Outcomes in the treatment of inner ear decompression sickness with hyperbaric oxygen therapy, a systematic review

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Abstract
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Introduction: The primary objective of this review was to evaluate the effectiveness of hyperbaric oxygen therapy (HBOT) in the treatment of inner ear decompression sickness (IEDCS). Secondary objectives were to summarise the diver characteristics, HBOT parameters and outcome measures.

Methods: All descriptive observational study designs including case series and individual case reports involving divers suffering IEDCS treated with HBOT were included. PubMed, Scopus, CINAHL and EMBASE were used to search for texts reporting the outcome for divers treated with HBOT. Eligible studies were appraised by two independent reviewers and any disagreements resolved via the third reviewer. Data were extracted using standardised tools and narrative synthesis was undertaken.

Results: 3,683 records were identified with 24 included in the final review representing 539 cases of IEDCS. Mean age was 44, average (in-water) dive depth 29 metres of seawater and dive duration 38 minutes. Mean onset of symptoms was 32 minutes and 74% had a right sided lesion. Only 37% had residual symptoms on discharge despite 68% showing dysfunction on laboratory testing. Follow-up duration and assessment methods were variable. Vestibular rehabilitation was underutilised and only 46% of divers went on to have patent foramen ovale (PFO) screening despite the well-established link to IEDCS.

Conclusions: A standardised method of examination and assessment of symptoms should be considered along with vestibular rehabilitation (or referral to this service). All divers should be counselled on PFO screening. A standard 3-month follow-up is recommended to allow for assessment of residual dysfunction / symptoms and discussion regarding returning to diving. Further research should focus on assessment of vestibular deficit / symptoms over time to assess efficacy of HBOT including the effects of delay to recompression and number of treatments. Laboratory testing should be utilised to determine the mechanism of injury and recovery.

Introduction

Inner ear decompression sickness (IEDCS) presents with acute vestibular symptoms (nausea, vertigo, nystagmus) ± cochlear symptoms (deafness, tinnitus) either following a dive or a change in the composition of inert gas in the breathing mixture. It is usually unilateral and can occur in isolation or as part as a more severe decompression sickness (such as a spinal decompression sickness). At least 70% of divers with IEDCS have an underlying right to left cardiac shunt / patent foramen ovale (PFO), allowing the venous bubbles formed during diving to cross into the arterial circulation, causing embolisation and risk of decompression sickness.[1]

IEDCS is particularly resistant to treatment with recompression, with divers often requiring several repeat treatments with hyperbaric oxygen therapy (HBOT) before recovery or a plateau of symptoms.

Choice of which HBOT tables may be used to treat IEDCS is often based on convention at the time but fundamentally all treatment tables for decompression illness must reach at least 284 kPa (2.8 atmospheres absolute [atm abs]) of pressure with 100% oxygen. The most widely used form of these tables is the USN 5 for mild decompression illness (symptoms must resolve within 10 minutes after reaching 284 kPa) and the USN 6/RN 62 with or without extensions for all other decompression illness. Tables involving compression to higher pressure e.g., the Comex 30 are sometimes used for more severe cases.[2] Approximately equivalent tables with alternative names are used in hyperbaric centres worldwide.

There is currently little guidance for dive physicians in the acute phase of treatment of IEDCS with regards to a standardised way to assess these patients, and indeed little in the way of guidance or support for general practitioners or ear nose throat (ENT) specialists who may be involved with these patients over the longer term. Often divers are left with residual symptoms and deficits in their balance.[3]

To determine how effective the current standards of care are in the acute phase of treatment for these divers a systematic review was undertaken focussing on rate of recovery following hyperbaric therapy, and how dive physicians quantify symptom burden during the hyperbaric treatment period, at discharge and at follow up. We considered factors that may affect treatment outcome such as number of HBOT sessions given and the time delay from symptom onset to the first recompression.

There are several case reports and case series documenting rate of recovery for divers with decompression sickness. Studies that involve inner ear decompression sickness treated with recompression with hyperbaric oxygen therapy according to either US Navy or UK Royal Navy standards will be included.

A preliminary search of PROSPERO, MEDLINE, the Cochrane Database of Systematic Reviews and the *JBI Evidence Synthesis* was conducted and no current or underway systematic reviews on the topic were identified.

REVIEW QUESTIONS

The review was designed to address the following questions.

- How do divers with IEDCS present and how is this assessed by physicians?
- How many hyperbaric treatments are given?
- What is the time delay from symptom onset to first recompression?
- What hyperbaric treatment tables are used and what proportion of divers are left with residual symptoms?
- What measures are being used to assess and manage residual symptoms in divers with IEDCS?

Methods

The review was conducted in accordance with the JBI methodology for systematic reviews of effectiveness evidence.[4] The review was registered with the PROSPERO registry: CRD42024521384.

INCLUSION CRITERIA

This review included descriptive observational study designs including case series and individual case reports.

All studies involving divers who had been diagnosed with a decompression sickness involving the inner ear were included. Any divers with an alternative inner ear diagnosis such as barotrauma or alternobaric vertigo were excluded. Studies that involved recompression with hyperbaric oxygen therapy were included with consideration of the number of treatments given and delay to recompression therapy.

Studies that reported the outcome for divers following recompression therapy were included with the anticipation that this was primarily reported as 'residual symptoms' or 'no residual symptoms'. We also reviewed how different centres / clinicians assess for recovery in this population and whether they are comparable methods.

SEARCH STATEGY

A three-step search strategy was applied for this review. First, an initial limited search of PubMed was undertaken to identify articles on the topic. The text words contained in the titles and abstracts of relevant articles, and the index terms used to describe the articles were used to develop a full search strategy for four databases: PubMed, Scopus, CINAHL and EMBASE (see *Appendix I). The search strategy, including all identified keywords and index terms, was adapted for each included database and/or information source. The reference list of all included sources of evidence was screened for additional studies involving case reports or case series of divers with inner ear decompression sickness.

Initial search terms used included the following: ('Inner ear decompression sickness' OR 'IEDCS' OR 'Vestibular') AND ('Hyperbaric oxygen therapy' OR 'HBOT'). Only studies published in English were included.

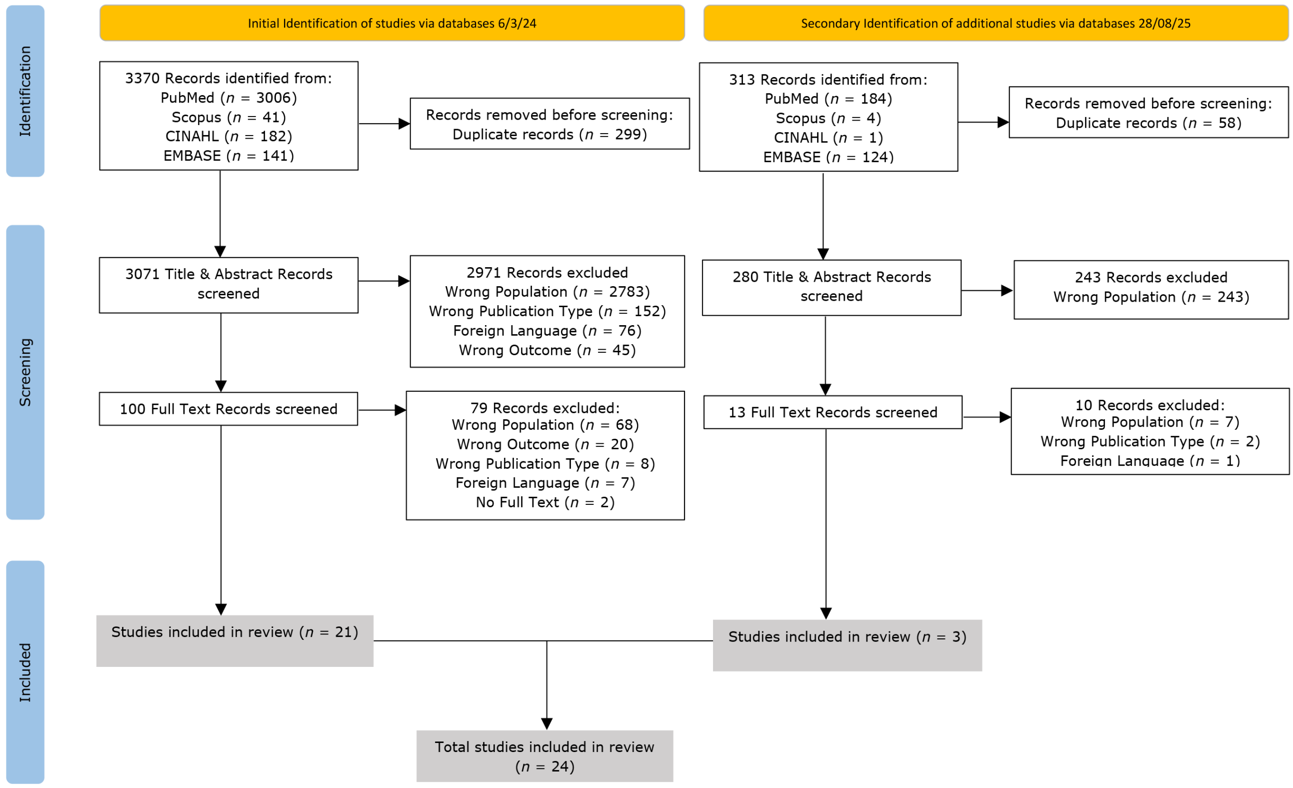
STUDY SELECTION

Following the search, all identified citations were collated and uploaded into Rayyan[5] and duplicates removed. Following a pilot test, titles and abstracts were screened by two independent reviewers for assessment against the inclusion criteria for the review. Potentially relevant studies were retrieved in full, and their citation details imported into the JBI System for the Unified Management, Assessment and Review of Information (JBI SUMARI).[6] The full text of selected citations were assessed in detail against the inclusion criteria by two independent reviewers. Reasons for exclusion of articles at full text that did not meet the inclusion criteria were recorded. Any disagreements that arose between the reviewers at each stage of the selection process were resolved by an additional reviewer. The results of the search and the study inclusion process have been reported in full and presented in a Preferred Reporting Items for Systematic Reviews and Meta-analyses (PRISMA) flow diagram (Figure 1).[7]

* **Footnote:** Appendix I is available online on our website https://www.dhmjournal.com/index.php/journals?id=398

Figure 1

PRISMA diagram for literature search results and study selection



ASSESSMENT OF METHODOLOGICAL QUALITY

Eligible studies were critically appraised by two independent reviewers for methodological quality in the review using standardised critical appraisal instruments from JBI for case series and case reports.[8,9] Any disagreements that arose were resolved through discussion, or with a third reviewer. The results of critical appraisal were reported in narrative form and in a table. All studies, regardless of the results of their methodological quality, underwent data extraction and synthesis (where possible). GRADE evaluation was not used in this review due to the descriptive nature of the data and lack of comparative outcomes in case series / reports.

DATA EXTRACTION

Data were extracted from studies included in the review by two independent reviewers using the standardised JBI data extraction tool.

The data extracted included the study design, the demographic details of the divers, details of the provoking dive including maximum depth and breathing gas composition, the number of hyperbaric treatments, time to first recompression and the outcome; either 'residual symptoms' or 'no residual symptoms' at the end of the acute phase of treatment with hyperbaric oxygen therapy. Where this was not explicitly stated, a judgement was made based on the description of the diver post treatment.

Any disagreements that arose between the reviewers were resolved through discussion or with a third reviewer. Authors of articles were contacted to request missing or additional data, where required.

DATA SYNTHESIS

Summary data, as well as data from each individual case of IEDCS were extracted where sufficient detail was provided. This included demographic characteristics (age, gender, underlying patent foramen ovale/right to left shunt), the dive profile (depth, duration, mixed-gas use), and the treatment details (time to first recompression, number of hyperbaric treatments, method for assessing residual symptom burden, recovery outcome at time of discharge, use of vestibular rehabilitation). Results are presented for each study with the range, mean values calculated where possible. Results from all the studies were pooled to provide overall mean, range and percentage values. To evaluate whether factors such as time to recompression, age, dive depth, onset of symptoms or number of HBOT had an impact on chance of residual symptoms, all studies with sufficient details for each of these factors were pooled. Outliers were identified using box and whisker plots and removed from analysis. IMB SPSS Statistics (Version 28) was used to perform binary logistic regression with a *P*-value of < 0.05 used to assess significance.

Results

STUDY INCLUSION

There were 3,370 records identified in the initial search on 6/2/24. As seen in the PRISMA flow chart (Figure 1) 299 duplicates were removed. At the title and abstract screening stage 2,971 records were excluded. Some were due to the 'wrong population' (*n* = 2,783) with the exclusion of articles that either did not include IEDCS or were cases with concurrent disease (such as barotrauma). Some were due to the 'wrong publication' (*n* = 152) with exclusion of articles that were not case reports or case series. Articles with the 'wrong outcome' (*n* = 45) were excluded as they did not detail any treatment with recompression. Finally, articles were excluded if they were 'foreign language' (*n* = 76), leaving 100 articles for full text review.

After the full text review, a further 77 were excluded at this stage due to wrong population (*n* = 68), wrong publication type (*n* = 8), 'foreign language' (*n* = 7), 'wrong outcome' (*n* = 20) or no full text available (*n* = 2) (see *Appendix II). This process resulted in the inclusion of 21 articles.

A second search was completed on 28/08/25 with 313 new records identified, 58 duplicates were excluded. At the title and abstract screening stage 280 records were excluded due to the 'wrong population' resulting in 13 records for full text screening. Ten full text records were excluded due to 'wrong population' (*n* = 7), 'wrong publication type' (*n* = 2), or 'foreign language' (*n* = 1) (included in *Appendix II). This process resulted in the additional inclusion of three articles, giving a total of 24 articles.[3,10–32]

METHODOLOGICAL QUALITY

Methodological quality of the case reports (*Appendix III) was at a reasonable standard for extraction of the required information. Diver demographics and dive profiles were described. Diagnostic tests, where used, were described in varying detail. Outcome post recompression was generally reported as diver reported 'recovered' or 'not recovered'. Some articles described this in more detail with patient's residual symptoms or signs on clinical tests reported. No adverse events were reported in any of the case reports.

For the case series (*Appendix III), again methodological quality was of a reasonable quality, with clear criteria for inclusion/ exclusion. For articles including all divers with inner ear symptoms the results between divers with IEDCS and inner ear barotrauma were clearly divided. Some articles (*n* = 2) did not present the demographic details of the divers but did include the dive profiles, other articles with a larger number of subjects did not include details of the individual divers/dive profiles (*n* = 4). This missing data meant that these large cohort studies were unable to be included in the analysis of factors influencing chance of symptoms at discharge/ follow-up, therefore diminishing the reliability of the results.

CHARACTERISTICS OF INCLUDED STUDIES

The year of publication of included studies ranged from 1976 to 2024 and were from a variety of worldwide locations including USA, Central America, Europe, Australasia, Asia and South Africa (*Appendix IV). Most of the case reports and case series were from hyperbaric treatment centres (*n* = 20) and the rest were from ENT/ otorhinolaryngology departments (*n* = 4). Most articles involved recreational divers (*n* = 20), with others reported cases involving military divers (*n* = 2), commercial divers (*n* = 1) or hyperbaric attendants (*n* = 1). Some articles included all divers with inner ear symptoms however those who did not have a diagnosis of IEDCS or did not receive recompression treatment were easily identified and could be excluded from the systematic review analysis.

REVIEW FINDINGS

From the 24 articles, 539 cases of IEDCS that had been treated with recompression were included. Details of the diver demographics and initial presentation are shown in Table 1, with a summary infographic shown in Figure 2. For those articles in which demographic details were included (*n* = 22) mean age was 44 (range 20–77). Eighty-five percent of the divers were male and 15% female. For those articles in which the dive profiles were described (*n* = 20), mean dive depth was 32 metres of seawater (msw) (range 7–198) and mean dive time was 39 minutes (range 15–240). When looking at only the in-water cases of IEDCS (excluding hyperbaric chamber induced IEDCS) the mean depth and time was 29 msw (range 7–122) and 38 minutes (range 15–180) respectively.

In articles where the breathing mixture had been detailed (*n* = 14), 238 divers (79%) were breathing air, 38 (13%) nitrox, 16 (5%) heliox, and 10 (3%) trimix.

Mean onset of symptoms was 32 minutes after surfacing (range 0–1,140). Sixty five percent of divers had purely vestibular symptoms, 23% cochleovestibular, and 12% purely cochlear symptoms. Twelve articles included an assessment of the laterality of the lesion and of the 213 cases of IEDCS, 159 (74%) had a right sided lesion and 53 (25%) had a left sided lesion. Only one case was reported as bilateral. Sixty-two percent of divers presented with purely IEDCS symptoms whereas 38% of cases were associated with other symptoms of decompression illness.

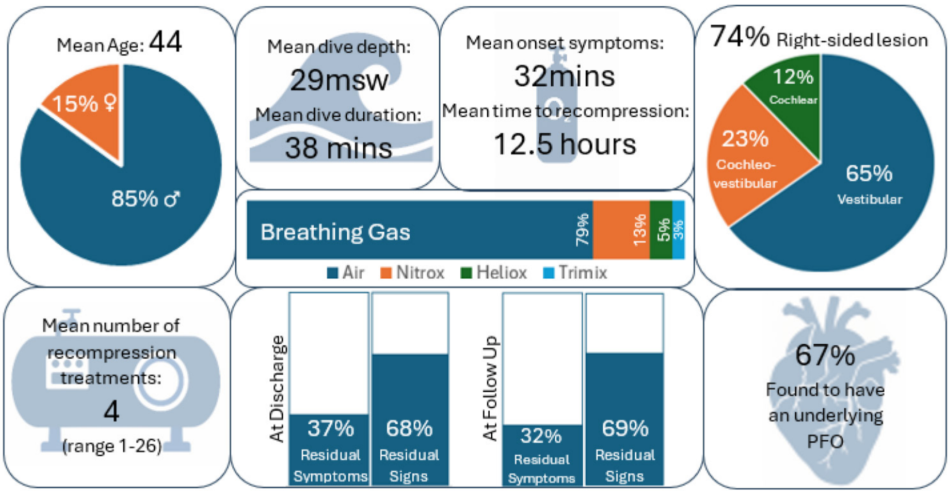
*** Footnote:** Appendix II, III and IV are available online on our website https://www.dhmjournal.com/index.php/journals?id=398

Table 1

Cases of inner ear DCS treated with hyperbaric oxygen demographics, diving, and initial presentation; means are presented with standard deviations (SD) or ranges; A – Air; C – Cochlear; CV – Cochleovestibular; F – Female; H – Heliox; I – Isolated; M – Male; N – Nitrox; N/A – not available; NI – Not isolated; Rec – Recreational diver; Tec – Technical diver; T – Trimix; V – Vestibular

Ref	*n*	Mean age	Gender	Mean depth (metres)	Mean duration (mins)	Breathing gas	Cochlear/ vestibular	Side of lesion	Isolated / non– isolated symptoms	Mean symptom latency (mins)
22	17	–	–	114 (21–198)	84 (15–240)	3 A, 14 H	5 C, 6 V, 6 CV	–	N/A	18 (0–206)
10	1	55	1M	14	90	1 A	1 CV	1 Left	1 I	5
11	115	44 (SD 11)	99 M, 16 F	41 (SD 12)	38 (SD 13)	110 A, 2 N, 3 T	7 C, 8 V, 20 CV	92 Right 23 Left	98 I, 17 NI	Median 20 (0–00)
23	1	51	1 M	50	60	1 N	1 V	1 Right	1 NI	N/A
3	99	48 (SD 11)	82 M, 17 F	37	42	–	5 C, 78 V, 16 CV	–	88 I, 11 NI	30 (8–60)
24	33	46 (31–61)	31 M, 2 F	37 (15–78)	43	22 A, 5 N, 6 T	1 C, 19 V, 13 CV	–		30 (0–120)
12	2	21 (20–21)	2 M	9	40	–	2 V	–		255 (150–360)
13	2	30	2 M	41 (32–50)	50 (35–65)	–	2 CV	2 Right	2 I	15
25	6	–	–	36 (25–55)	55 (35–65)	5 A, 1 T	1 C, 3 V, 2 CV	–	6 I	–
26	14	–	–	–	–	–	1 C, 8 V, 5 CV	–	13 I, 1 NI	–
14	2	36 (33–39)	1 M, 1 F	16 (7–24)	35 (25–45)	2 A	2 V	–	2 I	90 (0–180)
15	1	47	1 M	50	67	1 A	1 CV	1 Left	1 I	10
27	89	38 (31–44)	67 M, 22 F	Tec Median 45 (33–75) Rec Median 27 (18–34)	Tec Median 80 (56–115) Rec Median 40 (26–52)	45 A, 26 N	6 C, 72 V, 11 CV	18 Right, 4 Left 67 Unknown	16 I, 17 NI	–
28	24	45 (25–72)	22 M, 2 F	24 (10–62)	43 (15–125)	21 A, 3 N	3 C, 15 V, 6 CV	–	2 NI	89 (0–1140)
16	1	30	1 M	7	30	–	1 V	–	1 I	–
29	26	36 (22–69)	26 M	35 (15–122)	45 (22–180)	–	4 C, 8 V, 14 CV	18 Right, 8 Left	12 I, 14 NI	30 (0–120)
17	1	24	1 M	18	37	1 A	1 CV	1 Left	1 I	16
30	61	47 (24–75)	47 M, 14 F	–	–	–	28 C, 24 V, 9 CV	–	–	–
18	1	22	1 M	25	40	–	1 CV	1 Right	1 I	60
19	1	40	1 M	22	45	1 A	1 V	–	1 NI	20
31	11	40 (24–69)	11 M	32 (SD 13)	35 (SD–12)	–	3 C, 3 V, 5 CV	7 Right, 3 Left 1 Bilateral	11 Isolated	45 (5–300)
32	28	46 (20–77)	28 M	28 (15–61)	45 (25–180)	26 A, 2 H	19 V, 9 CV	16 Right, 12 Left	23 I, 5 NI	74 (10–960)
20	2	28 (25–31)	2 F	–	–	–	2 V	1 Right, 1 Unknown	1 I, 1 NI	240 (180–300)
21	1	33	1 M	27	37	1 N	1 V	–	1 NI	30

Figure 2
Infographic summarising key findings presented in Table 1



Details of the recompression treatment, assessment methods used, and outcome are shown in Table 2. Mean time from onset of symptoms to recompression treatment was 12.5 hours. Of the 451 cases in which the initial treatment table was described, 183 (41%) had a USN 6 / RN62, 166 (37%) had a USN 5, and (15%) had a Comex 30. The remaining 35 (8%) had 'other' tables. The mean number of recompression treatments was 4 (1–26).

When considering treatment outcome most articles reported whether patients had residual symptoms on discharge. Of 331 cases, 124 divers (37%) had residual symptoms, with 207 divers (63%) asymptomatic. However, few articles mentioned clinical/ laboratory examinations on discharge. Of those which did (63 cases), 43 (68%) had signs of either cochlear or vestibular dysfunction.

When considering longer-term follow-up there was little consistency in follow up periods, ranging from one week to 10 years. Of the 239 cases who had a follow-up assessment, 76 divers (32%) had residual symptoms. Of the 88 cases that had a clinical/ laboratory examination at follow-up, 61 (69%) had signs of either cochlear and/or vestibular dysfunction. Of this cohort of divers who had undergone laboratory testing with dysfunction identified, 23 cases also had the presence/ absence of symptoms described with 16 (70%) symptomatic.

The methods of assessment for IEDCS varied from simple bedside tests for nystagmus and postural stability (mentioned in 21 of the 24 articles) to full neuro-otological laboratory testing (14 of the 24 articles). Those studies based in ENT / otolaryngology departments had more comprehensive investigation when compared to hyperbaric centres, as expected due to the availability of specialist equipment and expertise. Three articles used scoring systems or questionnaires as patient outcome measures. Lindfors 2021 and Smerz 2007 used functional scoring systems whilst Gempp 2016 used the European Evaluation Vertigo Scale (EEV).[3,27,32]

Age, depth of the incident dive and time of onset of symptoms had no significant influence on the chance of symptoms at discharge or follow up. Time to recompression had no impact on the chance of symptoms at discharge but did show a relationship with chance of symptoms at follow-up ($R^2 = 0.42$, $P = 0.007$). The number of recompression treatments also showed a relationship to the chance of symptoms at discharge ($R^2 = 0.82$), $P < 0.001$), but not at follow-up ($R^2 = 0.26$, $P = 0.258$).

Of the 245 divers that had PFO testing via either transcranial doppler or bubble echocardiography, 165 (67%) had a PFO detected.

Discussion

HOW DO DIVERS WITH IEDCS PRESENT AND HOW IS THIS ASSESSED BY PHYSICIANS?

Diver demographics

Mean age (44 years old) was higher than the predominant age range for scuba divers (20–29 years old) reported by PADI Worldwide[33] however divers undertaking new certifications with PADI are a slightly different demographic to those diving as a regular sport or for occupation therefore the age disparity is not wholly unexpected. There were few cases of female divers reported, likely due to the historic male predominance in scuba diving (only nine of the 24 articles in the systematic review were within the last 10 years).

Dive details

When looking at purely in-water incidents of IEDCS with hyperbaric chamber / experimental incidents excluded, the mean dive depth and duration are within recreational limits and the gas used was mainly air or nitrox. This is as expected, as the presence of an underlying PFO represents a significant

Table 2

Recompression treatment and outcomes; BRA – brainstem response audiometry; CT – computed tomography; ENG – electronystagmography; EOG – electrooculography; HBOT – hyperbaric oxygen treatment; MRI – magnetic resonance imaging; N/A – not available; Rec – Recreational diver; SHA – sinusoidal harmonic acceleration; Tec – Technical diver; USN – United States Navy; Vest rehab – vestibular rehabilitation; VNG – videonystagmography

Ref	Mean time to HBOT (hours)	Treatment table	Mean No. HBOT	Symptoms at discharge	Symptoms at follow up	Methods of assessment	Vest. rehab	PFO testing
22	1 (0–6)	17 Other	1	6 of 17 symptomatic	N/A	Nystagmus, Audiogram	No	N/A
10	5	1 USN6	7	1 of 1 symptomatic 1 of 1 signs	1 of 1 symptomatic (3 months)	Nystagmus, Rinne/Weber, Postural instability (Gait, Romberg's), MRI scan	Yes	0/1 +ve
11	4 (0.5–35)	76 USN5 13 USN6 26 Comex30	Median 5 (2–11)	12 of 58 symptomatic 34 of 50 signs	N/A	Nystagmus (Frenzel's), Postural stability (Romberg, Fukuda, Tandem Walk), Lab tests (Audiometry, ENG, calorics, posturography)	No	95/115 +ve 20/115 -ve
23	2	1 USN5	1	1 of 1 symptomatic 1 of 1 signs	1 of 1 symptomatic 1 of 1 signs (6 weeks)	Nystagmus (Frenzels), Postural stability (Romberg's), Lab tests (ENG, caloric, tympanometry, audiometry)	Yes	0/1 +ve
3	Median 3	77 USN5 12 USN6 10 Other	N/A	N/A	25 of 99 symptomatic 39 of 58 signs (3 months)	Laboratory tests (audiometry, posturography, VNG, caloric), Postural stability (Gait)	Yes	N/A
24	6 (1–36)	1 USN5 21 USN6 11 Comex30	9 (1–20)	26 of 33 symptomatic	10 of 33 symptomatic (3 months)	Postural stability (Romberg, Unterberger)	No	3/33 Not tested 24/30 +ve 6/30 -ve
12	NA	2 USN6	2 (1–2)	0 of 2 symptomatic	0 of 2 symptomatic (6 weeks)	'Physical examination', 'Laboratory studies', CT Head	No	0/2 +ve
13	1.5	N/A	1.5 (1–10)	0 of 2 symptomatic	0 symptomatic 0 signs (2 months)	Postural stability (Romberg), Lab tests (Audiometry, Tympanometry, Caloric, Auditory brainstem responses, MRI)	No	1/1 +ve
25	10 (1.5–24)	N/A	N/A	2 of 6 symptomatic 5 of 6 signs	N/A	Lab. tests (tympanometry, audiometry, BRA, caloric), MRI scans	Yes	8/9 +ve 1/9 -ve
26	41 (1.5–240)	N/A	N/A	N/A	10 of 14 symptomatic 11 of 14 signs (1 week – 36 months)	Laboratory tests (audiometry, energy video-oculography)	No	11/14 +ve 3/14 -ve
14	N/A	2 Other	1	0 of 2 symptomatic	N/A	N/A	No	N/A
15	4.5	1 RN62	7	0 of 1 symptomatic	0 of 1 symptomatic 0 of 1 signs (4 weeks)	Nystagmus, Fistula test, Rinne/Weber Postural stability (Romberg)	No	1/1 Not tested

Table 2 continued.

27	Tec. Median 17 (6–24) Rec. Median 24 (7–60)	15 USN5 71 USN6 3 Other	Median 2 (1–5)	29 of 89 symptomatic	4 of 49 symptomatic (N/A)	Postural stability	No	N/A
28	49 (4–216)	23 USN6 1 Other	6 (1–15)	10 of 24 symptomatic	N/A	Nystagmus, Audiometry (46%)	No	13/23 Not tested 6/10 +ve 4/10 -ve
16	12	1 RN62	2	0 of 1 symptomatic	N/A	Postural stability (Gait, Romberg, Unterberger), Rinne/Weber, Fistula test, Lab tests (Audiometry)	No	N/A
29	24 (1–336)	22 USN6 2 Comex30 2 Other	5 (1–12)	NA	21 of 26 symptomatic (1 week – 4.5 years)	Tuning fork, Nystagmus (Frenzel's), Head thrust, Lab tests (Audiometry, EOG, calorics, SHA, ABR), CT/MRI head	No	N/A
17	22	1 USN6	2	1 of 1 symptomatic 1 of 1 signs	NA	Nystagmus, Postural stability (Gait), MRI scans, Laboratory tests (caloric)	Yes	1/1 +ve
30	N/A	N/A	N/A	27 of 61 symptomatic	N/A	Nystagmus, Lab tests (VNG, audiometry)	No	19/61 +ve 42/61 -ve
18	1.5	1 USN6	1	0 of 1 symptomatic 1 of 1 signs	0 of 1 symptomatic 0 of 1 signs (1 week)	Nystagmus, Postural stability (Romberg, gait), Rinne/Weber, Fistula test, Lab tests (audiometry, tympanometry)	No	N/A
19	10	1 USN6	4	0 of 1 symptomatic	N/A	CT scanning, Laboratory tests (audiometry, tympanometry), Postural stability (Romberg's, gait)	No	1/1 +ve
31	12.9 (3–48)	11 USN6	N/A	N/A	4 of 11 symptomatic 10 of 11 signs (22–119 months)	Tuning fork, nystagmus (Frenzel's), head thrust, Postural stability (Romberg's, tandem walk, stepping), Laboratory tests (Audiometry, ENG, caloric, SHA, posturography)	No	N/A
32	9 (2–35)	28 Other	6 (1–26)	9 of 28 symptomatic	N/A	Postural stability (Rombergs, Fujuda, Unterberger, heel-toe), Nystagmus (Frenzels), Rinne/Weber, Lab tests (ENG, audiogram, tympanography)	No	25 not tested 1/1 +ve
20	60 (26–96)	1 USN 5 1 USN 6	1	0 of 2 symptomatic 0 of 2 signs	N/A	Postural stability (Fukuda, tandem walk), Lab tests (audiometry, tympanometry, ENG, SHA)	No	N/A
21	4	1 RN62	6	0 of 1 symptomatic 0 of 1 signs	N/A	Nystagmus, Postural stability (Romberg's, gait)	No	1/1 +ve

risk factor in the majority of IEDCS cases,[1] allowing bubble shunting to occur within table limits. The 1976 Farmer paper included US Navy experimental dives with much deeper profiles (majority were 100–170 msw) and results should be interpreted with caution, however it is valuable in demonstrating the danger of such provocative profiles.[22]

Symptom presentation

Time from the end of the dive to the onset of symptoms had a large range, as often seen in clinical practice. The mean onset of symptoms of 32 minutes post dive correlates with other studies that include a broader range of decompression sickness cases. A large series in China of 5,278 cases had 2,548 divers (48%) with symptom onset within the first 30 minutes post-dive, and 1,648 (31%) within 30 minutes to one hour post-dive.[34]

Laterality of the lesion to the right in IEDCS supports prior findings in the wider literature and is thought to be due to the anatomical asymmetry in the diameter of the vertebral arteries, with the right often narrower than the left and therefore more prone to embolisation.[35,36] However, the focus of pathology in IEDCS, whether it affects the end organ and / or nerve and whether there is a predilection for certain structures (e.g., semicircular canals / otoliths) is unclear.

Clinical assessment

There was little detail in how divers were assessed at the hyperbaric centres but a basic bedside assessment of eye movements for nystagmus and assessment of gait / Romberg's for postural stability did seem to be routinely used. The lack of detailed vestibular assessment is due to the lack of specialist vestibular equipment and expertise at these sites. The clinical head impulse test, which is a simple bedside test used to detect the presence and laterality of a peripheral vestibular lesion first described in 1988[37] was not mentioned by any of the articles.

HOW MANY HYPERBARIC TREATMENTS ARE GIVEN?

The mean number of recompression treatments was 4 (range 1–26). In the large series in China including all cases of decompression illness 97% of the patients had only one recompression treatment but there was a large range of additional sessions (1–100+) for those who had incomplete/no recovery after the first recompression.[34] A Geneva based case series reported a median of five sessions (range 1–55) for their severe cases, significantly higher than their mild cases (median 2, range 1–4).[38] It can be inferred that IEDCS symptoms are more likely to persist after the first recompression therapy when compared to all decompression cases and that a similar number of repeated sessions are required to those with severe decompression sickness (e.g., spinal).

WHAT IS THE TIME DELAY FROM SYMPTOM ONSET TO FIRST RECOMPRESSION?

Time from onset of symptoms to recompression therapy had a wide range from 0 to 336 hours likely representing the variances in geographical location as well as access to recompression services and diver awareness of symptoms of decompression sickness. In the large case series in China, they had a median time delay of nine hours (1–204 hours) reporting that many divers failed to recognise that their symptoms were decompression sickness or were reluctant to seek treatment.[34]

WHAT HYPERBARIC TREATMENT TABLES ARE USED AND WHAT PROPORTION OF DIVERS ARE LEFT WITH RESIDUAL SYMPTOMS?

Choice of dive tables are often institution / region specific. The Diving Medical Advisory Committee (DMAC) advises that following air or nitrox dives to 50 msw almost all cases of decompression illness can be treated with a 284 kPa (18 msw) table, i.e., a USN 6 or RN 62. However, IEDCS with only partial improvement during initial compression may benefit from a Comex 30 table.[39]

The USN 5 table is a short 284 kPa (18 msw) table recommended for pain-only decompression sickness therefore deeming it an inadequate treatment for IEDCS.[40] It is unclear why it was used in such a high proportion in these studies (37%); however, it may have been due to mild symptoms, or resolution of symptoms at treatment pressure.

When considering residual symptoms, IEDCS appears to be quite resistant to hyperbaric therapy. Studies including other types of decompression illness show varying resolution rates with severity of decompression illness correlating with outcome.[34,38] As there is no consistent way of assessing or grading the severity of symptoms in IEDCS the studies lack sufficient detail to understand if this is also the case in IEDCS. Review of patient reported outcomes vs vestibular laboratory testing outcomes showed that although around two thirds of patients have signs of vestibular dysfunction only one third report residual symptoms. This mismatch is felt to reflect central compensation which is a known phenomenon that occurs in peripheral vestibular disorders and involves processes including adaptation, sensory substitution and habituation to allow the brain to adjust to the abnormal and asymmetric vestibular function.[41]

Increasing age has been identified as a risk factor for decompression illness and risk of incomplete recovery[42] however no correlation was seen in this review. There was also no statistically significant correlation between depth of the incident dive or time of onset of symptoms and the chance of symptoms at discharge / follow-up.

Some relationship was seen between time to recompression and the chance of symptoms at follow-up (R^2 = 0.42,

$P = 0.007$). There is little consistency of published data on the effect of delay to recompression and long-term outcomes. Studies have shown that delayed recompression remains effective[43] however, it is widely accepted that immediate recompression results in better outcomes (as suggested by the 1976 Farmer paper).[22] There are likely several confounding variables affecting outcome for example use of first aid normobaric oxygen which was not detailed by any of the papers.

The number of recompression treatments had a significant relationship with the chance of symptoms at discharge ($R^2 = 0.82$, $P < 0.001$). As the standard practise is to repeat HBOT until symptoms resolve or plateau it correlates that those with residual symptoms were given more HBOT sessions and may have still been symptomatic at discharge (i.e., at plateau). There was no relationship to chance of symptoms at follow up ($R^2 = 0.26$, $P = 0.258$) which may be due to the smaller population size, or improvement of symptoms post-hyperbaric therapy (between discharge and follow-up).

WHAT MEASURES ARE BEING USED TO ASSESS AND MANAGE RESIDUAL SYMPTOMS IN DIVERS WITH IEDCS?

Only three sites used functional scoring systems / patient outcome measures as an objective measure of residual symptoms. The large range in follow up period makes it difficult to compare outcomes from recompression therapy.

Five of the articles mentioned use of vestibular rehabilitation but none detailed the specifics of the exercises used, duration, or compared used vs. not used. Meta-analysis has shown that vestibular rehabilitation is effective for unilateral peripheral vestibular dysfunction (moderate to strong evidence)[44] and literature reviews have detailed the exercises that can be used in these cases.[45]

The strong correlation between PFO and IEDCS has long been established[46,47] however, only 245/529 (46%) of divers underwent PFO screening. Some of this may be due to the diver not returning to diving or it was the diver's preference not to have the test, but it is important that PFO screening is explained to divers if they present with IEDCS as it will impact on their safety if considering returning to diving.

LIMITATIONS

There are several limitations in this systematic review. Firstly, only English-language studies were included, and grey literature was not utilised. Of the studies that were included there is likely to be a high risk of publication bias due to the nature of case reports / case series.

The absence of individual diver data in several of the large case series meant that they were unable to be included in analysis of factors influencing change of symptoms at discharge / follow-up. There was also often insufficient detail in how the divers were considered recovered / not recovered which resulted in incomplete or inconsistent reporting of outcomes across the included studies.

Conclusions

Overall, there was clear description of diver demographics, dive profiles, initial presenting symptoms and treatment given. However, there was scant detail regarding the assessment of severity of symptoms and how this changed following treatments. Very few centres used objective scoring systems or questionnaires to measure symptom burden. There appeared to be a divide between articles by ENT / neuro-otologists with detailed vestibular assessment and articles by hyperbaric / dive physicians with very basic clinical review of eye movement and gait. There was little mention of vestibular rehabilitation or discussion on how residual damage may impact returning to diving. Follow-up assessments revealed that whilst only 32% of divers reported residual symptoms, 69% had signs of either cochlear and / or vestibular dysfunction. A surprisingly low number of divers had PFO investigation despite the well documented link to IEDCS, it is unknown what proportion of these divers returned to diving.

RECOMMENDATIONS FOR PRACTICE OR POLICY

A standardised method of clinical assessment by hyperbaric physicians should be considered for divers with IEDCS. Although this needs further development and research, one suggested initial approach would be: the head impulse test and assessment of nystagmus with / without Frenzel's glasses, a stopwatch timed Sharpened Romberg's test (best of three with consistency of preferred leading leg), and the dynamic gait index.[48] There is currently no appropriate validated questionnaire to provide an objective measure of symptom burden in both the acute and chronic stages of IEDCS and this should be an area of focus for future research.

Alongside this, a standardised follow-up period should be considered to allow for assessment of residual vestibular dysfunction/symptoms and discussion regarding risks involved in returning to diving. Current DMAC guidance advises a three month period without diving following IEDCS and this would be an optimum time point for this assessment.[49]

Vestibular rehabilitation (or referral to this service) should be considered at first presentation to optimise symptom recovery. All presenting divers should be counselled on the link between IEDCS and PFO and should be advised to have screening if they intend to return to diving.

RECOMMENDATIONS FOR RESEARCH

Further research to establish a standardised method of assessment of residual vestibular deficit / symptom burden pre-treatment, post-treatment and at a set follow up periods would allow for a better understanding of the time course of recovery, efficacy of hyperbaric treatment and the effects of delay to recompression and number of hyperbaric treatments. Despite detailed vestibular laboratory assessments have been undertaken in some of the IEDCS cohort, results have not provided an understanding of the mechanism of injury i.e., which parts of the vestibular system are affected and how functionality changes over time. Lastly, vestibular rehabilitation is underutilised and there is little understanding on its efficacy in divers with IEDCS; it could theoretically provide adjunctive therapy to promote recovery of vestibular impairment or adaptation to a persistent ipsilateral lesion.

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