Review article

Inner ear barotrauma in divers: an evidence-based tool for evaluation and treatment

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Key words
Hearing loss, sudden; ENT; Decompression sickness; Systematic review

Abstract
(Rozycki SW, Brown MJ, Camacho M. Inner ear barotrauma in divers: an evidence-based tool for evaluation and treatment. Diving and Hyperbaric Medicine. 2018 September;48(3):186–193. doi: 10.28920/dhm48.3.186-193. PMID: 30199891.)
Objective: To systematically search the literature for studies evaluating the typical presentation and testing that is performed for divers with inner ear symptoms and then to create a tool for clinicians when evaluating a diver with inner ear symptoms.
Methods: Nine databases, including PubMed/MEDLINE were systematically searched through 31 January 2018. The PRISMA statement was followed.
Results: Three-hundred and two manuscripts were screened, 69 were downloaded and 21 met criteria to be included in this review. The articles were evaluated for symptomatic trends and initial evaluation work-up primarily focusing on inner-ear barotrauma (IEBt) and inner ear decompression sickness (inner ear DCS). The trends for IEBt were compared to typical inner ear DCS presentation based on large study inner ear DCS results consistent with the plethora of research available. Finally, the HOOYAH Tool was developed to assist the receiving provider to better determine the most likely diagnosis and thus initiate appropriate treatment. The HOOYAH Tool is comprised of the following: 1) H: hard to clear; 2) O: onset of symptoms; 3) O: otoscopic exam; 4) Y: your dive profile; 5) A: additional symptoms and 6) H: hearing. For each of these components, the typical presentation is described allowing the provider better to discern the correct diagnosis.
Conclusion: The diagnosis of IEBt remains difficult to define short of visualization through surgical exploration. Early treatment is defined by conservative management with a subsequent observational period to determine symptomatic resolution and need for surgery. However, a similar differential diagnosis is inner ear DCS which requires early recompression. The HOOYAH tool provides a method for assisting the provider in forming a more confident decision regarding the underlying pathology and facilitation of the appropriate treatment.

Introduction

For underwater divers, whether novice or experienced, there are many risks assumed whenever a new dive is planned. Amongst these risks, there are the ever-present spectra of decompression illness and barotrauma. This article focuses on the intersection of these two processes in inner ear barotrauma (IEBt) and inner ear decompression sickness (inner ear DCS).

The inner ear is a complex system encased within the bony labyrinth consisting of two major functional parts; the vestibular apparatus concerned with balance and the cochlea dedicated to hearing, converting sound waves into electrical impulses passed to the brain. The cochlea is composed of three main divisions called scala within the bony labyrinth, the scala vestibuli most superior, scala media in the middle, and the scala tympani most inferior. These scala are separated by membranes, Reissner's membrane between the scala vestibuli and media and the basilar membrane between scala media and tympani. The scala vestibuli and tympani are filled with a fluid called perilymph and scala media with a similar fluid called endolymph. Although very similar, these fluids are unique in their ionic compositions, which is important since the Organ of Corti, which is where sound waves are converted to electrochemical impulses, is located in the *scala media* on the basilar membrane and is bathed in endolymph.

The pressure of the stapes bone in the middle ear moving in and out as it vibrates causes pressure waves within the perilymph fluid. These waves travel through the perilymph, pass to the endolymph and into the Organ of Corti where they are transformed into nerve impulses sent to the brain along the vestibulocochlear nerve. This is a fragile system, with any break of the basilar membrane causing disruption of the Organ of Corti and consequential hearing loss; and disruption of Reissner's membrane causing mixing of endolymph and perilymph with similar outcomes. At the base of the cochlea, inferior to the oval window in the vestibule of the membranous labyrinth sits the round window, which compensates for the pressure changes in the fluid by flexing in and out in time with the fluid waves to prevent damage to the sensitive membranes. This places the round window, as well as the oval window at risk of barotrauma with sudden changes in pressure.

There are two main ways the inner ear can experience barotrauma, through explosive or implosive means. As a diver descends, the tympanic membrane (TM) will be pressed medially as the external pressure increases. This will in turn press the stapes into the oval window causing increased pressure in the cochlea and bulging of the round window. At a pressure differential of > 90 mmHg (12 kPa) the Eustachian tube will 'lock' closed preventing a successful Valsalva.[1] As the diver feels increased pressure, an attempt will be made to equalize, and when this is unsuccessful the diver will often resort to repeated increasingly forceful Valsalva manoeuvres which increase intracranial pressure. This is transmitted through the perilymphatic duct to the cochlea, further increasing the pressure in the cochlea, which can cause a rupture of the round window or annular ligament. In cats, a pressure as low as 13.6 cm H_2O can rupture the round window.[2]

The rupture caused by an increase in perilymphatic fluid pressure is termed an explosive rupture. On the other hand, rupture caused by a decrease in perilymph fluid pressure is an implosive rupture. This occurs with a sudden increase in middle ear pressure after a forceful Valsalva that is successful in opening the Eustachian tube. With the sudden increase in size of the middle ear, the TM expands rapidly outwards, pulling the bones of the ear with it, and with the bones, so too the oval window through the attachment of the annular ligament creating low pressure in the cochlea. This can cause a tear of the oval or round window due to the velocity of change. It is also reasonable to imagine these forces can have the added effect of rupturing an internal membrane of the cochlea, Reissner's or basilar membrane. Only small pressure differentials are required to rupture the membrane causing mixing of endolymph and perilymph,[3,4] and these values are reached with a round or oval window rupture.

Inner ear DCS is less well understood, but is thought to be brought about by one of two mechanisms, or some combination of the two. Firstly, autochthonous bubble formation may occur in the endolymphatic and perilymphatic spaces due to local supersaturation of inert gas, with the vestibular apparatus more at risk than the cochlea as it has lower arterial perfusion and slower inert gas washout.[5] Secondly, it is thought a bubble from the venous circulation travels through a right-to-left shunt and lodges in the labyrinthine artery which supplies the vestibular apparatus and cochlea.[6]

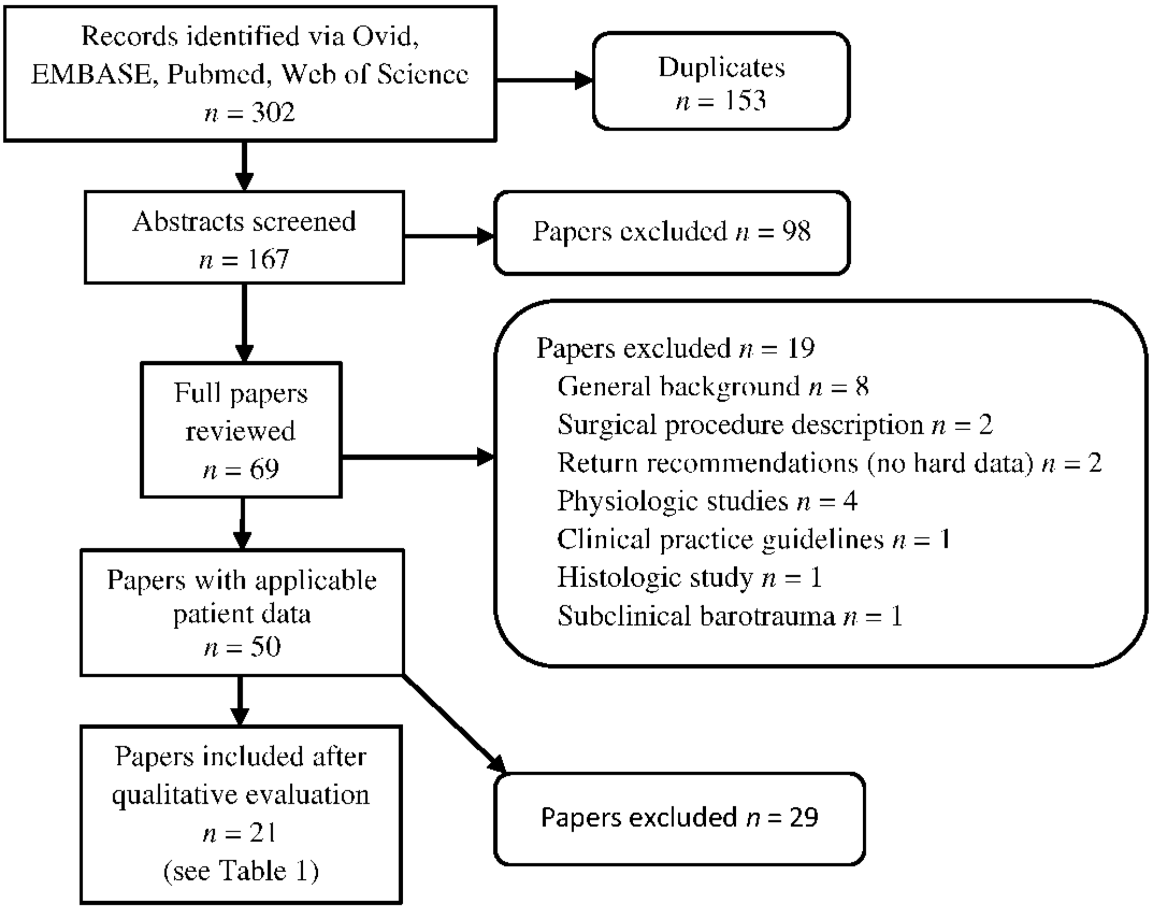
As both injuries affect the inner ear, both inner ear DCS and IEBt can present with similar symptoms of hearing loss and tinnitus (cochlear symptoms), as well as nausea, vertigo, and nystagmus (vestibular symptoms). This leads to difficulty distinguishing between the two diagnoses potentially delaying appropriate treatment. IEBt often requires surgical management if symptoms fail to improve with conservative treatment, with some recommendations including an observational period of up to 10 days from the known acute injury.[7] Contrarily, the gold standard treatment for inner ear DCS is early recompression with oxygen (HBOT), ideally initiated within six hours from injury.[8] Delayed treatment beyond this results in some degree of permanent inner ear damage in 90% of casualties.[9] Permanent damage has been reported even when treatment is started one hour after the known injury occurred.[10] Therefore, it is crucial that providers have an awareness of the typical presentations of both IEBt and inner ear DCS so that the appropriate treatment is initiated in a timely fashion. This paper explores the current literature to evaluate the typical presentation and testing in an attempt to create a tool for clinicians to utilize when evaluating a diver with inner ear symptoms, thus facilitating the most appropriate and prompt treatment.

Methods

Two authors (SWR, MJB) independently searched the international literature – in all languages – from the inception of each database through 31 January 2018. The databases that were systematically searched included PubMed, Ovid MEDLINE, EMBASE, and Web of Science. An example of a search strategy for Ovid MEDLINE is: 'Inner ear barotrauma', 'diving', 'middle ear', 'inner ear', 'barotrauma', and 'inner ear decompression illness'. Results included a total of 320 papers with 153 duplicates identified through Prepostseo plagiarism/duplication identification software (https://www.prepostseo.com/plagiarism-checker) leaving a total of 167 unique papers for evaluation. The remaining titles and abstracts were then personally reviewed by SWR and MJB to determine possible relevance to the diagnosis and treatment of IEBt and inner ear DCS. Reasons for exclusion included: only addressed middle ear barotrauma; focus on anatomy outside of the ear; focus on alternate pathology associated with diving (e.g., facial nerve baroparesis, hypothermia, alternobaric vertigo); foreign language, unable to access full text of paper. In total, 69 papers were identified as pertinent and the full text was reviewed for inclusion in the study (Figure 1). Additionally, a manual search was completed of texts of diving medicine that address IEBt and inner ear DCS including lecture and workshop material from the US Navy Diving and Salvage Training Centre.

Of the 69 full papers reviewed, 19 were determined to be outside the scope of this paper (Figure 1). The 50 papers identified as germane to the topics at hand were taken, and the reported patient data were compiled and examined for general trends. Those 50 papers were then examined (by

Figure 1
Flow chart for study selection; *n* – number of studies



SWR and MJB) for quality of evaluation, study design and comprehensive scope of evaluation. This resulted in 21 primary studies for analysis according to the quality assessment of cases series studies checklist from the National Institute for Health and Clinical Excellence (NICE; https://www.nice.org.uk) (Table 1).

1. Was the case series collected in more than one centre, i.e., multi-centre study?
2. Is the hypothesis/aim/objective of the study clearly described?
3. Are the inclusion and exclusion criteria (case definition) clearly reported?
4. Is there a clear definition of the outcomes reported?
5. Were data collected prospectively?
6. Is there an explicit statement that patients were recruited consecutively?
7. Are the main findings of the study clearly described?
8. Are outcomes stratified? (e.g., by abnormal results, disease stage, patient characteristics)?

The articles selected were evaluated for symptomatic trends and initial evaluation work-up primarily focusing on IEBt. These trends for IEBt were compared to typical inner ear DCS presentation based on large study inner ear DCS results that are consistent with the plethora of research available. Finally, a tool (HOOYAH) was created to assist the receiving provider to better determine the most likely diagnosis.

Results and discussion

TINNITUS

Tinnitus was reported as a symptom of IEBt in 21 of the full-length articles. Of the articles that specifically delineated patients with tinnitus symptoms, it was found that tinnitus was present in 187/256 (73%) of the patients with diagnosed IEBt, with findings ranging from 30%–81%. There were small studies that had 100% of patients reporting tinnitus, however, these sample sizes are too small to be of statistical significance. Resolution of the tinnitus after IEBt appears to be fairly impressive. Only two studies tracked follow-up of the symptoms, with tinnitus resolving in all patients in one, and in the other, tinnitus completely resolved in 15/19 patients who required surgical repair.[11] One study differentiated between perilymphatic fistula (PLF), inner ear hemorrhage (IEH) and intracochlear membrane tear (ICMT), but there was no significant difference in the prevalence of tinnitus between the different locations of injury.[12]

Table 1
General characteristics and quality criteria of included studies; quality assessment of cases series studies checklist from National Institute for Health and Clinical Excellence (NICE) (see text for details of the eight questions in the checklist)

First author Study design	Country	Evidence level	Outcomes analyzed	1	2	3	4	5	6	7	8
Shupak[1] Case series	Israel	4	Nystagmus, audiometry, CT	N	Y	Y	Y	N	N	Y	N
Klingmann[5] Case series	Germany	4	Symptoms, timing of symptoms and association with right-to-left shunt	N	Y	Y	Y	N	N	Y	N
Nachum[8] Case series	Israel	4	Vestibular symptoms, cochlear symptoms, residual symptoms post treatment	N	Y	Y	Y	N	N	Y	N
Shupak[9] Case series	Israel	4	Clinical symptoms, Nystagmus, ENG, Audiometry	N	Y	Y	Y	Y	N	Y	N
Healy[11] Systematic review Case series	USA	4	Nystagmus, Romberg and fistula tests, hearing loss	Y	Y	N	Y	N	N	Y	N
Parell[12] Case series	USA	4	Audiogram, vestibular symptoms, worsening tinnitus after return to diving	Y	Y	Y	Y	N	N	Y	Y
Roydhouse[13] Prospective observational	New Zealand	4	Hearing loss, balance, tinnitus pre and post op	N	Y	N	Y	Y	N	Y	N
Edmonds[14] Case series	Australia	4	Audiogram, ENG, tinnitus	N	Y	Y	Y	N	N	Y	N
Cantais[15] Case series	France, USA	3	Association of DCS symptoms and right-to-left shunt	Y	Y	Y	Y	N	N	Y	Y
Goplen[16] Prospective longitudinal	Norway	3	Audiometry	N	Y	Y	Y	Y	N	Y	Y
Podoshin[17] Case series	Israel	4	CT, ENG, fistula test, audiometry	N	Y	Y	Y	N	Y	Y	N
Klingmann[18] Cross-sectional controlled	Germany	3	Audiometry	Y	Y	Y	Y	N	N	Y	Y
Zulkaflay[19] Cross-sectional	Malaysia	3	Hearing loss, age	N	Y	Y	Y	Y	N	Y	Y
Vartiainen[20] Retrospective series	Finland	4	Fistula test, audiogram, ENG	N	Y	Y	Y	N	N	Y	Y
Taylor[21] Cross-sectional, descriptive survey	Australia, USA	4	History of "*squeezes*", membrane rupture, hearing loss, tinnitus, balance	Y	Y	Y	Y	N	N	Y	N
Freeman[22] Case series	Australia	4	Audiogram	Y	Y	Y	Y	N	N	Y	N
Lo[23] Case report	Taiwan	4	Clinical symptoms, surgical outcome	N	Y	N	Y	N	N	Y	N
Duplessis[24] Observational, cohort	USA	3	Otoacoustic emission test for transient emission shift	N	Y	N	Y	Y	N	Y	N
Gempp[25] Case series	France	4	Dive profile, clinical symptoms, presence of right-to-left shunt	N	Y	Y	Y	N	N	Y	N
Smerz[26] Case series	USA	4	Epidemiology associated with inner-ear DCI	N	Y	Y	Y	N	N	Y	N
Livingstone[27] Systematic review of case series	Multiple papers	4	Pathophysiology, diagnosis and treatment of otologic complications	Y	Y	Y	N	N	N	Y	N

VERTIGO

Vertigo was reported in 28 of the reviewed articles. Overall prevalence of symptomatic vertigo in patients with IEBT was found to be 71/156 (46%), with findings ranging from 28–77%. One study of 1,110 cases of diving-related otologic complaints found vertigo in 203 cases (18%); however, the paper did not specify if all of these cases were IEBt versus other causes of diving-related vertigo (e.g., caloric vertigo alternobaric vertigo or inner ear DCS).[13] Not surprisingly, the study that delineated between anatomic variations of IEBt found differing incidences of vertigo: 4/4 PLF; 3/10 IEH and 3/10 with ICMT.[12] This is expected, given the more isolated injury in IEH and ICMT that is more typically associated with isolated hearing loss/tinnitus. Symptomatic response to treatment was also very successful. In 50 Australian cases of IEBt, 16 reported vertigo, and all improved over the span of weeks-to-months with conservative treatment only.[14] Conservative management was by far more utilized than surgical intervention; even so, surgery carried a dramatic immediate improvement with 12/13 cases showing immediate post-surgical improvement in vertigo, primarily when PLF was identified or suspected and subsequently patched.

MIDDLE EAR BAROTRAUMA (MEBt)

It is commonly thought of that inner ear barotrauma is associated with MEBt.[28] However, in the studies evaluated, only three discussed MEBt to any extent. In one study, 26/50 divers with IEBt had concomitant MEBt.[14] However, in 150 randomly selected occupational divers studied for chronic audiological complaints, 40 (27%) had a history of MEBt, but there were no reported cases of IEBt. Similarly, in 67 occupational divers over a span of more than 27,000 dives, there were no cases of IEBt, further demonstrating the low prevalence of this injury.[16] A chronic threshold shift was not associated with a history of MEBt.[16] Therefore, whilst it can be concluded that there is a relatively high incidence of MEBt when a diver presents with IEBt, MEBt is often isolated and does not necessarily have any connection with inner ear damage whether in the initial case or after a repeated history of MEBt. Therefore, providers, particularly on the dive-site or initial receiving providers (emergency room, primary care, etc.), should avoid treatment modalities used for IEBt (e.g., steroids, bed rest, etc.) if only isolated MEBt is suspected.

ELECTRONYSTAGMOGRAPHY

Electronystagmography (ENG) can be utilized to better localize the site of pathology for vertigo (e.g., central or peripheral), and can be executed in the hospital setting to better quantify the severity of the reported vestibular symptoms. The variety and complexity of the tests are beyond the scope of this paper, however, the utility is important to discuss. In the retrospective study of 50 divers with IEBt, the reported symptoms were verified with pure tone audiometry (PTA) and/or ENG.[14] Another study of 53 suspected cases of PLF found that ENG had a sensitivity and specificity of about 77%. It is important to note that those cases were restricted to only those suspected to be PLF, which is only one subset of IEBt, as previously discussed.[17] However, when considering more global IEBt, the ENG revealed pathology in only four of 50 divers when there were no subjective complaints.[14] The body's adaptive and restorative capabilities are displayed in this study as all vestibular symptoms resolved over weeks-to-months, and the only evidence of persistent vestibular pathology was on repeat ENG testing.

HEARING LOSS

Hearing loss is extremely important for US Navy Divers. Divers are monitored closely with annual audiograms in order to identify any possible development of disabilities. Historically, it has been suspected that occupational divers have a higher rate of hearing loss than the general public. Whilst this may be true, the underlying cause is always in question: Is it due to repeated exposure to pressure, or isolated incidents of trauma? In a study of 60 divers of all ages, no statistically significant difference in hearing threshold was found between divers and non-divers.[18] This study specifically excluded divers with a history of IEBt or inner ear DCS, suggesting that non-acute exacerbations do not increase hearing loss.[18] This was further clarified in another study which found that chronic hearing loss in divers was likely due to a single event (e.g., IEBt or inner ear DCS) rather than chronic exposures to higher atmospheric pressure.[19]

Adding to this, hearing loss was the most common symptom reported for cases of IEBt. Of the studies evaluated, 16 discussed hearing loss and, of the aggregate, 228/253 (90%) of patients presented with hearing loss. As mentioned above, hearing loss was the most prevalent symptom noted more so than vestibular complaints. One large study found that all patients with vertigo reported hearing loss, whereas hearing loss was commonly reported as an isolated symptom, with vertigo almost never an isolated symptom in the acute phase.[13] This is intuitive when considering the various anatomic locations where IEBt can occur (IEH, ICMT, and PLF), seeing as how IEH and ICMT are more likely to be associated with hearing loss and having no effect on the vestibular system.[12]

Based on the available studies, recovery of hearing loss is inconsistent. Of 50 divers with IEBt, cochlear symptoms resolved within hours/months, whereas recovery of hearing loss occurred in less than two-thirds of the divers.[14] In a study primarily focusing on PLF, 44/51 patients receiving surgical correction did not have hearing improvement > 20 dB; surgery was considered to be an unsuccessful intervention for hearing loss.[20] Divers with chronic hearing

Table 2

In analyzing presenting symptom trends, diver history, and various tests available to the clinician, the authors have created a tool to provide insight into the aetiology of a diver with inner ear symptoms: the HOOYAH criteria. * N.B. It is essential that patients undergo a full otologic exam to include otoscopic, tuning fork and bedside vestibular testing (e.g., head impulse test). While these tests will provide insight into the type of hearing loss and/or vestibular patterns, potentially identifying conductive versus sensorineural hearing loss, there was no evidence to suggest improved ability to differentiate between inner-ear decompression sickness and inner-ear barotrauma; therefore, these are not included in the following criteria

	HOOYAH criteria	Typical in IEBt	Typical in inner ear DCS
H	Hard to clear	Present on descent or ascent; forceful Valsalva	Difficulty clearing not associated with inner ear DCS
O	Onset of symptoms	May occur on descent, ascent or on surface after diving	May occur on ascent (technical diving) or on surface after diving
O	Otoscopic examination	Association with MEBt	Normal otoscopic exam
Y	Your dive profile	Profile with no/low risk of DCS; fast ascent or descent	Decompression diving; missed decompression stops; repetitive dives; any dive profile with risks for DCS
A	Additional symptoms	Isolated inner ear	Association with other DCS symptoms
H	Hearing	Very common; high frequency loss; fluctuating hearing loss	Vestibular symptoms more common; often right-sided symptoms

loss had a history of MEBt or recurrent middle ear squeezes, and it was postulated by these authors that these patients likely had some previously undiagnosed IEBt which caused the residual deficits.[21] The studies focusing on recovery primarily involved patients with PLF, which is the most extreme variation of IEBt; therefore, it is not unexpected that they carry a higher incidence of chronic disability.

PURE TONE AUDIOMETRY (PTA)

Utilizing audiometry is difficult in these patients because of the non-specific nature of the tests. However, PTA is essential in the diagnosis of IEBt, and is recommended universally. The pattern of hearing loss is variable, with a large majority showing flat or down-sloping audiograms of varying severity and/or high frequency loss,[22] but also isolated of cases of low frequency loss.[12] These isolated low frequency losses may be secondary to a localized IEH or possibly ICMT. It is also important to note that given the mechanism of injury and the correlation of possible MEBt, that a diver may present with a mixed hearing loss pattern.[23] Acknowledging this is doubly important when considering that patients may be suspected to have only MEBt, but a sensorineural hearing loss (SNHL) also needs to be considered in order to facilitate appropriate care (e.g., in combined MEBt and IEBt conservative treatment would include steroid therapy and bed-rest.)

Based on the research analyzed, PTA was the best and most readily available audiometric test to facilitate in the diagnosis and observation of IEBt. Alternate audiometric tests have been studied, including otoacoustic emissions (OAE) testing.[24] This study investigated the potential of OAE to identify clinical and subclinical IEBt (defined as a transient emission shift without an accompanying transient threshold shift on PTA). OAE testing identified significant transient emissions shift in an intense repetitive diving protocol, supporting the theory that clinical and subclinical IEBt can lead to chronic SNHL.[19] Based on these results, while not evaluated in the acute setting, it was postulated that OAE can be used for medical surveillance and support early intervention.

COMPARISON TO INNER EAR DCS

There are some important differences from IEBt presentation in dive casualties with suspected inner ear DCS. Typically, symptomatic onset for inner ear DCS presents soon after a dive. Six different studies consisting of 138 dive casualties found that the average onset of symptoms was around 36 minutes after surfacing (range 13–206 minutes).[5,8–10,25–27] There are documented cases of symptom onset while on ascent from a dive, but these are far less common.[10] However, in review of all of the articles related to IEBt, there was no identifiable trend, even within individual studies, regarding timing of symptom onset: IEBt symptoms are likely to present themselves on either descent, ascent or soon after surfacing.

In contrast to IEBt, where the large majority of cases present with cochlear symptoms, inner ear DCS casualties have a preponderance of vestibular symptoms. One retrospective study found that patients presented with a pure vestibular disorder in up to 75% of cases, with only 6% having isolated cochlear symptoms, whilst combined cochleovestibular symptoms occurred in 17.5%.[25] Other reviews have found higher rates of cochlear symptoms, although far less than that observed in IEBt.[8,26,28] This could be explained by the comparatively lower perfusion and slower inert gas washout in the vestibular apparatus leading to increased risk for DCS symptoms in the vestibular apparatus. Stated simply, the vestibular apparatus has a higher tissue volume to blood supply ratio in comparison to the cochlea, leading to higher rates of local supersaturation and arterial microbubble load.[5] Interestingly, one study of 115 cases of inner ear DCS found that symptoms lateralizing to the right in 72% of cases.[8]

It is important for the clinician to understand that inner ear DCS can occur in isolation, or in conjunction with other DCS symptoms. A key indicator of likely inner ear DCS versus IEBt would be the presence of such DCS-related symptoms. However, the evidence is not straight forward. Whilst previous studies found that 24–34% of divers with DCS reported cochleovestibular symptoms,[8,15] a more recent study found only 17% of inner ear DCS patients had other DCS-related symptoms.[5] These findings indicate inner ear DCS to be a discrete pathological process that commonly presents in isolation, but may also appear with a constellation of other DCS symptoms. Therefore, it is important that in any divers with inner-ear symptoms a thorough, full history and examination be undertaken in order to establish the most likely diagnosis. By better understanding the variations in presentation based on past research, the HOOYAH criteria was developed as a way to assist forming a more confident decision regarding the underlying pathology and facilitation of the appropriate treatment (Table 2).

Should a scenario arise where there is a concern for an injury involving both inner ear DCS and IEBt, we recommend that bilateral tympanotomies be performed prior to initiating HBOT, similar to the scenario where there is concern for the patient's ability to equalize. We do not recommend tube placement initially prior to pressurisation as simple tympanotomies should suffice for acute hyperbaric management. Tube insertion would require more specialized providers and equipment that would delay treatment. If the patient needs additional HBOT, then insertion of tympanostomy tubes may be coordinated on a less emergent basis.

Conclusions

The diagnosis of IEBt remains difficult to define short of visualization through surgical exploration. Early treatment is defined by conservative management with a subsequent observational period to determine symptomatic resolution and any need for surgery. However, a similar differential diagnosis is inner ear DCS which requires early recompression. The HOOYAH tool provides a method for assisting the provider in forming a more confident decision regarding the underlying pathology and facilitation of appropriate treatment.

References

1 Shupak A, Doweck I, Greenberg E, Gordon CR, Spitzer O, Melamed Y, et al. Diving-related inner ear injuries. Laryngoscope. 1991;101:173–9. Epub 1991/02/01. doi: 10.1288/00005537-199102000-00013. PMID: 1992269.
2 Miriszlai E, Sandor P. Investigations on the critical perilymphatic pressure value causing round window membrane rupture in anesthetized cats. Acta Otolaryngol. 1980;89:323–9. Epub 1980/03/01. PMID: 7395501.
3 Simmons FB, Mongeon CJ. Endolymphatic duct pressure produces cochlear damage. Arch Otolaryngol. 1967;85:143–50. Epub 1967/02/01. PMID: 6017586.
4 Simmons FB. The double-membrane break syndrome in sudden hearing loss. Laryngoscope. 1979;89:59–66. Epub 1979/01/01. doi: 10.1288/00005537-197901000-00006. PMID: 423653.
5 Klingmann C. Inner ear decompression sickness in compressed-air diving. Undersea Hyperb Med. 2012;39:589–94. Epub 2012/03/10. PMID: 22400449.
6 Money KE, Buckingham IP, Calder IM, Johnson WH, King JD, Landolt JP, et al. Damage to the middle ear and the inner ear in underwater divers. Undersea Biomed Res. 1985;12:77–84. PMID: 4035820.
7 Elliott EJ, Smart DR. The assessment and management of inner ear barotrauma in divers and recommendations for returning to diving. Diving Hyperbaric Med. 2014;44:208–22. PMID: 25596834.
8 Nachum Z, Shupak A, Spitzer O, Sharoni Z, Doweck I, Gordon CR. Inner ear decompression sickness in sport compressed-air diving. Laryngoscope. 2001;111:851–6. Epub 2001/05/19. doi: 10.1097/00005537-200105000-00018. PMID: 11359165.
9 Shupak A, Gil A, Nachum Z, Miller S, Gordon CR, Tal D. Inner ear decompression sickness and inner ear barotrauma in recreational divers: a long-term follow-up. Laryngoscope. 2003;113:2141–7. Epub 2003/12/09. doi: 10.1097/00005537-200312000-00017. PMID: 14660917.
10 Farmer JC, Thomas WG, Youngblood DG, Bennett PB. Inner ear decompression sickness. Laryngoscope. 1976;86:1315–27. Epub 1976/09/01. doi: 10.1288/00005537-197609000-00003. PMID: 957843.
11 Healy GB, Strong M, Sampogna D. Ataxia, vertigo, and hearing loss: A result of rupture of inner ear window. Arch Otolaryngol. 1974;100:130–5. doi: 10.1001/archotol.1974.00780040136010.
12 Parell GJ, Becker GD. Inner ear barotrauma in scuba divers. A long-term follow-up after continued diving. Arch Otolaryngol Head Neck Surg. 1993;119:455–7. Epub 1993/04/01. PMID: 8457309.
13 Roydhouse N. Round window membrane rupture in scuba divers. SPUMS Journal. 1997;27:148–51.
14 Edmonds C. Inner ear barotrauma: A retrospective clinical series of 50 cases. SPUMS Journal. 2004;34:11–9.
15 Hexdall E. Barotrauma: The ins and outs of the pops and cracks. [cited 2017 May 16]. Available from: https://www.diveassure.com/wp-content/uploads/2015/05/Barotrauma-The-Ins-and-Outs-of-the-Pops-and-Cracks-Eric-Hexdall-RN-CHRN-Duke-Dive-Medicine.pdf.
16 Goplen FK, Aasen T, Grønning M, Molvær OI, Nordahl SH.

Hearing loss in divers: a 6-year prospective study. Eur Arch Otorhinolaryngol. 2011;268:979–85. PMID: 21246211.
17 Podoshin L, Fradis M, Ben-David J, Berger SI, Feiglin H. Perilymphatic fistula - the value of diagnostic tests. J Laryngol Otol. 1994;108:560–3. PMID: 7930889.
18 Klingmann C, Knauth M, Ries S, Tasman A-J. Hearing threshold in sport divers: is diving really a hazard for inner ear function? Arch Otolaryngol Head Neck Surg. 2004;130:221–5. PMID: 14967755.
19 Zulkaflay A, Saim L, Said H, Mukari S, Esa R. Hearing loss in diving - a study amongst Navy divers. Med J Malaysia. 1996;51:103–8. PMID: 10967988.
20 Vartiainen E, Nuutinen J, Karjalainen S, Nykänfn K. Perilymph fistula - a diagnostic dilemma. J Laryngol Otol. 1991;105:270–3. PMID: 2026938.
21 Taylor DM, O'Toole KS, Ryan CM. Experienced scuba divers in Australia and the United States suffer considerable injury and morbidity. Wilderness Environ Med. 2003;14:83–8. PMID: 12825881.
22 Freeman P, Edmonds C. Inner ear barotrauma. Arch Otolaryngol. 1972;95:556–63. Epub 1972/06/01. PMID: 4666425.
23 Lo S-H, Huang Y-C, Wang P-C. Pneumolabyrinth associated with perilymph fistula. Chang Gung Med J. 2003;26:690–4. PMID: 14651168.
24 Duplessis C, Fothergill D. Exploiting otoacoustic emission testing to identify clinical and subclinical inner ear barotrauma in divers: potential risk factor for sensorineural hearing loss. J Otolaryngol Head Neck Surg. 2009;38:67–76. PMID: 19344615.
25 Gempp E, Louge P. Inner ear decompression sickness in scuba divers: a review of 115 cases. Eur Arch Otorhinolaryngol. 2013;270:1831–7. PMID: 23100085.
26 Smerz RW. A descriptive epidemiological analysis of isolated inner ear decompression illness in recreational divers in Hawaii. Diving Hyperb Med. 2007;37:2-9.
27 Cantais E, Louge P, Suppini A, Foster PP, Palmier B. Right-to-left shunt and risk of decompression illness with cochleovestibular and cerebral symptoms in divers: case control study in 101 consecutive dive accidents. Crit Care Med. 2003;31:84–8. PMID: 12544998.
28 Livingstone DM, Smith KA, Lange B. Scuba diving and otology: a systematic review with recommendations on diagnosis, treatment and post-operative care. Diving Hyperb Med. 2017;47:97–109. doi: 10.28920/dhm47.2.97-109. PMID: 28641322.

Funding and conflicts of interest: nil

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Submitted: 01 March 2018; revised 18 May and 23 July 2018
Accepted: 06 August 2018