in all but the largest of bells. Almost all resuscitation attempts are futile without the early provision of high-quality chest compressions, so the first stage of the project was therefore an evaluation of the various manual chest compression techniques taught for use in a diving bell to deliver compressions to a seated casualty (or to a casualty lay prone across a rescuer's knees). The study team comprised a multi-disciplinary group of emergency medicine consultants, life support instructors, doctors, nurses and divers. Assessments took place in both a decommissioned diving bell and in a simulation centre; a Laerdal Resusci-Annie qCPR mannikin provided compression efficacy metrics. Our primary outcome was the percentage of compressions delivered to the correct depth (5–6 cm) and we evaluated head-to-chest CPR, seated knee-to-chest CPR, and prone knee-to-chest CPR (Figure 1). Secondary outcomes included compression rate, recoil, hand placement, sustainability, and adverse events such as pain for the CPR provider.

Prone knee-to-chest compressions, with the casualty lay across the rescuer's knee could not be delivered to a sufficient depth by any single provider; this technique was therefore not evaluated further.

Head-to-chest CPR, with the rescuer's head used to deliver compressions to a seated casualty, was shown to deliver some effective compressions; over two-minute compression-only resuscitation periods, ten rescuers delivered a median of 32% of chest compressions to target depth (IQR 61%). However, the technique caused significant side effects; indeed, the only rescuer who did not report negative effects did not deliver a single effective compression, and no rescuer thought the technique would be sustainable for the duration of a diver recovery to the support vessel. This technique cannot therefore be recommended for use or for further evaluation.

Seated knee-to-chest compressions involve a standing rescuer using their knee to deliver compressions to a seated casualty. The efficacy data were nuanced; the study team delivered a median of only 15% of compressions to depth (IQR 42%) and the median of pooled data (study team plus emergency department staff volunteers) showed only 12% of compressions delivered to depth. However, some providers were able to deliver compressions with similar metrics to that achieved using standard CPR techniques and reported excellent perceived sustainability. Following instruction and observation of these providers, other providers achieved an improvement in their results.

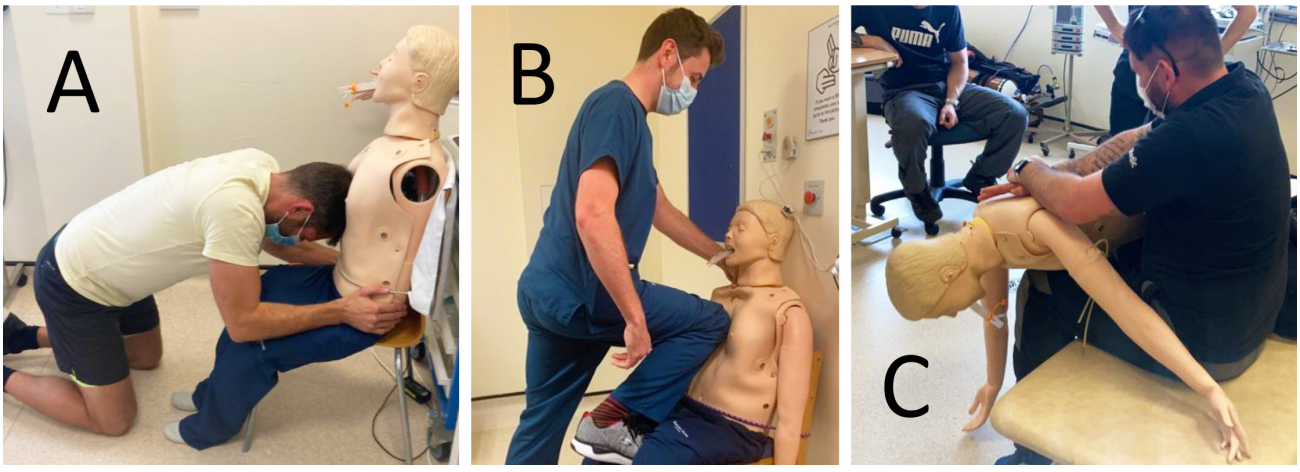
Mechanical CPR[7]

During the development of this study the Norwegian company NUI developed and released their Compact Compression Device (the NCCD). This device is low profile, gas driven, operated manually, and is specifically designed to be used in hyperbaric conditions. We assessed the device alongside the evaluation of manual chest compression techniques.

It showed excellent results, with 100% of compressions to target depth when applied to both supine and seated manikins and operated by those familiar with resuscitation.

However, we found that, particularly in the seated position, the device could become dislodged. This led to it slipping down and delivering compressions below the chest; the

Figure 1
A – head-to-chest cardiopulmonary resuscitation (CPR); B – seated knee-to-chest CPR; C – prone knee-to-chest CPR



manufacturer has since modified the device through the addition of a neck strap to prevent this from happening.

We examined what effect the diver's neoprene suit had on the efficacy of mechanical CPR (mCPR). It reduced efficacy in all positions and increased the slippage rate.

We also found that training novice rescuers on using the NCCD was easy and, following brief instruction, those familiar with CPR were able to use it without difficulty.

We concluded that the NCCD should be used for chest compressions for a diver in cardiac arrest in a diving bell whenever one is available. In its absence, seated knee-to-chest CPR may be a viable option. However, further work would be required before firm recommendations were taken to the industry.

Algorithm development[8]

The next stage of the work was establishing how these methods may be implemented in different diving bell configurations, and how the whole process of diver recovery to the bell, initial assessment, establishing CPR, then subsequently recovering the diver to the support vessel with CPR ongoing, should be protocolised in order to achieve the fastest and most effective order of events. A provisional algorithm, based closely on standard advanced life support (ALS) approaches to resuscitation wherever possible, was drafted based upon experiences during the first phase of the project.

A multi-professional, cross-industry team was then convened in a purpose-built simulation facility, this involved doctors, resuscitation experts, divers, dive supervisors, and industry representatives. An iterative approach was taken to algorithm development throughout the week-long project, with modifications made and tested as required.

The week started with a briefing day, and divers were then trained in the different techniques for manual and mCPR. The algorithm was then discussed in detail, and modifications made based upon the divers' experience of living and working in the hyperbaric setting. Over the following days, different stages of the proposed algorithm were simulated using either the Laerdal Resusci-Anne QCPR or a Ruth Lee manikin, which is weighted and designed for recovery training.

Following these testing and development phases, we performed several full algorithm simulations using live casualties. The setup was such that this involved dive control input and instruction, in addition to the divers in the simulated bell, 'wet-pot' and living accommodation.

The combined output of these work packages is the first algorithm for the recovery and management of a diver in cardiac arrest, developed with collaboration between medical and diving teams. The key recommendations that differ from the standard ALS approach are:

1. Rescue breaths, and early use of an iGel laryngeal mask
We advocate the use of rescue breaths immediately upon identification of a casualty in cardiac arrest. Hypoxia is a more likely cause of cardiac arrest then in other adult medical settings, and establishing effective chest compressions may take some time. Early use of the iGel laryngeal mask supports airway maintenance in an ergonomically challenging setting.

2. Early removal of the hot-water suit
We found that not only did the suit interfere with chest compressions, but it also made application of the NCCD more difficult and time consuming. Removal by cutting of the suit early, whilst the casualty is still in the hoist, was found to add little in the way of time, and brought benefits later with CPR consistency and efficacy.

3. Use of a cervical collar
This was an important addition, and was implemented for head control, rather than because of concern for managing/preventing cervical spine injury. Maintaining the airway even with the iGel laryngeal mask in place, and keeping the head stable, was near-impossible without the additional of the collar. Without it the casualty was also at increased risk of injury. Divers were adept at applying the cervical collar to the casualty whilst they were suspended from the hoist.

4. Use of the NCCD
The NCCD was consistently the most the reliable method for delivering effective chest compressions, and significantly reduced diver fatigue and cognitive load. Early deployment of this device, where available, is therefore strongly advocated. We also found it far simpler to apply with the casualty still in the hoist, rather than in the seat.

An additional advantage of employing the NCCD is that compressions can continue during the extrication of the casualty from the bell to the living accommodation, once the bell is on the surface. Reducing interruptions to effective chest compressions is known to improve outcomes in cardiac arrest.

5. Use seated knee-to-chest compressions if mCPR is not available; consider the Dunoon technique (see below)
No other manual technique for the provision of chest compressions to a seated casualty is supported by efficacy data. Divers found this technique to be deliverable and sustainable with good compression depths achieved.

6. Casualty positioning
The casualty will be managed initially in the bell seat, to enable the second diver to enter the bell (if needed), the bottom hatch to be closed, and the bell to leave bottom. Whilst some evidence exists to support head-up CPR, this is not yet sufficient to advocate its use in preference to supine CPR. As such, if mCPR is in progress (or if the bell floor

permits manual CPR using conventional techniques) then the casualty should be moved to the bell floor during bell ascent.

New CPR technique for the seated casualty[9]

An unexpected outcome of the work was the conception and evaluation of a new technique for delivering chest compressions to a seated casualty. Affectionately referred to within the group as 'the Dunoon technique', this involves delivering chest compressions to the seated casualty with clasped hands in the usual fashion, with the provider either standing or kneeling and bracing themselves against the bell-wall. This was found to be effective and sustainable, and offers a potential alternative to seated knee-to-chest compressions.

ALGORITHM IMPLEMENTATION

This algorithm was developed in collaboration with stakeholder and industry groups and with representation and support from the International Marine Contractors Association (IMCA). It is therefore envisaged that it will be adopted widely across the industry; its implementation will require setting-specific adjustments to account for bell type, size, and design, and it should therefore be woven within companies' Standard Operating Procedures (SOPs).

Whilst a standalone training course for diving bell resuscitations would be ideal, practical and financial constraints render such a venture unlikely to succeed. We therefore suggest that diving bell CPR training forms part of diver and dive medic training courses, with an expectation of simulated practice and regular at-work refresher training to avoid skill fade. The divers involved in the algorithm week felt that this would be a reasonable expectation; they practice and rehearse other critical aspects of their job routinely and felt that critical safety process should be no different.

An exercise in futility?

Cardiac arrest is a condition with a poor prognosis in the best of circumstances, and the diving bell setting presents many additional challenges to its effective management. There are also unavoidable delays associated with casualty extrication from a hyperbaric setting to definitive care or advanced medical intervention. It has therefore been proposed that the provision of CPR, especially in the absence of the ability to deliver defibrillation, may be futile.[10] We refute this suggestion strongly,[11] especially in light of the documented positive outcome from seemingly unrecoverable circumstances in recent years.[4] We suggest that given the oft-reversible aetiologies for cardiac arrest in this setting, and the challenges to early comprehensive medical assessment, it is imperative to provide the best possible care regardless of perceived prognosis. Furthermore, to sit by and do nothing throughout the recovery of bell and casualty to the surface would have unimaginable psychological consequences for fellow divers and friends.

Future research

One of the key research challenges for the field is the development and evaluation of an approach to defibrillation that is safe and suited to the setting. Defibrillation is usually available in the living chambers on board support vessels using one of two methods. One company has a device that is encased in a pressure housing which can operate within the saturation chamber, and requires a stethoscope to hear the commands through the housing, whilst the other option is to hardwire the defibrillator placed outside the living chamber through penetrators to pads on the inside. Both methods require clear protocols and regular drills. There is currently no defibrillation system that can work in a saturation diving bell setting; the pressure and heliox atmosphere are thought likely to impede capacitor function.[12]

Dysrhythmic cardiac arrests have better outcomes than non-shockable arrests in conventional settings, but the current inability to provide timely defibrillation grossly limits the ability to intervene meaningfully for this group of casualties. It is imperative that industry and medical experts collaborate to support the development of a device suited to the diving bell setting.

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Conflicts of interest and funding: nil

Submitted: 20 February 2025
Accepted after revision: 25 April 2025

Case reports

Healing fragile bones: a case report on hyperbaric oxygen therapy in pycnodysostosis

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Keywords
Bone remodeling; Fracture healing; Osteoclast; Pain

Abstract

(Canarslan-Demir K, Yel AK, Aydin G, Zaman T. Healing fragile bones: a case report on hyperbaric oxygen therapy in pycnodysostosis. Diving and Hyperbaric Medicine. 2025 30 June;55(2):191–194. doi: 10.28920/dhm55.2.191-194. PMID: 40544148.) Pycnodysostosis is a rare lysosomal storage disorder characterised by short stature, craniofacial dysmorphisms, dental anomalies, and increased bone fragility due to osteoclast dysfunction caused by cathepsin K gene mutations. This case report describes a 43-year-old female pycnodysostosis patient with recurrent subtrochanteric fractures and delayed bone healing following multiple surgical interventions, including femoral osteotomy and bone grafting. Despite these efforts, bony union was not achieved. The patient underwent 39 sessions of hyperbaric oxygen therapy (HBOT), administered at 243.2 kPa for 120 minutes daily, five days per week. Post-treatment radiographs revealed significant fracture healing, with improvements continuing one month after therapy. Visual analogue pain scores decreased from 4 to 1, and quality of life (SF-36) improved. HBOT enhances tissue oxygenation, stimulating osteogenesis, neovascularization, and immune responses, while optimising osteoclast function, making it a promising treatment for pycnodysostosis-related fracture complications. Although ideal, a controlled trial of HBOT in this rare disorder is probably unachievable. Nevertheless, this report highlights HBOT as a potentially useful adjunctive treatment for enhancing healing of refractory fractures in pycnodysostosis patients.

Introduction

Pycnodysostosis is a rare lysosomal storage disorder characterised by short stature, acroosteolysis of the distal phalanges, craniofacial dysmorphisms (e.g., midface hypoplasia, convex nasal ridge, prominent forehead, and micrognathia), dental anomalies, osteosclerosis, and increased bone fragility.[1,2] The pathogenesis of pycnodysostosis is associated with a mutation in the gene located on chromosome 1q21 that encodes the enzyme cathepsin K (CTSK). CTSK is an essential lysosomal cysteine protease that plays a key role in bone resorption and remodelling processes[3] by degrading bone matrix proteins such as type I and type II collagen, osteopontin, and osteonectin under low pH conditions.[4] A deficiency of this enzyme leads to osteoclast dysfunction, resulting in inadequate degradation of bone matrix proteins and an abnormally fragile bone structure.[5]

Pycnodysostosis is considered a rare disorder, with its prevalence estimated at approximately 1 to 1.7 per million.[1] Patients are typically diagnosed during childhood due to delayed anterior fontanel closure or short stature. In adulthood, however, they often seek medical attention for recurrent fractures, particularly in long bones, resulting from low-energy trauma.[5] As observed in our case, difficulties in fracture healing pose a significant challenge in the management of pycnodysostosis with no consensus regarding optimal treatment. While surgical methods are predominantly favoured, conservative approaches have been utilised in specific cases.[6]

This case report describes a 43-year-old female patient referred to our clinic by orthopaedic and traumatology specialists due to recurrent subtrochanteric fractures and delayed fracture healing following a right femoral osteotomy. In this case, the impact of pycnodysostosis on the bone healing process was thoroughly evaluated, and the potential role of hyperbaric oxygen therapy (HBOT) in this context was explored.

Case report

The patient provided written informed consent for the publication of the case details and accompanying images.

A 43-year-old patient, previously diagnosed with pycnodysostosis, underwent surgery for a right femoral shaft fracture. The initial treatment involved open reduction and internal fixation with a plate and screws. Fifteen years later, due to bone deformation, the operation was revised. However, bony union was not achieved after the revision surgery. One-year post-revision, the patient had another fracture proximal to the initial site due to trauma and underwent surgery. The same surgical procedure was employed, yet bony union was again not obtained. Nine months later, a bone grafting operation was performed to address the issue.

At her initial evaluation at our clinic, conducted two years after the revision surgery, she reported experiencing hip pain during movement, with a visual analogue scale (VAS) score of four out of 10, as well as reduced hip mobility. Computerised tomography (CT) and X-ray imaging revealed one subtrochanteric fracture line with bone graft, one fracture line on the femoral shaft, one plate and 16 screws.

We performed 39 HBOT sessions (243 kPa for 120 minutes), once daily, five days a week. No complications or adverse effects related to HBOT were observed. A radiograph taken after the 39 HBOT sessions revealed callus formation at the distal fracture site. Additionally, a radiograph taken one month after the HBOT sessions showed healing at the proximal fracture line (Figure 1). The patient's hip pain, as measured by the VAS score, decreased from 4 to 1.

The Short Form-36 (SF-36) and Beck Depression Inventory (BDI) was administered at the first and last of the treatments (Table 1). Four months after the treatment, the patient reported no recurrence of fractures or pain.

Discussion

This case report highlights the challenges associated with long bone fracture healing in pycnodysostosis patients and examines the potential benefits of HBOT in overcoming these difficulties. Pycnodysostosis is characterised by defective bone resorption due to osteoclast dysfunction, leading to increased bone fragility.[5] This condition results in frequent recurrent fractures, either spontaneous or caused by low-energy trauma, as well as delayed healing processes in pycnodysostosis affected patients.

In our case, multiple surgical interventions were performed to address osteotomy and non-union of recurrent subtrochanteric fractures in the right femur. However, bony union could not be achieved following any of these procedures. This outcome is consistent with the osteoclast dysfunction that underlies the fundamental pathophysiology of pycnodysostosis. The inability of osteoclasts to degrade bone matrix proteins disrupts the bone remodelling process, significantly increasing the risk of nonunion.[5]

Following 39 sessions of HBOT, radiographic evaluation demonstrated healing at the distal femoral fracture site, with additional healing observed at the proximal femoral fracture site one month later. Furthermore, HBOT was associated with a reduction in the patient's pain VAS score, an improved quality of life as measured by the SF-36 scale, and an enhanced mood state as indicated by the Beck Depression Inventory.

HBOT involves the administering 100% oxygen to patients in a hyperbaric chamber, where the pressure exceeds normal atmospheric levels (101.3 kPa). This process

Figure 1

Radiographic images taken before HBOT (left), at the end of HBOT (middle), and one month after the completion of HBOT (right); green arrows indicate areas of fracture healing; blue arrows indicate callus formation at the fracture site

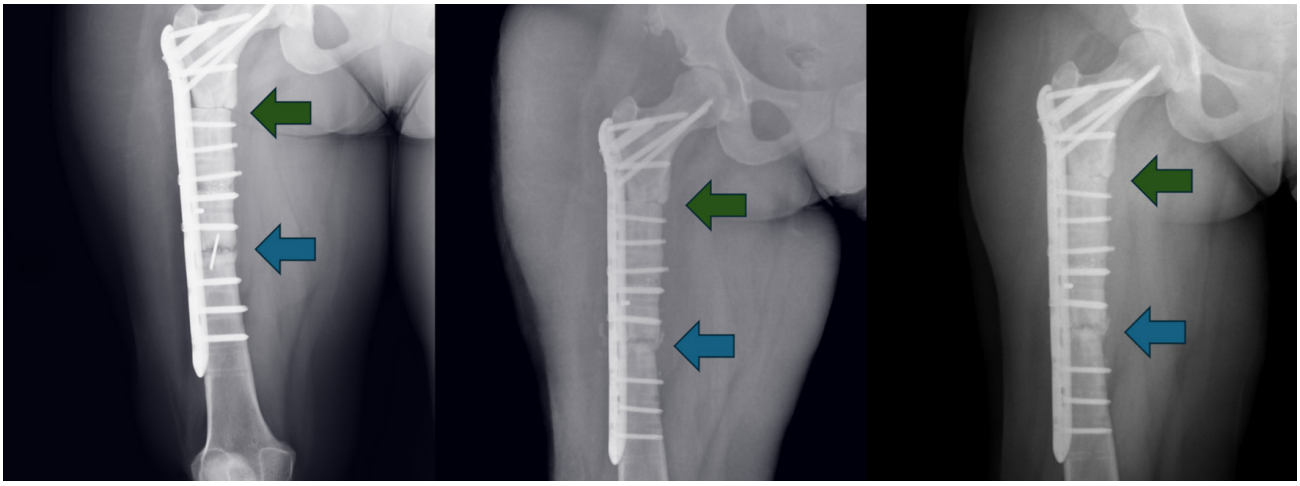

Table 1
Short Form-36 and Beck Depression Inventory scores before and after treatment

Short Form-36 scores		
SF-36 Domains	**Pre**	**Post**
Physical functioning	5	40
Role Limitations – Physical	0	0
Role Limitations – Emotional	0	0
Energy/fatigue	40	55
Emotional well-being	56	52
Social Functioning	50	75
Pain	25	75
General Health	25	55
Health Change	50	75
Beck Depression Inventory scores		
Pre	**Post**	
12	3	

increases oxygen delivery to partially ischaemic or hypoxic tissues, enhancing oxygen-dependent leukocyte activity by stimulating the production of reactive oxygen species such as hydrogen peroxide and superoxide.[7] Additionally, hyperoxia promotes bone osteogenesis and supports the development of neovascularization, aiding in the replacement of damaged tissue with healthy bone. The improved vascular network enables better infiltration of immune cells, antibodies, and antibiotics into affected areas. Furthermore, HBOT aiding the clearance of bone debris by optimising osteoclast function.[7]

HBOT appeared to make a significant contribution to the treatment of this patient. Numerous studies have demonstrated that HBOT supports fracture healing both histologically and radiologically, accelerates callus formation, increases bone mineral density, and enhances osteoblastic activity and neovascularization.[8–10] Furthermore, a recent study suggests that hyperbaric oxygen therapy (HBOT) may support bone healing in refractory orthopaedic conditions such as avascular necrosis by preventing disease progression and reducing the need for surgical intervention.[11] Given their high metabolic activity, osteoblasts and osteoclasts are highly dependent on oxygen. HBOT enhances tissue oxygenation, providing the oxygen required by both osteoblasts and osteoclasts, potentially boosting their activity. This process supports new bone formation and accelerates the fracture healing process. Therefore, HBOT contributes to the early union of fractures and positively influences the balance between bone formation and resorption processes.[12,13] These mechanisms suggest that HBOT may serve as a potential treatment option for addressing complications such as non-union in pycnodysostosis patients.

Importantly, throughout the treatment sessions, no complications or adverse effects related to HBOT were observed. HBOT is a safe treatment when administered under proper protocols and monitoring. While there are potential side effects of HBOT, such as barotrauma or oxygen toxicity, the absence of such complications in this case highlights its tolerability, even in a complex condition like pycnodysostosis.

The 39-session HBOT protocol applied in this case was associated with a significant reduction in the patient's pain scores and a noticeable improvement in quality of life (SF-36). Significant improvements observed in the 'Physical Function' and 'Pain' subscales underscore the potential benefit of HBOT not only in pain alleviation but also in facilitating the patient's engagement in daily activities and enhancing overall quality of life. These findings suggest potential value of HBOT as an adjunctive treatment option in the challenging fracture healing processes associated with conditions such as pycnodysostosis.

Although ideal, a controlled clinical trial of HBOT in this rare indication is probably unachievable. Nevertheless, this report identifies HBOT as a potentially useful adjunctive treatment for fracture healing in pycnodysostosis patients. Additional factors influencing bone healing in pycnodysostosis patients, such as nutritional status, comorbidities, and genetic variations, must also be considered. The optimal HBOT protocol, including parameters such as the number of sessions, pressure, duration, and combination with other therapeutic modalities is unknown, but as indicated above, would be hard to study.

In conclusion, this case report highlights the potential efficacy of HBOT in addressing fracture healing impairments in pycnodysostosis patients and emphasises the need for exploring novel therapeutic strategies for this rare genetic disorder.

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Conflicts of interest and funding: nil

Submitted: 25 December 2024
Accepted after revision: 22 February 2025

Gastric barotrauma following submarine escape training

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Keywords
Decompression illness; Decompression sickness; Gastro-intestinal tract; Medical conditions and problems; Morbidity

Abstract

(Risberg J, Phillips S, Sletteskog N, Grong K. Gastric barotrauma following submarine escape training. Diving and Hyperbaric Medicine. 2025 30 June;55(2):195–198. doi: 10.28920/dhm55.2.195-198. PMID: 40544149.)
Seventeen case reports of gastric barotrauma following diving have been published previously. We report the case of a 32-year-old healthy male suffering gastric barotrauma in 1987. The incident happened during a military submarine exercise. The patient escaped the submarine at 150 metres water depth but was entangled for a short time in the escape tower and, likely distressed and in a state of panic, swallowed significant amounts of air. He experienced abdominal pain during ascent. Given the special circumstances of this event, medical personnel primarily expected symptoms to be caused by decompression sickness and initiated therapeutic recompression on site. No improvement occurred during recompression, and he was admitted to hospital. Abdominal X-ray disclosed free abdominal gas which was exsufflated in the emergency room. Emergency abdominal surgery revealed a 9 cm rupture of the lesser gastric curvature which was sutured. Recovery was uneventful. We discuss the proper approach to divers experiencing abdominal pain following ascent.

Introduction

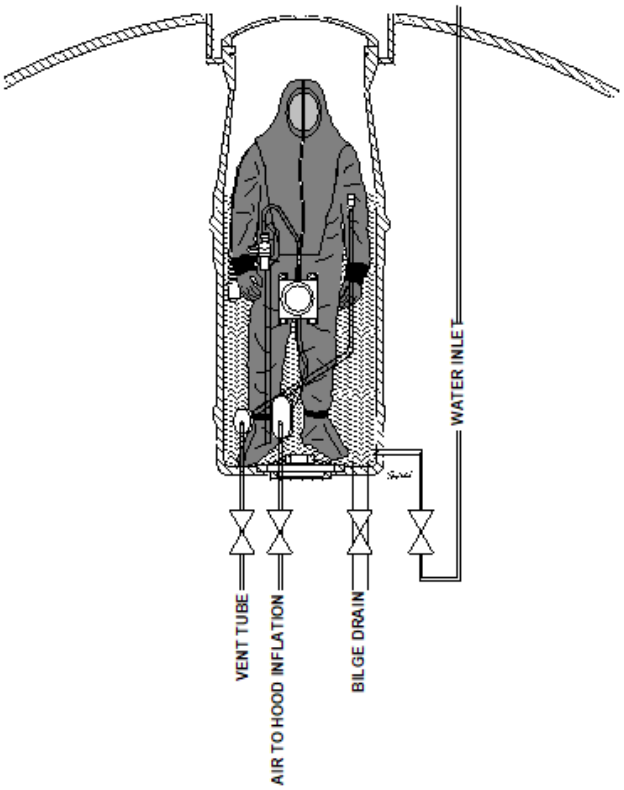
Several rescue systems are located worldwide to allow safe evacuation of crewmembers trapped within a submarine disabled at sea bottom. These systems are conventionally based on a rescue vehicle that can connect to the rescue hatch of the submarine. Submariners may transfer from the submarine interior through the escape trunk and enter the rescue vehicle without exposure to water. The submarine rescue vehicle will transport the crew members to a surface vessel. While this is the preferred and usually safest route of evacuation, the mobilization time for these rescue systems may exceed expected survivability for the crew. For this reason, many nations prepare for an alternative, individual immersed ascent through the water column ('single escape').

In the event of a single escape the submariner will don a submarine escape immersion suit. The suit is equipped with an 'ascent hood', a flexible and transparent hood surrounding the head and fixed to the outside of the suit. The ascent hood is closed except for an opening on the chest allowing expanding air to escape. The suit is equipped with a hose allowing the hood to be filled with compressed air through a hood inflation system installed within the escape trunk. The submariner will enter the escape trunk, and the lower hatch will be closed. Verbal communication is not possible from this time, but the escapee and submarine crew may communicate with pre-defined messages using hammer signals. The escape trunk (Figure 1) will be filled with water venting the air into the submarine, which keeps the escape trunk at surface pressure until most of the air has escaped. The escapee will inflate the hood with air from the hood inflation system allowing normal breathing. In the last part of water filling, the internal vent will be closed and the pressure of the escape trunk will double approximately every four seconds. Once pressure is equalised to the surrounding water pressure, the upper hatch will open and the escapee will ascend through the water column. The expanding gas within the suit and hood will provide buoyancy as well as breathing gas during the ascent.

Many submariners are regularly trained for this procedure. For logistical and safety reasons, most training is done in a 20–30 metre deep submarine escape training tank rather than from a submarine. The most common complications of escape training are ear and sinus barotrauma, but pulmonary barotrauma and arterial gas embolism are recognised as more severe, though less frequent, complications. Here, we report a rather unique case of gastric barotrauma taking place during escape training from a submarine. Gastric barotrauma following conventional diving has been reported previously, such as the recent report by Ben Ayad et al.[1] However, we are not aware of this injury being reported following submarine escape training. In addition, we would like to discuss the

Figure 1

Drawing illustrating the escapee dressed in an escape suit within the escape trunk. Upper and lower hatch is closed. When water has reached the upper level of the vent tube, the valve will be closed, and further water ingress will increase internal pressure. The upper hatch will open once pressure is equalised with ambient water pressure. 'Air to hood inflation' – Hood inflation system. Reproduced with permission from Peter Arfert



optimal way to handle abdominal pain presenting shortly after surfacing a dive.

Case report

The incident occurred 38 years ago, and this report is based on review of his medical records written at the time of event, a personal interview with the patient, recollection from the surgeon treating him (NS) and an internal report, never published in the open domain, by the UK Royal Navy (RN) Institute of Naval Medicine.[2] The patient has reviewed the manuscript and approved it for publication.

In 1987 the RN completed a series of submarine escape exercises in Norwegian waters. The exercises were ethically approved by the UK Ministry of Defence and were completed to verify the performance of the Mk 8 escape suit during deep water escape. The subject was a 32-year-old male working as an instructor in the RN submarine escape training establishment. He had previously been admitted for appendectomy, suffered a middle ear barotrauma with perforated eardrum and one possible, but not medically attended or treated, incident of decompression sickness (DCS). He had not experienced any other abdominal illness. He had successfully completed ascents from 90 and 120 metres on two separate days earlier in the exercise. He had taken two tablets of ibuprofen for an unknown reason the preceding day. The incident occurred during escape from 150 metres.

During water filling of the escape trunk his arm got entangled in the rope to the signaling hammer and as a result of this incident, in the ensuring panic and anxiety, it is likely he unintentionally swallowed significant amounts of air during the process of getting free. During ascent, following the release from this rope, he focused on exhalation to avoid pulmonary barotrauma. He experienced increasing abdominal discomfort during ascent and vomited at surface. He was initially therapeutically recompressed to a pressure equivalent of 50 metres of seawater according to RN treatment table 63. He suffered severe abdominal pain and suffered haematemesis on three occasions during the treatment, but physical examination did not reveal peritonism or hypotension. The absent improvement and the need for opiate analgesia suggested an alternative diagnosis of a perforated viscus. A decision was made to surface him and admit him to Haukeland University Hospital for further treatment.

On admission he still suffered abdominal pain; his abdomen was distended, tender and a plain abdominal X-ray showed a large amount of intra-abdominal gas which was exsufflated bedside with a wide-bore intravenous cannula, partly relieving the symptoms. A laparotomy with upper midline incision revealed a rupture of the gastrocolic ligament. Following incision of the omental bursa, a 9 cm perforation starting approximately 10 cm from pylorus and running proximally on the gastric lesser curvature was found and sutured in two layers. No abdominal contamination was visible. Recovery was uneventful and he was discharged from the hospital after eight days.

Discussion

Molenat and Boussuges published a review on gastric barotraumas in 1995.[3] Panic, swallowing of water and deep dives preceded most of the 12 cases listed in that review. The present case shares many similarities though there is no suggestion of swallowing of water. This is the first published incident of gastric rupture following free ascent training. However, the mechanism is like that shared with divers breathing compressed gas. Gas within the stomach will expand during ascent and will distend it unless released through belching or through the pyloric channel. Cadaver experiments reported by Margreiter et al.[4] concluded that a constricted stomach will rupture if the transmural pressure exceeded 17 kPa. Distension of the stomach reduces the Angle of His which may cause the cardio-esophageal junction to act like a one-way valve, not allowing expanding gastric gas to pass through the oesophagus.[5] A rupture will most commonly present at the lesser curvature, possibly

Table 1
Symptoms and findings previouly suggested by the authors for diagnostic assessment of divers presenting with abdominal pain following diving; DCS – decompression sickness

Symptoms and findings suggesting DCS	Symptoms and findings suggesting other diagnosis
Additional extra-abdominal symptoms or findings characteristic of DCS (e.g. skin rash, joint pain, neurological symptoms or findings)	The onset of initial symptoms presenting before, during or several hours (> 3–6 h) after the dive
Improvement during normobaric oxygen treatment or therapeutic recompression	Low inert gas load (short and/or shallow dive)
Normal findings of abdominal physical examination	Abdominal distension
	Findings of physical examination, laboratory studies or diagnostic imaging characteristic of other diagnosis
	No improvement or worsening during therapeutic recompression

caused by differences in mucosa thickness, muscular thickness, ligament fixation and tensile forces due to the gastric geometry.[3,6]

Patients suffering acute abdominal pain, abdominal distension, guarding, rigidity or local tenderness would normally justify a diagnosis of 'acute abdomen' and further surgical referral. However, in divers such abdominal pain may be a symptom of decompression sickness (DCS). The differential diagnosis may be challenging if acute abdominal pain appears shortly after surfacing since gastric barotrauma is a rare event and only seventeen case reports have been published earlier.[1] We will discuss this in further detail below.

Abdominal distension and tenderness have been reported in some of the previous case reports of gastric barotrauma but was not present initially in this case. Paracentesis and exsufflation of a pneumoperitoneum may relieve symptoms as described in the present case as well as that shared by Ben Ayad et al.[1] However, pneumoperitoneum may develop without confirmed gastric barotrauma and can be successfully treated conservatively as discussed in an extensive review by Kot et al.[7] While gastroscopy can confirm a mucosal injury it can't be used to confidently define the depth of a gastric laceration, i.e. whether it is a perforation. The surgical approach for repair of gastric tears caused by diving barotraumas have usually been by laparotomy, though Ben Ayad[1] reported the first case of laparoscopic access for such purpose.

Abdominal pain may be a symptom of spinal DCS or intestinal venous gas embolism as discussed by Beale et al.[8] Immediate therapeutic recompression would usually be indicated in these cases. The increasing availability of point of care ultrasound may support diagnostics[9] and emergency hospital referrals if gastric barotrauma is suspected. However, divers suffering spinal or abdominal DCS may experience severe sequelae, and treatment delay may worsen the outcome.[8,10,11] To the best of our knowledge only one report has been published relating gastric rupture to a fatal diving accident. The rupture was identified post mortem following unsuccessful cardiopulmonary resuscitation (CPR).[12] Gastric rupture is a rare but well recognised complication of CPR.[13] We are unaware of sequelae following any of the other published cases of gastric barotraumas even though many of them were therapeutically recompressed initially and surgical treatment delayed for this reason. We support the notion of Kot et al.[7] recommending a multidisciplinary approach to abdominal pain appearing shortly after dives. To the best of our knowledge, no scientifically appraised clinical guideline has been published addressing diagnostic criteria discriminating DCS from other abdominal illnesses for divers suffering abdominal pain following diving. Based on our personal experience we suggest (Table 1) some aspects to be considered in the diagnostic process. We would still conclude that the general approach to diving accidents: 'if in doubt-recompress' seems valid.

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Acknowledgement

We appreciate the kind support from Peter Arfert, Swedish Defence Research Agency, allowing use of his illustration.

Conflicts of interest and funding: nil

Submitted: 9 February 2025
Accepted after revision: 21 March 2025

Post-traumatic wound infection after diving caused by *Vibrio alginolyticus*: a case report

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Keywords
Bacteriology; Diving; Marine; Seawater; Sports medicine

Abstract

(Cebrián-López J, Jover-Díaz F, Infante-Urrios A, Piqueras-Vidal PM, Ortiz de la Tabla-Duccasse V. Post-traumatic wound infection after diving caused by *Vibrio alginolyticus*: a case report. Diving and Hyperbaric Medicine. 2025 30 June;55(2):199–202. doi: 10.28920/dhm55.2.199-202. PMID: 40544150.)
Vibrio alginolyticus is a facultatively anaerobic, Gram-negative bacillus that is a common component of marine flora. Infections caused by *Vibrio alginolyticus* are rare and typically occur following exposure to seawater or marine animals. This report details the clinical presentation and follow-up of a 65-year-old immunocompetent male who developed a wound infection due to *Vibrio alginolyticus*. Advanced diagnostic tools, such as MALDI-TOF mass spectrometry, can enhance the identification of these bacteria. Sport clinicians need to recognise *Vibrio* infections in seawater-contaminated wounds, as infections may be serious and the therapeutic approach may differ from conventional treatments.

Introduction

Vibrio alginolyticus is a facultatively anaerobic, Gram-negative bacillus that is commonly found in marine flora. Infections caused by *V. alginolyticus* are rare and typically occur following exposure to seawater or marine animals. This report presents the clinical case and follow-up of a 65-year-old immunocompetent male with a wound infection caused by *V. alginolyticus*. Advanced diagnostic tools, such as MALDI-TOF mass spectrometry, can improve the identification of these bacteria. Doctors attending divers need to recognise *Vibrio* infections in seawater-contaminated wounds, as the therapeutic approach may differ from conventional treatments.[1]

Case report

The authors have obtained written informed consent from the patient to publish his case and related images.

A 62-year-old healthy male was admitted to the emergency room with a 7 cm incised wound on the lateral edge of his left foot, caused by direct trauma from an scuba cylinder while diving. The wound was cleaned and sutured, and the patient was prescribed amoxicillin-clavulanic acid (875/125 mg orally, three times daily for 10 days). Five days later, the patient was hospitalised due to an infected wound dehiscence with purulent discharge (Figure 1).

Surgical cleaning and wound debridement were performed in the operating room, followed by intravenous piperacillin/tazobactam. Multiple samples were collected for culture on blood agar, chocolate agar, McConkey agar, and Columbia nalidixic acid agar incubated in a 5% CO_2 atmosphere, as well as Schaedler agar and selective anaerobic Schaedler Kanamycin-Vancomycin agar in an anaerobic environment. Few leukocytes were observed in the Gram stain, and no microorganisms were initially detected. However, after 18 hours of incubation, mucous and greyish colonies grew on the blood agar and chocolate agar plates (Figure 2), showing pleomorphic gram-negative bacilli on the Gram stain. These were identified as *V. alginolyticus* using matrix-assisted laser desorption ionization-time of flight (MALDI-TOF®, Bruker Daltonics) with a score of 2.32.

The antimicrobial susceptibility was assessed using microdilution (MicroScan®) and disc diffusion methods, interpreted according to Clinical and Laboratory Standards Institute criteria. The strain was sensitive to tetracyclines, trimethoprim-sulfamethoxazole, ciprofloxacin, meropenem, piperacillin-tazobactam, and cefotaxime. Antibiotic treatment was adjusted to doxycycline 100 mg every

Figure 1
Post-traumatic wound infection with pus leakage

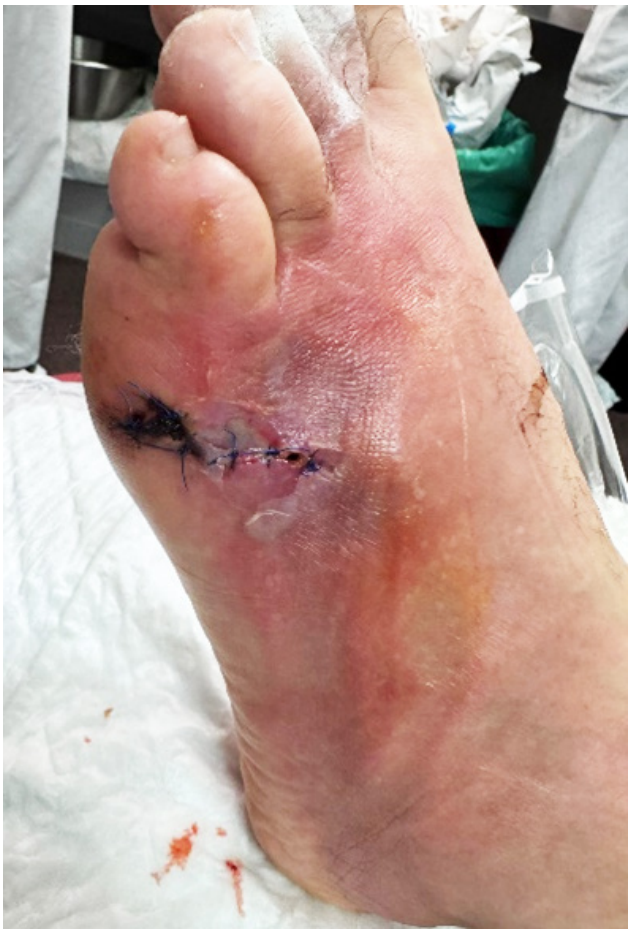
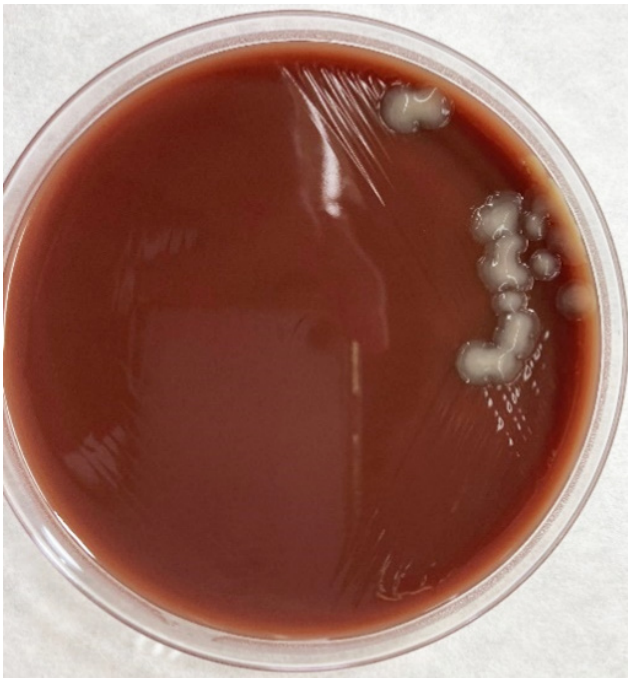


Figure 2
Mucous and greyish colonies grew on the blood agar and chocolate agar plates identified as Vibrio alginolyticus



12 hours for 10 days. One month following the onset of symptoms, the patient had a well-healed scar with no evidence of infection and was able to start walking with progressive partial weight-bearing.

Discussion

V. alginolyticus is a halophilic, Gram-negative, motile, curved bacterium that belongs to the *Vibrionaceae* family. It is widespread in seawater globally.[2] Recently, global warming has led to increased marine temperatures, facilitating the spread of these pathogens to northern regions, particularly when water temperatures exceed 17°C.[3] Furthermore, *V. alginolyticus* is the most halophilic of all Vibrio species, capable of thriving in high saline concentrations. Its reservoirs include seawater and marine-origin food contaminated with seawater.

V. alginolyticus is one of the 12 Vibrio species known to cause human infections. It was first identified as a human pathogen in 1973 and has since been associated with wound and ear infections.[4] The incidence rate in the USA was only 0.048 per 100,000 people in 2011, but it increased significantly during the summer due to warmer seawater temperatures.[5] In Florida, between 1998 and 2007, *V. alginolyticus* accounted for 131 cases, nearly 20% of all vibriosis infections.[6] A recent multicenter French study reported that *V. alginolyticus* was responsible for 34% (23/67) of Vibrio-infected cases.[7]

Divers face an elevated risk of *V. alginolyticus* or *V. vulnificus* infections due to increased exposure to seawater, particularly in warm coastal areas. The risk is further compounded by the inadvertent ingestion of marine water during diving activities. Studies have quantified this exposure, revealing that occupational divers swallow an average of 9.8 mL of marine water per dive, while sport divers ingest slightly less at 9.0 mL per dive.[8] This consistent exposure to potentially contaminated water, combined with the possibility of skin abrasions or wounds during diving, creates a conducive environment for *V. vulnificus* infections, underscoring the importance of awareness and preventive measures among the diving community.

Some articles have highlighted the risk of infections caused by marine *Vibrio* species in individuals exposed to seawater, particularly in the context of diving or injuries. Tsakris et al. described a Greek diver who developed complicated suppurative otitis media caused by a marine halophilic *Vibrio* species.[9] The infection occurred after diving in seawater, highlighting the potential risk of marine bacteria in ear infections among divers. Lopes et al. presented a case of *V. alginolyticus* bacteraemia and probable sphenoiditis in a patient following a sea dive.[10] Finally, Opal and

Saxon reported an unusual intracranial infection caused by *Vibrio alginolyticus* following a head injury in salt water.[11] These cases underscore the potential for serious infections by marine *Vibrio* species among individuals exposed to seawater after traumatic injuries in aquatic environments.

Despite its relatively low virulence and inability to invade intact skin, *V. alginolyticus* possesses several virulent factors, including haemolysis, haemagglutination, and protease production.[12] These factors enable it to cause acute soft tissue infections, such as cellulitis, ulcers, abscesses, and necrotising fasciitis, through breaks in skin integrity like cuts or abrasions.

Vibrio infections typically exhibit a rapid progression, with symptoms often developing within 24 hours of exposure. These patients often experience systemic symptoms alongside the localised manifestations. Fever and chills are common, indicating the body's response to the infection. Skin infections typically exhibit severe cellulitis, intense swelling, and pain. As the infection advances, fluid-filled blisters or bullae may form, potentially becoming haemorrhagic. In severe cases, the condition can quickly progress to necrotic ulceration, gangrene, or even necrotising fasciitis, underscoring the aggressive nature of this pathogen.

The infection commonly affects the lower extremities, especially in cases of primary septicaemia. It may be localised to the site of a wound exposed to seawater or brackish water. Wound care and prompt medical attention are crucial for injuries in marine environments. The rapid progression and potential for severe complications emphasise the need for early recognition and aggressive treatment of *Vibrio* infections.

Most Vibrionaceae family members are susceptible to a wide range of antimicrobial agents. However, *V. parahaemolyticus* and *V. alginolyticus* may exhibit β-lactamase activity.[13] Common treatments for wound infections caused by *Vibrio* species include doxycycline combined with ceftazidime or a fluoroquinolone for 10–14 days. For expedition divers, several oral antibiotics are recommended to treat diving-related infections. Doxycycline is often considered the first-choice antimalarial agent for divers and can also prevent other infections such as leptospirosis and rickettsial infections. For treating impetigo and other superficial skin infections caused by *Staphylococcus aureus*, cephalexin or dicloxacillin are effective choices. Divers should always consult with a diving medical officer before using any medication and avoid diving while actively treating infections, waiting until symptoms have fully resolved before returning to diving activities.

The recently introduced MALDI-TOF diagnostic technique, which uses proteomic technology, represents a powerful tool for the rapid and accurate identification of *Vibrio* species and related bacteria.[14]

Conclusions

Vibrio species should be regarded as potential causative organisms in patients with non-healing wound infections associated with swimming or trauma in coastal areas. With marine temperatures increasing due to global warming, this consideration should be applied year-round, not just during the warmer seasons. Doctors attending divers need to be aware of and consider marine *Vibrio* species as possible causes of non-healing wound infections in this patient group.

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Conflicts of interest and funding: nil

Submitted: 13 January 2025
Accepted after revision: 25 April 2025

World as it is

Extremely deep bounce dives: planning and physiological challenges based on the experiences of a sample of French-speaking technical divers

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Keywords
Gas density; Helium; HPNS; Hydrogen; Mixed-gas; Rebreather; Solo diving

Abstract
(Gouin E, Dugrenot E, Gardette B. Extremely deep bounce dives: planning and physiological challenges based on the experiences of a sample of French-speaking technical divers. Diving and Hyperbaric Medicine. 2025 30 June;55(2):203–210. doi: 10.28920/dhm55.2.203-210. PMID: 40544151.)
Introduction: Extreme deep technical diving presents significant physiological challenges. While procedures often blend elements from both recreational and commercial diving, many remain empirical and unvalidated for this purpose. The rise of closed-circuit rebreathers has reduced gas cost and logistical barriers, enabling more divers to reach unprecedented depths. This study, based on the experience of deep divers, explores the limits of extreme-depth diving and the strategies developed to overcome them.
Methods: Eight rebreather divers (one female, seven males) with experience beyond 200 metres depth were interviewed regarding their preparation, planning, and execution of such dives. The dive profiles of their deepest dives were analysed.
Results: All were highly experienced technical divers. The median maximal depth was 227 [209–302] metres, with a median total dive time of 290 [271–395] minutes. The gas density of the trimix mixture, oxygen exposure, and ascent rate consistently exceeded current recommendations. High pressure nervous syndrome did not appear to be a major limiting factor, whereas decompression posed greater challenges. Three divers experienced decompression sickness following their deepest dives, highlighting the uncertainty around decompression procedures.
Conclusions: These dives require rigorous preparation, robust support systems, equipment modifications, and perfect skills to reduce risks, which remain excessively high. Data are lacking to validate current practices. Decompression procedures must be adapted for these demanding mixed-gas dives, which are inevitably prolonged. A dry underwater habitat could improve decompression tolerance. The role of hydrogen as a breathing gas remains uncertain and still needs to be clarified, but some consider it a promising avenue for further exploration.

Introduction

Scuba diving is widely regarded as a recreational activity, typically involving shallow compressed-air open-circuit dives within no-decompression limits. However, advancements in specialised equipment and helium-based mixed gases have significantly expanded the possibilities for deeper and longer dives. Adding helium reduces nitrogen narcosis and gas density, allowing divers to explore depths once considered unreachable.[1] Closed-circuit rebreathers (CCR) are further revolutionising deep underwater exploration, enhancing efficiency and safety.[1,2] As a result, participation in non-commercial extreme-depth dives has surged, accompanied by record-breaking achievements. While depths of 100–150 m are now relatively common, some divers have exceeded 300 m.

Extreme deep technical diving poses significant physiological challenges and heightened hazards associated with exceeding recreational limits. These risks encompass technical failures, decompression sickness, oxygen toxicity, carbon dioxide (CO_2) retention, high-pressure nervous syndrome (HPNS),

hypothermia,[1,3–6] and an increased likelihood of fatalities.[7] Equipment and processes must be adapted to the unique demands of these deep bounce dives, inspired by those developed for deep occupational diving, although the contexts of practices differ significantly.[8,9]

An increasing number of technical divers are pushing beyond conventional diving limits, occasionally sharing their experiences through individual online articles or in the specialised press. This article aims to examine the preparation and practices involved in these extremely deep dives, which frequently exceed current guidelines for technical bounce diving, a domain that remains largely uncharted. By these narratives, we will discuss these limits, and the solutions implemented to attempt to overcome them.

Methods

This study was approved by the data protection officer of the University of Western Brittany in accordance with the European Union's General Data Protection Regulation (Réf-ORPHY24229). All divers provided consent for data analysis.

The technical diving community is relatively small, with a limited number of divers having reached extreme depths. Known experienced 'very deep' technical divers from the French-speaking community were invited to participate in the study. To ensure relevance and minimise memory bias, the study focused on divers whose personal deepest dives exceeded 200 m and were conducted within the past two years. This depth limit is purely arbitrary but introduces additional physiological and logistical constraints, while experience in 'middle-range' deep diving (i.e., 100–150 m) continues to grow. Semi-structured interviews were conducted by phone between November and December 2024. The average call duration was 69 minutes [IQR 40–107].

The interview was divided into three sections. The first covered demographic data, diving experience, and significant diving-related incidents history. Participants provided details on their dive certifications, total number of dives, and deep dive experience before their first 200 m dive. The second section explored physical, nutritional, mental, and technical preparation for deep diving projects. Divers shared information on their training routines, dietary adjustments, and hydration strategies before dives. Additionally, they were asked about their mental preparation, the factors motivating them to undertake these dives, and any guidance they received from deep diving experts, including divers, physicians, or physiologists. The final section focused on the planning and execution of their deepest dive. Data on the diving environment (location, water temperature) and equipment (breathing apparatus, redundancy, mixed gas, decompression algorithm, conservatism, etc.) were collected. The dive profile was analysed, including the maximum depth reached, descent duration, ascent speed to the first stop, and partial pressures of oxygen (PO_2) used. Any incidents or accidents during these dives were also investigated, along with their outcomes.

STATISTICAL ANALYSIS

Statistical analysis was performed with GraphPad Prism v10.4.1 (GraphPad Software Inc., San Diego, CA, USA). Most responses were analysed descriptively, and continuous variables were presented as median [interquartile range].

Results

A total of eight divers (one female / seven males), aged 44 [34–55] years, were interviewed. Their median body mass index was 24.6 [22.7–26.5] $kg.m^{-2}$. Six divers reported having experienced decompression sickness symptoms (DCS) on previous dives. Only one diver received hyperbaric oxygen (HBO) treatment, while three others performed in-water recompression (IWR), primarily when symptoms appeared before surfacing. Additionally, three divers reported having previously experienced symptoms consistent with HPNS.

At the time of attempting their first 200 m dives, their median age was 37 [33–43] years old. They had accumulated 22 [11–26] years of diving experience and 11 [6–16] years of trimix certification. They had logged 2,000 [600–3,000] dives, including 163 [70–200] to depths of up to 100 m. At the time of the interview, they had completed 8 [2–48] dives beyond 200 m, with individual experience ranging from one to 150 such dives. All cave divers expressed a strong drive for exploration and pushing boundaries. Five divers aimed to break records, while two were motivated by a marine-scientific interest in documenting extreme-deep environments.

PREPARATION FOR DEEP DIVE PROJECT

In preparation for these dives, seven divers intensified their physical training through endurance and aerobic exercises for 6 [3–6] hours per week. Two of them incorporated strength training. Regarding diet, only two divers made adjustments, focusing on high-protein foods or slow-release carbohydrates during the preparation phase. Hydration was a key focus for four divers, who reported consuming at least 2,000 ml of water per day in the week leading up to the dive. Mental preparation varied among participants. The three divers with fewer than five extreme deep dive experiences practiced pre-dive verification rituals (e.g., visualisation exercises, mental rehearsal of problem-solving strategies, etc.) while more experienced divers relied on intuition and self-awareness to mitigate unnecessary risks. However, all divers consistently performed a pre-dive checklist. Technical preparation mainly involved frequent deep dives in the weeks leading up to the record dive for at least five of them. Two divers reported testing all their backup equipment at

Table 1

Extreme deep dives parameters; all PO_2 diluent, equivalent narcotic depth (END) and gas density calculations were made based on the mixed gas in the diluent cylinder at maximal depth.[1] CCR – closed circuit rebreather; Environ – diving environment; GF – gradient factors; gradient factors are expressed by a combination of low / high; OW – open water; SP – set point for PO_2 selected by the diver; Rebreathers – JJ-CCR (JJ ApS, Presto, Denmark), Megalodon CCR (Innerspace System Corp, South Hallsville, TX, USA), X-CCR (iQSub Technologies s.r.o, Orlova, Czech Republic), Liberty sidemount CCR (Divesoft s.r.o, Hálkova, Czech Republic), Joky mCCR (Homemade rebreather, designed by Frédéric Badiér, France); *indicates redundancy by a second rebreather (model may be different from the primary apparatus)

Environ	Personal depth record (m)	Primary rebreather model	GF	Mixed gas (O_2/He)	PO_2 SP (bar)	END (m)	PO_2 diluent (bar)	Gas density ($g.L^{-1}$)
					At maximal depth			
OW	202	JJ-CCR	20/60	5/80	1.3	30	1.1	8.54
OW	204	JJ-CCR	30/60	5/79	1.3	33	1.1	8.85
OW	223	Megalodon*	50/80	4/82	1.4	31	0.9	8.85
OW	224	Megalodon*	85/85	4/85	1.3	23	0.9	8.14
Cave	230	Megalodon	70/85	5/80	1.4	36	1.2	9.67
Cave	285	X-CCR	45/80	2/93	1.6	9	0.6	7.63
Cave	308	Liberty SM*	80/80	4/87	1.2	26	1.3	10.38
Cave	312	Joky*	40/80	4/86	1.6	31	1.3	10.85
Median [IQR]	227 [209–302]				1.4 [1.3–1.6]	31 [24–33]	1.1 [0.9–1.3]	8.85 [8.24–10.2]

great depths during their training dives. Beyond personal experience and discussions with diving community, five divers sought advice from physiologists and decompression specialists to refine their dive plans.

PLANNING AND EXECUTION

Although some divers initially used open circuit systems for their first deep dives, all now consider CCR essential for record-setting dives (Table 1). Four divers use a redundant CCR setup, and two others are considering adopting this configuration for next projects. All divers used drysuit, with five incorporating active heating system for thermal protection. Diver propulsion vehicles (DPVs) were universally used, with two cave divers employing a redundant DPV for added safety (Figure 1).

Decompression was managed using the Bühlmann model, and all dives were conducted with Trimix mixtures (Table 1). The water temperature was 18.5 [18–20.5]°C. The maximal depth was 227 [209–302] m, with a total dive time of 290 [271–395] minutes. The descent took 14 [9–17] min at a rate of 18 [16–24] $m{\cdot}min^{-1}$. The ascent speed prior the first decompression stop was 16 [9–28] $m{\cdot}min^{-1}$. The PO_2 set points were respectively 1.4 [1.3–1.6], 1.6 [1.3–1.8] and 1.6 [1.5–1.6] bar during the bottom time, during ascent and during the last decompression stops. All divers reported significantly exceeding the 100% oxygen central nervous system (CNS) clock limits. One diver reported taking 'air breaks' during decompression to reduce the risk of oxygen toxicity. An example of this diving profile is shown in Figure 2.

The four cave divers reached the bottom solo. One completed the entire dive alone, while the others had safety divers meeting them around 100–120 m during ascent. Open water divers were supported by surface safety team and a dive buddy. Five divers reported a specific emergency plan, and three notified hyperbaric medical facilities before their dives. One cave diver deployed a diving bell at 12 m to enhance decompression comfort and safety.

The two dives exceeding 300 m were complicated by severe DCS symptoms during ascent, including inner-ear and pulmonary 'chokes' manifestations. In-water DCS events were self-managed through oxygen adjustments and brief recompression by descending slightly before resuming ascent. All symptoms resolved before surface. Another diver suffered musculoskeletal DCS after surfacing, and he received medical treatment with no HBO therapy due to the remote location and the rapid favorable outcome. All reported complete recovery.

Figure 1
Photo of an extreme deep diver and his equipment (Reproduced with permission from A. Legrix and F. Swierczynski ©Photosub)

Figure 2
An example of a very deep diving profile (courtesy of X. Meniscus); the dark grey area indicates the calculated decompression profile

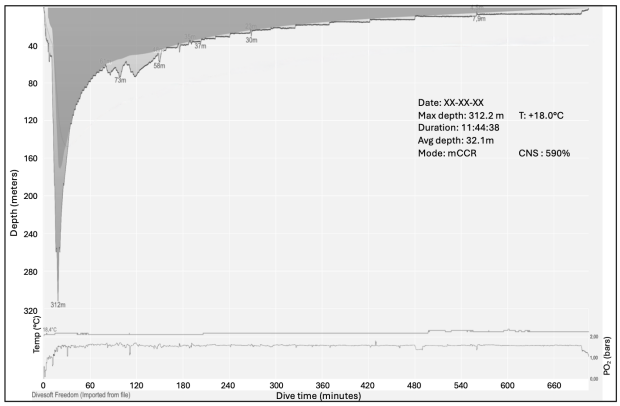

Table 2
Summary of currently known diving records using data retrieved from openly accessible online sources; Environ – diving environment; *Deepest scuba dive validated by the Guinness World Records for male (♂) and female (♀) divers (https://www.guinnessworldrecords.com)

Environ	Open water				Cave			
Diver	**Depth (m)**	**Holder**	**Location**	**Year**	**Depth (m)**	**Holder**	**Location**	**Year**
♀ OC	211	C. Serpieri	?	?	246*	K. van den Oever	Boesmansgat (South Africa)	2022
♂ OC	332*	A. Gabr	Dahab (Egypt)	2014	283	N. Gomes	Boesmansgat (South Africa)	1996
♀ CCR	222	G. Giesen	Cassis (France)	2024	?	?	?	?
♂ CCR	316	J. Macedonski	Lake Garda (Italy)	2018	312	X. Meniscus	Font Estramar (France)	2024

Discussion

The current deepest bounce dive is held by Ahmed Gabr who reached 332 m in seawater for a 14-hour dive time in 2014 (Table 2). It seems likely that other divers will attempt to approach this milestone, and those attempts will carry great risk. The use of CCR technology in deep diving simplifies gas cylinder logistics and lowers costs compared to similar dives on open circuit. This makes such attempts more accessible to divers. The current 'safe' operational limit would be around 150–200 m.[2] The crucial advantage of a CCR is recycling the exhaled gas through a CO_2 absorbent, significantly increasing gas autonomy independent of depth, and thereby extending the limits of exploration.[1] To accomplish these dives, divers must deal with many challenges. The interviewed divers were highly trained and experienced. However, making extreme depths more accessible might expose less experienced and less 'physiologically prepared' divers to perilous situations. The pursuit of records can sometimes lead to catastrophic outcomes.[10]

RIGOROUS PREPARATION

Physical fitness is essential to ensure adequate functional capacity for the normal and emergent demands of diving.[11] Some evidence suggests that higher aerobic fitness may reduce decompression stress.[12] While divers preparing for these highly demanding explorations seem aware of this, 20% of technical divers report low physical activity.[6] Hydration receives significant attention by divers. Although hydration status is widely perceived as a DCS risk factor, evidence remains inconclusive in humans.[12] The optimal fluid intake before and during a dive is unknown, but one study found that consuming 1,300 ml of fluid before diving reduced post-dive circulatory bubbles and helped to limit dehydration.[13] Dive duration may exacerbate this effect, potentially requiring greater fluid intake throughout the dive. Many technical divers mitigate this by hydrating in-water using flexible bottles. Conversely, some authors have suggested that hyperhydration may increase the risk of immersion pulmonary oedema (IPO). However, this remains a subject of debate in scuba diving, where physical exertion, water temperature, and breathing resistance from

equipment are considered the primary extrinsic risk factors.[14] Energy expenditure increases during the dive, rising disproportionately beyond 200 m.[15] Despite this, many divers reported consuming only a light meal beforehand. Insufficient intake during prolonged dives may impair thermal regulation and cognitive function. Consuming water, condensed milk or stews during decompression stops is unlikely to fully compensate for this negative balance. Pre-dive nutrition may also influence decompression stress. Some data suggest that a ketogenic or antioxidant diet could help counteract diving-induced oxidative stress and inflammation, both suspected contributors to DCS, but a related preventative role remains untested at this time.[12,15]

These dives require self-control, effective stress management, and the ability to handle unpredictable events while maintaining situational awareness.[10] Divers gathered information from various sources to refine planning, gain experience, and minimise risks, though many unknowns remain. However, it is impossible to determine to what extent these factors influence planning. A specific emergency plan is crucial, as rescue operations at extreme depths are logistically complex and hazardous. Risk prevention and optimised emergency response require rigorous training.[16] When conducted privately, these dives present certain ethical and economic considerations for initiators. However, operating outside a professional framework enables divers to push outside the regulations and conventional limits.[5]

HELIUM MIXED-GASES AND DECOMPRESSION CONSIDERATIONS

From a physiological perspective, gas density and HPNS are factors limiting access to extreme depths.[5] In bounce dives, however, the very long in-water decompressions appear to be the primary challenge. Nitrogen narcosis is easily mitigated by replacing nitrogen with helium in mixed gases.[1] Helium, being significantly lighter than nitrogen, reduces breathing gas density. However, gas density increases proportionally with depth, rapidly exceeding the critical 6.2 $g \cdot L^{-1}$ threshold at extreme depths.[17] This raises airway resistance, breathing effort, and limits ventilation, leading to CO_2 retention and cardiopulmonary constraints.[5,18,19] These risks are often underestimated by technical divers and become unmanageable at these ranges of depth.[6] For instance, at 250 m with a 4% oxygen and 96% helium mix, gas density reaches 6.3 $g \cdot L^{-1}$. Eliminating nitrogen entirely introduces other challenges, as discussed below. Many technical divers exceed this threshold without exhibiting evident adverse effects. This limit, based on limited data, remains uncertain and further research is needed.[6,17] Preventive strategies for divers include reducing gas density and utilising DPVs to minimise exertion and CO_2 production. However, hypercapnia can impair work capacity, cognition, and decompression safety. It also lowers seizure thresholds, and has been linked to fatalities.[3] Recognition is challenging, and subjective symptoms are often ignored. In this context, reliable respiratory circuit monitoring is essential to enhance safety. In addition, the rebreather itself may contribute to increased respiratory workload. Back-mounted counterlungs exacerbate hydrostatic imbalance creating a negative static lung load, particularly in the prone position. This may amplify the negative transpulmonary pressure gradient, potentially promoting IPO. It has been suggested that chest-mounted or side-mounted counterlungs, positioned in front of the shoulders, may have a beneficial effect.[14,19]

HPNS is well-documented in saturation diving.[20] Symptoms include cognitive impairment, dizziness, visual disturbances, nausea, drowsiness, muscle tremors, and coordination issues.[5,21] Symptom severity depends on compression rate and hydrostatic pressure.[21] Severe impairments of judgment and motor coordination alteration may contribute to fatalities during deep bounce dives. However, HPNS was generally not reported above 250 m among respondent divers, though individual susceptibility varies.[5,22] Additionally, the absence of physical exertion and the normothermia at the beginning of the dive (unlike hyperthermia induced by compression in dry chambers) could contribute to the mild impact of these symptoms, despite the rapid compression rate.[23] The duration of exposure at depth may also be insufficient for severe neuro-motor symptoms to develop. Finally, adding 5–8% nitrogen to the gas mix helps control symptoms, though exceeding 10% increases the risk of nitrogen narcosis and increases gas density.[21]

The high inert gas load presents significant challenges for safe decompression with divers adopting and accustomed to different approaches at these extreme depths. This is especially critical as no validated decompression protocol exists for such dives, and some models penalise high-helium mixtures extending decompression requirements.[24] Decompression obligations are rapidly accumulated and divers spent 96% of their diving time in ascent. Their goal is to minimise total dive time without compromising safety. In helium-based saturation decompression, ascent is very slow and conducted in a dry, heated, and controlled environment.[20] In contrast, to limit the saturation of slow-tissue compartments and to reduce decompression time, deep bounce divers interviewed used faster ascent rates than the recommended 6–10 $m \cdot min^{-1}$ by technical diving standards.[25] Nevertheless, there are no data supporting this practice, so perhaps slower rates should be respected while accepting the extended decompression this requires.

Decompression profiles can also be adjusted using gradient factors (GF), where the low-GF influences the depth of the first stop, and the high-GF affects shallower stop duration. Decompression strategies vary widely, often based on personal experience and GF is not directly linked to experimentally validated decompression profiles.[6,24] In this context, helium's lower solubility and faster washout may produce more circulating bubbles implicated in the pathophysiology of DCS. High PO_2 reduces inert gas load and accelerates its elimination. All surveyed divers significantly exceeded CNS clock exposure limits, dismissing them

as unnecessary. Although optimising the oxygen window offers decompression benefits, using PO_2 levels above the recommended thresholds increases the risk of neurological oxygen toxicity.[25,26] The decompression advantage during the bottom phase remains uncertain. A reasonable compromise would be to initially maintain PO_2 below 1.3 bar, where the reduction in inert gas uptake is relatively modest, in order to preserve the ability to use higher oxygen levels more safely during shallow decompression stop.[6] Intermittent 'air breaks' (typically 5 min every 20 min) during oxygen breathing have been shown to reduce the risk of convulsions in dry chambers. A similar protective effect is presumed in actual diving scenarios; however, data on its feasibility and effectiveness underwater remain limited.[27] Susceptibility to oxygen toxicity varies between individuals and there is no evidence that tolerance improves with practice. This toxicity is cumulative, potentially leading to seizures and drowning, especially during prolonged exposure.[28] While exceeding limits does not appear to cause significant lung function decline, reversible symptoms like chest tightness or dry cough have been reported.[26]

MATERIAL AND ENVIRONMENTAL CONSIDERATIONS

Equipment malfunctions at extreme depths can be catastrophic, as many devices are not designed or certified for such conditions. Several incidents have been reported within the diving community, including the implosion of a DPV at depth, as described by one of the interviewed divers, which could have resulted in a serious secondary accident. Technical divers emphasise the importance of redundant critical systems to ensure a safe return.[16]

Rebreathers address gas volume limitations where the time limiting factor is only the CO_2 absorbent capacity.[1,2] In very deep or prolonged dives, especially in caves where carrying sufficient cylinders is challenging, bailout CCR offers a very attractive redundancy option.[2,29] In open water, decompression gases can be supplied from the surface, but risks such as missing the shot line or losing contact with the support team remain problematic. Compared to OC systems, the use of bailout CCR increases the risk of human-error due to its more complex nature. Moreover, in the event of hypercapnia, a rapid switch to an alternate breathing apparatus is critical. Without a bailout valve (BOV) or an open circuit stage regulator, a second rebreather may reduce CO_2 washout efficiency caused by the re-inhalation of contaminated breathing gas. A BOV integrates an open circuit regulator within the breathing loop mouthpiece, but at extreme depths, regulator performance may be compromised, and an open circuit gas supply might only last just a few minutes. A second consideration in preventing hypercapnia is scrubber duration, which depends on soda lime quality, quantity, proper filling, and storage.[30] Most manufactured scrubbers are designed for three to four hours of efficacy based on testing at 4°C with ventilation and CO_2 addition to simulate a high exertion level. While this is generally sufficient for extended dives in temperate waters with minimal effort, some divers attempt to extend scrubber capacity through homemade modifications or the use of radial scrubbers.

As previously discussed, keeping divers warm and well-hydrated is crucial for effective decompression. Limiting environmental exposure helps mitigate these challenges. Adequate thermal protection is essential, and an active heating system can reduce the risk of hypothermia. However, after a 'warm' period, the heating system may malfunction during decompression, which could be detrimental.[4] Another component of this strategy is the use of dry decompression habitats, which are relatively simple and cost-effective. These habitats provide a refuge during final decompression stops and often induce a 'segmented staged decompression' prolonging the overall runtime and potentially the quality of decompression.[2,31] The diver is comfortably sitting, which allows for fluid and caloric intake, helps improve thermal comfort, and reduces the risk of fatalities in the event of oxygen toxicity.[2,31] Thus, this practice shares many similarities and advantages with saturation diving and might be the 'reasonable' approach to allowing sufficient decompression for these deep dives.

EXCEEDING THE LIMITS?

The present reports from extreme dives highlight a high accident rate, including severe DCS cases, with symptoms emerging in the water that could have led to fatal outcomes. Special attention has been given to inner-ear DCS in technical diving, likely caused by the arterialisation of circulating bubbles, which then pass to the inner ear's terminal circulation in a supersaturated inert gas environment.[12] These findings suggest current decompression procedures and gas management are inadequate for extreme deep dives, underscoring the need for further research to enhance safety. Self-adjustments to reduce decompression time, whether by modifying ascent rates or oxygen exposure, exhibit an element of randomness and could even be dangerous. High skills and experience allow for minimal exertion and perfect stabilisation during dives, reducing respiratory effort and the risk of hypercapnia. This helps mitigate the effects of narcosis, HPNS, oxygen toxicity, and potentially the risk of DCS.[32] However, physical effort may be required in the event of an unexpected situation or equipment failure, which could exacerbate these risks.

It has long been hypothesised that hydrogen-containing gases could enhance safety and performance in extremely deep dives. These mixed gases have enabled the record of deepest dives (534 m in open sea and 701 m in a hyperbaric chamber).[8] A recent report in recreational deep diving suggests hydrogen may mitigate physiological limitations by reducing breathing gas density and alleviating HPNS symptoms.[22] However, careful attention must be given to managing this highly flammable gas and its unknown decompression profile. Additional factors, such as

counter-diffusion issues and thermal hazards, also need consideration.[8,33] Unfortunately, a case of severe DCS was recently documented on social media after a hydrogen bounce dive, highlighting the unknown risks and new challenges ahead. The solubility of hydrogen in fats and its diffusion rate could contribute to neurological injury, as previously observed, leading to the termination of the Hydra-Ludion experiments (non-published data, reported by author BG). COMEX reports have shown that while hydrogen effectively reduces HPNS and improves respiratory comfort, it does not allow accelerating decompression compared to helium in saturation diving.

Technological advancements, particularly in real-time diver monitoring, and procedural adjustments remain necessary to push the limits of depth exploration. Divers must approach this challenge with humility, responsibility, curiosity, and an unwavering commitment to safety. In this field, collaboration between the diving and research communities is essential in advancing knowledge and minimising the risks associated with such explorations.

LIMITATIONS

This report has several limitations. Although from different backgrounds, only divers within the researchers' network were contacted, introducing a recruitment bias. Consequently, the study focused on a limited number of highly specialised divers, whose dive planning methods may not be generalisable. Practices vary widely based on individual experience. Additionally, a recall bias may be present, despite the dives being recent and based on computer records. Nonetheless, this study seeks to discuss current practices and explore the future of deep diving and the limits of human endurance.

Conclusions

Extreme deep diving is both exhilarating and demanding, requiring specialised training, advanced equipment, and meticulous planning. This pursuit pushes human limits, as evidenced by record-breaking achievements. Success in extreme deep bounce dives depends on overcoming significant physiological and logistical challenges. Decompression remains a primary obstacle, as ascent rates seem difficult to accelerate regardless of the gas mixture used. Accepting that reaching great depths necessitates an extended decompression period is crucial. Submerged habitats could help mitigate the adverse effects of prolonged time spent in the water. Careful preparation, robust support systems, and continuous protocol advancements are essential for risk mitigation. Additionally, physiological monitoring should play a crucial role in improving safety and assessing divers' tolerance to extreme depths.

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Acknowledgements

The authors thank the divers who agreed to share their deep diving experience, for the kind discussions and the passion they have for their activity. We thank Dr Bruce D'Souza for his assistance and advice in manuscript revision.

Conflicts of interest and funding: nil

Submitted: 27 March 2025
Accepted after revision: 2 May 2025

Letter to the Editor

Challenges in the administration of hyperbaric oxygen therapy (HBOT) for complicated cases in a tertiary care setting

We are writing to share insights from a recent clinical case involving a 65-year-old female patient who presented with osteoarthritis of the left knee and underwent genicular artery embolisation under general anaesthesia. Following the procedure, she developed compartment syndrome, necessitating fasciotomy. To aid her recovery, a multidisciplinary approach was employed, including serial debridement and daily hyperbaric oxygen therapy (HBOT) sessions of 90 minutes, intended to optimise wound healing and minimise infection risk.[2] We also managed a 32-year-old female case of abdominal wall dehiscence, where the patient underwent HBOT and vacuum-assisted closure followed by split thickness skin grafting. The patient ultimately made a full recovery. In both patients we encountered a number of operational and administrative challenges during their HBOT treatment that are worth discussing for the benefit of clinical practice and institutional improvements.

Challenges and administrative issues

STAFFING CONCERNS

One of the primary administrative issues observed in both patients was the lack of female attendants and nursing staff to assist with the patient during her HBOT sessions.[1] This may often be the case in hyperbaric units based in military establishments. As the patient was a female, the absence of appropriately trained female staff in the chamber raised significant concerns regarding comfort, privacy, and emotional well-being. This is an area where our healthcare facility could improve by ensuring that adequate, trained female staff are available to support female patients undergoing HBOT.

Measures taken: We motivated female staff ward sahikas (multipurpose health workers) to accompany the patient in and out of the facility and to help them in their personal activities i.e., in going to washroom, transferring them in and out of the chamber. However, they did not enter the chamber as they were not trained in this regard.

PATIENT MOTIVATION AND COMPLIANCE

During the initial phase of HBOT, the first female patient experienced difficulty in remaining in the chamber for the full 90-minute duration. Convincing the patient to comply with the required treatment time posed a psychological barrier,[2,3] which we addressed through motivational counselling and teaching relaxation techniques such as Valsalva manoeuvres. However, motivating the patient to extend her time gradually to the 60–90-minute target required persistent encouragement from the medical staff, indicating the need for more effective patient education protocols.[4]

Also explaining to the patient about the possible side effects and complications of HBOT in a thorough yet non-threatening manner was a delicate task as even some other speciality doctors involved in her case had apprehensions about HBOT.

Measures taken: Frequent counselling and communication by senior consultants and diving staff for the patient and her medical officers was undertaken. To allay the apprehension of the patient, we chose a dive attendant from the same state and of the same religion to help with therapy acceptance.

There are no widely accepted protocols for such a case being subjected to HBOT and rare citations are available in literature. The entire department of marine medicine met under the guidance of the Head of Department (HOD) to design an appropriate protocol for administrating HBOT with the aim of safely maximising benefits.

STAFF ENGAGEMENT AND ENTHUSIASM

While these challenges were notable, it is important to recognise the importance of enthusiasm and dedication shown by both medical and non-medical staff in attempting to meet the patient's needs.[5] The multidisciplinary team collaborated closely to ensure optimal care, but the logistical issues highlighted above remain important areas for improvement.

Conclusions

The case of these two very ill female patient underscores not only the clinical benefits of HBOT in managing complex surgical outcomes but also the operational and administrative challenges that can hinder its successful implementation. Our experience emphasises the need for healthcare teams to also be mindful of cultural dynamics and to implement better staffing protocols, patient communication strategies, and operational adjustments that are sensitive to gender and cultural background. Addressing these issues would allow healthcare facilities to provide more efficient and compassionate care, ultimately improving patient outcomes.[5]

We hope that sharing these experiences will stimulate further discussion and improvement, particularly in scenarios involving sensitive gender and cultural issues.

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Submitted: 30 March 2025
Accepted: 4 April 2025

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Keywords
Hyperbaric facilities; Hyperbaric medicine; Hyperbaric medicine; Hyperbaric research; Women; Wounds

Notices and news

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

President's report

Jean-Eric Blatteau

Serendipity and zemblanity in diving and hyperbaric medicine: learning from the unexpected

Scientific progress is not always linear. In clinical practice and research alike, we often learn as much from what surprises us as from what we predict. Two concepts help frame these dynamics: *serendipity*, the fortunate and unexpected discovery of something valuable, and *zemblanity*, the emergence of unfavorable outcomes that are predictable, even if undesired. Both can illuminate the development of our understanding and practice in diving and hyperbaric medicine.

A telling example of *serendipity* comes from the repeated observation that patients receiving long-term hyperbaric oxygen therapy (HBOT) for chronic wounds often report improvements in neurocognitive function. These effects were not the original goal of treatment, but have opened new lines of inquiry into the use of HBOT for conditions such as traumatic brain injury, long COVID, and neurodegenerative disorders. What began as an incidental clinical observation has grown into a research frontier.

In contrast, *zemblanity* is exemplified by the well-known side effect of transient myopia during HBOT. This is not a surprising finding but it is an undesirable one. However, a more nuanced understanding has emerged: the incidence and severity of HBOT-induced myopia are influenced by the oxygen delivery interface. Studies have shown that patients treated with hoods are more prone to develop myopia than those using masks, likely due to prolonged ocular exposure to high oxygen levels. This insight, while stemming from a predictable adverse effect, enables a pragmatic response: for patients who develop myopia, switching from a hood to a mask can reduce exposure and allow HBOT to continue, depending on the urgency and importance of the treatment indication.

Serendipity and *zemblanity* both remind us that medicine advances through careful observation and responsiveness to outcomes, whether welcome or not. By staying open to unexpected benefits and attentive to predictable risks, we can refine our clinical approaches and expand the horizons of hyperbaric therapy.

Perhaps it is time to explicitly recognise the value of these phenomena in our scientific community. Should we consider introducing themes or dedicated sections in our congresses and in the pages of the *Diving and Hyperbaric Medicine* journal that explore serendipitous discoveries and zemblanitous lessons in our field? These reflections could inspire innovation, humility, and progress – rooted not only in what we seek, but also in what we happen to find.

I would be delighted to discuss all of this further and to see many of you at the upcoming EUBS Congress in Helsinki this September – an opportunity not only to share science but also to discover the beauty of Finland together. It will also be for me a special moment to conclude my mandate as President of the EUBS and to warmly congratulate our new President, Bengüsu Mirasoğlu. I extend my heartfelt thanks to the entire Executive Committee and in particular to our Secretary-General, Peter Germonpré, for their outstanding work and continuous commitment to energising our society.

Jean-Eric Blatteau
EUBS President

EUBS Notices and news

EUBS2025 Scientific Meeting on Diving and Hyperbaric Medicine

After the great success of its 48th edition in Brest, France, the EUBS Annual Scientific Meeting will move to Helsinki (Finland) for our 49th meeting which will take place from 2–6 September 2025. Finland has been recognised as the world's happiest country by the UN World Happiness Report for an impressive seven consecutive years. As a member of the European Union, Finland is welcoming and English-friendly, making communication easy despite the complexity of the Finnish language.

Finland is renowned for its beautiful nature and clean environment. It is the most forested country in Europe and is often called the "*Land of a Thousand Lakes*" – though tens of thousands would be more accurate. Finnish summers are marked by endless daylight, along with numerous events and festivals across the country.

Helsinki, the capital of Finland, is the northernmost capital in the European Union. It has over 681,000 inhabitants and is nearly 480 years old. The central Helsinki area is compact, making it easy to explore on foot. The city's coastal location offers numerous islands and coastlines to visit, along with plenty of greenery and parks, including a large central park that gradually transitions into forested areas as you move farther from the city center.

Reaching Finland is convenient, with direct flights available from major European cities, as well as destinations in Asia and North America. Travelers from Central Europe can also reach Finland by ferry (or train + ferry). Ferries from Estonia, Germany, Poland, or Stockholm provide a picturesque and relaxing journey.

EUBS will be delighted to welcome you to participate in this Meeting to contribute to its success. If you have not yet registered, visit the conference website http://www.eubs2025.com for all information and registration.

So gear up, register – remember to bring your partner and kids along – and we'll meet again sooner than you think.

EUBS Elections –Member-at-Large

Around the time of publication of this issue of DHM, the election process for the 2025 ExCom Elections will have been started. This year, we not only need to elect a new Member-at-Large to serve the society for the next four years, it is also time to elect a new Vice-President. Jean-Eric Blatteau will move to the position of Immediate Past President, and Bengusu Mirasoğlu will assume the post of President for the next term.

We will be saying goodbye to Dr Evangelos (Vangelis) Papoutsidakis (Barcelona, Spain) as Member-at-Large 2021. ExCom extends its thanks to Vangelis for the work he did in ExCom.

Candidates for the position of Vice-President and Member-at-Large 2025 will be presenting themselves on the EUBS website with a picture and short CV (https://www.eubs.org/?page_id=1918), and you should by the time this Journal issue is published, have received an internet ballot by e-mail allowing you to cast your vote.

If you have not received such an email yet by the end of June, 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.

Website and social media

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

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, logos and contact information on the

Corporate Members page under menu item "*The Society*". Please follow our Facebook, X 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, X 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 known as 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.

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

I am now about to enter the final year of my second 3-year term as SPUMS President. The position of SPUMS President-elect was decided at the Bali 53rd SPUMS Annual Scientific Meeting (ASM) Annual General Meeting (AGM), with Stephan Roehr elected as the successful candidate. Congratulations Stephan.

Stephan has a year to 'learn the ropes' prior to becoming President at the completion of my second 3-year term at the 2026 AGM.

I have just returned from the 53rd SPUMS ASM held at the Ramayana Candidasa Hotel in Bali, Indonesia. This conference had over 120 delegates and was a great success. Approximately 50 of these were first time SPUMS conference attendees.

The scientific program "*Oxygen: Too little, too much or just right*" covered a broad range of topics and was presented by leaders in their field, including Bruce Derrick, Pieter-Jan van Ooij, Peter Lindholm and Simon Mitchell. I would like on behalf of SPUMS to thanks all speakers and attendees as well as Xavier Vrijdag and Hanna van Waart, our Bali ASM Convenors, Diveplanit our travel provider and Bali Diving Academy.

The academic program, the diving and the functions were all well organised and well received, with many indicating that they will be back for more next year.

The SPUMS 54th ASM in 2026 will be in Palau, Micronesia at the Palasia Hotel. Our ASM is being convened by Doug Falconer and Ian Gawthrope. There will be a new moon bump head parrotfish spawning event on the 13th/14th May – an enormous spectacle and not to be missed.

SPUMS 54th Annual Scientific Meeting
Palasia Hotel, Palau
10–15 May 2026
Theme: *Free diving*
Save the date.

Qantas are currently flying to Palau, departing Brisbane on Saturday mornings and returning Sunday morning. Further details will be available on the SPUMS website soon.

It was my privilege as SPUMS President to be able to award Clinical Professor David Smart, AM, Life Membership of our Society at our Bali AGM.

David has been a great servant for SPUMS, serving two terms as SPUMS President and been a member of SPUMS for 40 years.

His Life Membership citation was presented at the AGM and appears in this issue of the journal. Congratulations David. An honour roll of our current and former Life Members can now be found on the SPUMS website: South Pacific Underwater Medicine Society - SPUMS - Life Members.

The updated SPUMS and UKDMC Joint Position Statement (JPS) on persistent (patent) foramen ovale (PFO) and diving originally published in 2015, was published in the March issue of *Diving and Hyperbaric Medicine*. The update was the subject of one of the workshops at the 2025 ASM in Fiji. The JPS includes an Appendix with photographs highlighting important quality control issues for bubble contrast echocardiography.

The ANZHMG Introductory Course in Diving and Hyperbaric Medicine will next be held from mid-February 2026, again in Fremantle. The 2026 course is almost full, so I strongly suggest that you register your interest if you are considering attending. Course link here: 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.

I am pleased to be able to announce the commencement of data entry into the Australasian Decompression Illness (DCI) Registry from 1st July 2024. Almost all Australasian hyperbaric facilities are currently participating, with

the remainder hopefully completing the bureaucracy to participate soon. The Registry is hosted by Monash University and generously funded by ADSF and collects data on all divers treated for DCI. In the near future, data will be available for research purposes. This data set will be a useful resource for those seeking to complete their SPUMS Diploma thesis.

Finally, I would like to thank members of ExCom for their hard work and support, as well as Nicky Telles our Editorial Manager and Web Manager for her tireless efforts.

I'm looking forward to the final year of my Presidency and will continue to work for SPUMS as Immediate Past President from the 2026 AGM.

Dr Neil Banham
SPUMS President

Life Membership Citation

Clinical Professor David Smart AM
BMedSci, MBBS(Hons), MD(UTas), FACEM, FIFEM, FAICD, FACTM, FUHM, DipDHM, ANZCA DipAdvDHM

David has been a recreational scuba diver since 1983 with over 3,000 hours logged underwater. He currently has Master Diver qualification and is an enthusiastic recreational diving photographer.

David has been a SPUMS member from 1985 and has been working in the field of diving and hyperbaric medicine since, becoming a leader in the field. He has had a continuous commitment to diving safety and education in Australia, the South Pacific and Internationally, for almost 40 years. David was awarded his SPUMS Diploma (DipDHM) in 1989 with his thesis being "*The equivocal bend: do we treat with hyperbaric oxygen?*"

David is a Diving Medicine Specialist and was Medical Director, Department of Diving and Hyperbaric Medicine at Royal Hobart Hospital from 1998 until his recent retirement. He was the driver behind the Unit's acquisition of a new rectangular triple lock hyperbaric chamber system with hypobaric capability which opened in 2020.

Roles with SPUMS

- Executive Committee Member and Australian Standards Representative: 1999–present
- Chairman Australian and New Zealand Hyperbaric Medicine Group: 2001–2013
- SPUMS Education Officer and Censor: 2002–2013
- SPUMS President: 2014–2020
- SPUMS Immediate Past president 2020–present
- Diving and Hyperbaric Medicine Journal Academic Board 2008–2020
- *Diving and Hyperbaric Medicine Journal* Governance committee 2020–present
- SPUMS Representative Australian Standards Diving Safety Committees from 1999-2020 for Australian and New Zealand Standards AS/NZS 2299.1, 2299.2, 4005.1, 2815.1, 2815.2, 2815.3, 2815.4, 2815.5 and 2815.6, and 4774.2 (including revisions)
- Annual Scientific Meeting Convenor 2009 (Iririki Resort, Vanuatu), 2023 (Cairns, Australia) and 2024 (Pacific Harbour, Fiji)
- ANZHMG Introductory Course in diving and Hyperbaric Medicine Faculty 1998–present
- SPUMS Diving medical health risk assessment for diving (1999, 2011, 2020)
- Convenor, Medical Support of Occupational Offshore and Saturation Diving Course 2016
- Author SPUMS Guide Book for ASM convenors 2009, 2016, 2024

David is widely published with over 80 papers in peer reviewed journals, including many in *Diving and Hyperbaric Medicine*, with numerous citations (475 at last count).

David has made significant contributions to our field and to others outside of SPUMS which are too numerous to list here.

David was appointed Member of the Order of Australia (AM) in 2019 for services to Hyperbaric and Diving Medicine and professional organisations.

Throughout his career, David has been amazingly supported by his loving wife Annette.

I would like to recommend to SPUMS members that Professor David Smart be awarded Life Membership and I heartily commend him to the meeting.

Dr Neil Banham
MBBS, FACEM, DipDHM, ANZCA DipAdvDHM
SPUMS President

Mike Bennett Scholarship

Dr Sue Pugh, the wife of the late Professor Mike Bennett AM (a past SPUMS President and mentor to many), has bequeathed funds to create a Scholarship ('The Mike Bennett Scholarship') to fund the successful applicant to attend a Scientific Meeting of relevance to diving and hyperbaric medicine.

Suitable meetings may include (but are not limited to) the Annual Scientific Meeting (ASM) of South Pacific Underwater Medicine Society (SPUMS), Undersea and Hyperbaric Medical Society (UHMS), European Underwater and Baromedical Society (EUBS), Hyperbaric Technicians and Nurses Association (HTNA), British Hyperbaric Association (BHA).

The Mike Bennett Scholarship will be offered annually with one successful applicant chosen if they are considered to meet the selection criteria. The Scholarship may not be awarded in any given year if the applications received are not deemed suitable by the Selection Panel.

The Mike Bennett Scholarship is open to anyone working in the field of diving and hyperbaric medicine, including doctors, technical staff, nurses and those performing research in the field. Applications from those from Pacific nations who might not otherwise have the opportunity to attend an international scientific meeting are also encouraged.

Selection of the successful applicant will be overseen by a SPUMS Selection Panel comprising:

Dr Sue Pugh
SPUMS President (currently Dr Neil Banham)
SPUMS Immediate Past President (currently Professor David Smart)
SPUMS Education Officer (currently Dr David Cooper)
Diving and Hyperbaric Medicine Journal Editor (currently Professor Simon Mitchell)

The successful applicant for The Mike Bennett Scholarship will have the actual costs of ASM Registration, travel and accommodation funded to a maximum of AUD $10,000. However, the applicant will be responsible for all other expenses incurred.

There are no rigidly defined selection criteria, however, preference will be given to the following:

- SPUMS members
- Presenting at the ASM:
  (1) A diving or hyperbaric medicine presentation
  (2) An evidence-based medicine presentation
- Those who have previously made a significant contribution to SPUMS.

Applications should include a brief synopsis (1–2 pages) of the project and be submitted to president@spums.org.au.

Closing date: 31 December 2025

Dr Neil Banham MBBS, FACEM, DipDHM, ANZCA DipAdvDHM
SPUMS President

HBOE
HBOEvidence

HBOEvidence

HBOEvidence 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 in the process of being integrated into the SPUMS website.

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

The Australian and New Zealand Hyperbaric Medicine Group

Introductory Course in Diving and Hyperbaric Medicine

Please note: This course is fully subscribed with a waiting list. If you are considering attending the course in 2026, dates will again be from mid to late February 2026 for two weeks.

Dates: 16–27 February 2026
Venue: Hougoumont Hotel, Fremantle, Western Australia
Cost: AUD$3,300.00 (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.

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.

Royal Australian Navy Medical Officers' Underwater Medicine Course

Dates: 13–24 October 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*

SPUMS Facebook page
Find us at:
SPUMS on Facebook

SPUMS Diploma in Diving and Hyperbaric Medicine

(Updated June 2025)

Requirements for candidates

For the Diploma of Diving and Hyperbaric Medicine (Dip DHM) to be awarded by the Society, the candidate must:

- be medically qualified;
- remain a current financial member of the Society for the duration of their candidacy for the Diploma;
- pay such administrative fees and charges (e.g., candidate registration fee) as may, from time-to-time, be approved by the Society's Executive;
- supply evidence of satisfactory completion of an examined two-week fulltime course in Diving and Hyperbaric Medicine at an approved facility. The list of such facilities may be found on the SPUMS website;
- have completed the equivalent (as determined by the Education Officer) of at least six months' fulltime clinical training in an approved Hyperbaric Medicine Unit;
- submit a written proposal for research in an area of relevance to underwater or hyperbaric medicine, in a standard format, for approval *before* commencing their research project;
- 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 written report should be a request to be considered for the SPUMS Diploma and supporting documentation for 1–5 above.

In the absence of documentation otherwise, 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 should broadly comply with the 'Instructions for authors' available on the SPUMS website www.spums.org.au or at South Pacific Underwater Medicine Society - Submitting to DHM.

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 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, independent peer review process.

Additional information – prospective approval of projects is required

The candidate must contact the Education Officer in writing (email is acceptable) to advise of their intended candidacy, and to discuss the proposed topic of their research. A written research proposal must be submitted before commencing the research project.

All research reports must clearly test a hypothesis. Original basic or clinical research is acceptable. Case series reports may be acceptable if thoroughly documented, subject to quantitative analysis, and the subject is extensively researched and discussed in detail. Reports of a single case are insufficient. Review articles may be acceptable if the international 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. Evidence of each author's specific contributions should be provided in the case of multi-author papers.

The preferred format for submission of the final project is as a single file (Word or unlocked pdf), 1.5-line spaced, Times New Roman 12-point font, unformatted, with all figures and tables embedded in the document at an appropriate location.

It is expected that all research will be conducted in accordance with the joint NHMRC/AVCC statement and guidelines on research practice, available at: http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/r39.pdf. or the equivalent requirement of the country in which the research is conducted. All research involving humans 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 project is approved prior to commencing research.

As of 01 July 2025, projects will be deemed to have lapsed if:
(1) The project is inactive for a period of three years, or
(2) 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 advise the Education Officer in writing if 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 in writing to the Education Officer for consideration by the SPUMS Executive. If a project has lapsed, then the candidate must submit a new application as per these guidelines.

Fees and charges: From 01 January 2026 a one-off Registration Fee of AUD $250.00 will be payable at the time of enrolment for the Diploma. This is in addition to the annual Society Membership Fee.

The Academic Board reserves the right to modify any of these requirements from time to time.

As of June 2025, the SPUMS Academic Board consists of:
Dr David Cooper, Education Officer
Associate Professor Simon Mitchell.

All enquiries and applications should be sent to:
Dr David Cooper
Email: *education@spums.org.au*

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

Courses and meetings

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/

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. For SPUMS members access will be available soon for you, GTÜM has a new website and access is being created specifically for you. There will be a link in the 'members only' area of the SPUMS website. This should be available in the next month, so keep an eye out.

Scott Haldane Foundation

As an institute dedicated to education in diving medicine, the Scott Haldane Foundation has organised more than 320 courses all over the world, over the past 33 years. SHF is targeting on an international audience with courses worldwide.

Below is the schedule of upcoming SHF-courses in 2025.

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).

Second half of 2025

8–15 November	In-depth course What a Diving doctor MUST know (level 2d) Bali, Indonesia
15–22 November	In-depth course What a Diving doctor MUST know (level 2d) Bali, Indonesia
On request	Internship HBOt (level 2d) NL/Belgium

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

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

Diving and Hyperbaric Medicine Journal copyright statement 2025

Diving and Hyperbaric Medicine: Instructions for authors

(Short 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 accompanies the manuscript. All manuscripts will be subject to peer review. Accepted contributions will also be subject to editing.

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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.

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 in the full version of these instructions.

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 (full version 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?

IN THE EVENT OF A LIFE THREATENING EMERGENCY PLEASE CALL YOUR LOCAL EMERGENCY SERVICES FIRST

For an accident in Australia, call the nearest public hospital with a Hyperbaric Unit and ask for the Duty Hyperbaric Doctor – see list below:

New South Wales/ACT **(02) 9382 2222** (Prince of Wales Hospital)
Northern Territory **(08) 8922 8888** (Royal Darwin Hospital)
Queensland **(07) 3646 8111** (Royal Brisbane Hospital) **(07) 4433 1111** (Townsville Hospital)
South Australia **(08) 7074 0000** (Royal Adelaide Hospital)
Tasmania **(03) 6166 8308** (Royal Hobart Hospital)
Victoria **(03) 9076 2000** (The Alfred)
Western Australia **(08) 6152 2222** (Fiona Stanley Hospital)

If you have a diver emergency **OUTSIDE AUSTRALIA**, please use one of the contact numbers below:

New Zealand from within New Zealand:
0800-4DES 111
(Diving Emergency Service)
New Zealand from overseas:
+64 9 445 8454
Asia, Pacific Islands **+618-8212 9242** (DAN World)
Americas **+1-919-684 9111** (DAN)
Europe **+39-06-4211 8685** (DAN EUROPE)
Southern Africa **+27-10-209 8112** (DAN SOUTHERN AFRICA)

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.
