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ORIGINAL ARTICLE

Auditory Complaints in Scuba Divers: an Overview

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Abstract Pre-1970s, diving was seen as a predominantly male working occupation. Since then it has become a popular hobby, with increasing access to SCUBA diving while on holiday. For a leisure activity, diving puts the auditory system at the risk of a wide variety of complaints. However, there is still insufficient consensus on the frequency of these conditions, which ultimately would require more attention from hearing-healthcare professionals. A literature search of epidemiology studies of eight auditory complaints was conducted, using both individual and large-scale diving studies, with some reference to large-scale non-diving populations. A higher incidence was found for middle ear barotrauma, eustachian tube dysfunction, and alternobaric vertigo with a high correlation among females. Comparing these findings with a non-diving population found no statistically significant difference for hearing loss or tinnitus. Increased awareness of health professionals is required, training, and implementation of the Frenzel technique would help resolve the ambiguities of the Valsalva technique underwater.

Keywords Diving medicine · Ear injuries · Barotrauma · SCUBA diving · Inner ear decompression sickness · Alternobaric vertigo · Frenzel technique

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Introduction

Over the last 40 years, recreational self-contained underwater breathing apparatus (SCUBA) diving as a leisure activity has increased in popularity. The ability to explore the ocean depths is an obvious attraction for many. In 1968, there were only 11,668 certifications of diving members of the worldwide organisation “Professional Association of Diving Instructors” (PADI). However by 2008, this number had increased dramatically to 17,532,116 members [1].

Although diving has become more accessible and the equipment is much safer now, diving still has its inherent dangers. Each year incidents occur, ranging from seasickness and sinus problems to heart conditions and mortality. Recent studies found that 80% of diving-related problems involve the head and neck region and the most common in recreational divers are those of the auditory system [2, 3]. The ear itself is a predominantly air-filled cavity, causing a number of complications when descending to increased hyperbaric pressures.

Due to the lack of dive training available to the public before the 1970s, many studies up until then could only address the effect on the auditory function of navy and technical divers [4]. Coles & Knight [5] conducted one of the first auditory investigations among navy divers, finding significant difference in hearing of the older divers and those who had also worked in gunnery. Studies from this period had difficulty in addressing the otological problems caused solely by diving, due to other contributing factors such as age-related deafness and noise exposure.

Recently in 2007, a study conducted by a German ear nose and throat (ENT) specialist Christoph Klingmann found over eight different auditory complaints and conditions among today’s recreational scuba divers attending his clinic. In the UK, no exact figure is specified for how many

PADI divers exist, however an extra 35,325 divers have recently been recorded by a separate organisation known as the British Sub-Aqua Club [6]. This raises the question of whether hearing health care professionals need to be more aware of these auditory complaints that are associated with diving. An epidemiological literature review of diver studies would help clarify this question. This will help address the causation, frequency, and testing required for diagnosing the conditions. Since training to undertake this sport may only take 4 days [7], awareness of the potential auditory problems encountered is an important issue that needs to be addressed. This article aims to provide an overview of the auditory complaints reported by scuba divers.

Search Strategy

A systematic literature search was conducted using various databases, including Medline, Pubmed, CINHAL, and Google Scholar. A search was also conducted at the resources of the diving disease research centre, the hyperbaric underwater society and the diver alert network research pages to locate studies. There was a focus on recreational diving studies, however if some auditory disorders were scarcely documented, studies of occupational divers were used as support. The search encompassed a large time range in order to uncover all of the pertinent early articles.

Auditory Complaints in SCUBA Divers

There are a variety of auditory problems reported by SCUBA divers that are related to both the outer and inner ear. The auditory injuries are usually acute in onset, however a small percentage of the population may report chronic disability such as hearing loss and tinnitus. The following section discusses some of the main complaints reported in published work.

Outer and Middle Ear Complaints of Divers

Otitis Externa

Otitis externa is a painful condition with symptoms of redness, swelling, itchiness, and occasionally discharge, that disrupts the healthy lining of the external auditory canal (EAC) [8]. Being in contact with water is a common factor, with otitis externa occurring five times more often in swimmers than non-swimmers [9]. Water exposure of any kind encourages extraneous flushing of the protective lining of the canal [10, 11]. This creates a perfect habitat for growth of bacteria such as *Pseudomonas aeruginosa* and *Staphylococcus aureus* [9]. Muth et al. [12] in their study observed that SCUBA divers are the most commonly affected by this condition especially in warmer climates. Specifically, saturation divers are a commonly affected category of working divers because they maintain little cerumen due to the constant flushing of the EAC, [10, 13, 14]. These divers spend days, sometimes weeks, underwater at a great depth, living within a helium-filled confined space to carry out study on a commercial or industrial basis. Being within such confines can establish a perfect environment for bacteria to develop, in warm constant temperature and humidity. Improvements to saturation divers' chamber hygiene has successfully reduced the risks of this in recent years, following the advice given by the Diving Medical Advisory Committee [15].

External Auditory Exostoses

SCUBA divers are at risk of exostoses because they cannot isolate their EAC from the surrounding cold water environment, due to the need for equalisation [16]. Due to the intruding nature of the exostoses, temporary hearing loss can be a concern and otitis externa can occur, besides water being trapped behind the protruding bony growths [17].

Table 1 summarises the extent to which this condition is present in SCUBA divers and many of the studies took place during the mid 1990s. Navy divers account for four out of five of the study populations described in Table 1 except for the study by Doherty & Sheard [20]. There is no ground for gender comparison due to this reason. There is a correlation between those who showed exostoses and a previous history of taking part in other water-based activities as well as diving [16]. However, two experienced divers showed exostoses but did not have a previous history of any other water-based activities, suggesting that diving alone may be a direct determinant of the condition.

The results found a higher incidence in the group in colder locations and a higher proportion of grade 2 exostoses. The unilateral exostoses found in the studies are unexplained.

Middle Ear Barotrauma

Barotrauma refers to "tissue damage resulting from an internal imbalance of physiological pressures within the body and pressure levels in the surrounding water" [21]. Specifically, 'middle ear barotrauma' (MEB) is due to an imbalance between the pressure within the middle ear cavity in comparison to the surrounding pressure outside the body. This may cause haemorrhaging and even rupture of the tympanic membrane (TM) with symptoms of pain and dizziness [10].

Table 1 Studies looking at exostoses in divers

Paper	Study design	Sample size	Average age and years of diving	Country of origin	Incidence and/or prevalence	Conclusions
Ohgaki et al. [18]	Cohort study	31 professional divers	NA	Japan	Incidence 12 of the divers (Over 40%)	Found no relationship between incidence of exostoses and length of divers' career
Karegeannes [16]	Cohort study	87 navy divers in comparison to 47 non-divers	Age = 29.5 Diving 8.5	USA	Incidence 23 (26%) of the divers and no controls	Relation found between diving career length and those undertaking aquatic activities for long periods of years
Ito & Ikeda [19]	Cohort study	97 military divers from 2 locations	Age = 34 Diving 11.5	Japan	$P = 54\%$	Supports findings that cold water encourages condition
Doherty & Sheard [20]	Cross sectional study	66 male, 35 female breath-hold divers	Age = M-32.8; F-30.8 Diving M18; F10	UK	$P = 89.7\%$	High prevalence due to underwater bursts similar to surfing, 0.6% increase per yr

Table 2 summarises studies on MEB in divers. The investigations of MEB have used a variety of study designs such as nine-step inflation/deflation technique [23, 25]. and the "Teed Classification" of MEB to assess severity [22]. Teed's classification refers to 0–5 grading of otological observation of the TM, from normal appearance to a perforation. The findings of Green et al. [22] showed a higher prevalence of otoscopy that did not correlate with tympanometry results, which may suggesting that normal 'middle ear pressure' (MEP) can be maintained even through MEB. However, a limitation of the MEB studies is that no audiometric testing was performed to support either tympanometry or otoscopy findings. The higher prevalence (90%) in those at beginner level presented changes of grade 3 or above in the classification, showing that the probability of this condition decreases with diving experience. Uzun [25] found nearly half of 31 divers presented symptoms of MEB 24 h after a dive.

Inner Ear Complaints of Divers

Sensorineural Hearing Loss

The strain caused by barotrauma can result in a temporary reduction of hearing thresholds [27]. Whether permanent hearing damage can be caused by continuous strains of hyperbaric pressure is still under question. Many studies investigated diving-induced hearing loss during the 1980s with samples of navy and military divers. A continuous follow-up of young occupational divers (average age 25), recently discovered decreased hearing thresholds in both ears for 4, 6, and 8 kHz, with 37% that were or until

Table 2 Studies looking at middle ear barotrauma (*MEB*) in divers

Paper	Study design	Country	Assessment	Sample & size	Disorder, frequency	Study conclusions
Green et al. [22]	Pilot study	USA	Multiple diving day otoscopy, tympanometry, Teed's classification	2 experienced scuba divers	23% otalgia 33% abnormal tymps 83% abnormal otoscopy by day 3	Long surface time intervals between multiple dives is important for MEB prevention
Uzun et al. [23]	Observational cohort study	Turkey	Toynbee/Vasalva/nine-step inflation technique within 24 h of diving	22 sports divers	N/A	The NSIDT is a valuable diagnostic measure for MEB
Uzun et al. [24]	Prospective Blinded	Turkey	Simplified rectangular dimension method	24 sports divers	MEB occurred in 11 divers (46%)	There is a relationship between the size of the mastoid pneumatisation
Uzun [25]	Prospective blinded	Turkey	Examined 24 h after diving	31 sports divers	MEB occurred in 14 (45%)	MEB tests should be performed as part of pre-dive examination
Ramos et al [26]	Observational study	Brazil	Four dives per day for 5 days audiology assessment + Teed's classification	19 recreational divers	MEB—71% otoscopic change noticed	Extending surface time may offer protection against MEB

recently had been daily smokers, an interesting factor for further research [28–30]. Due to noise being the most correlated factor for these hearing impairments, the studies were unable to provide a reliable representation of hearing diving-induced damage [31]. A cohort study by Hizel et al. [32] investigated hearing thresholds of recreational divers in comparison to controls. This study found no significant difference between groups using audiometry and otoacoustic emissions, although it was difficult to evaluate fully due to lacking hearing tests before commencing their diving careers. Another study by Klingmann et al. [33] tested a group of 60 divers and a control group of 63 outpatients and staff, in which otological history, audiometry, tympanometry, and stapidus reflexes were taken. The study found a slight difference with controls of 10 dB deterioration, without statistical significance.

Vertigo

Vertigo can be described as the hallucination of movement and/or the sensation that your surroundings are moving [34]. Diving conditions can interfere with the visual cues available, due to decreased visibility as well as the feeling of weightlessness that will cause a loss of proprioceptive input. Therefore, reliance on vestibular input is greatly increased underwater and any sudden encounter of vertigo will cause an increased safety risk to the diver [10].

Underwater, the diver's head position when descending and ascending is tilted at a 30-degree angle. This position is often used in vestibular testing as it stimulates the horizontal canal of the vestibular system (VS) [10]. A unilateral temperature or pressure input difference to one ear will cause stimulation to the VS by changing the density and temperature of the endolymph within the horizontal semi-circular canal (positioned near the TM). This endolymphatic change is similar to what occurs during head movement and since the information from the opposite ear does not agree, this results in vertigo. Moreover, rupturing of a TM underwater can stimulate the VS in a disabling manner through caloric irrigation causing hair-cell movement in the Crista, which leads to a 1 min sensation of nystagmus until the water warms up to body temperature [10]. If the ET restricts the release of air on ascent, any resultant MEB can cause vertigo through unequal MEP's, and dizziness can last between 3 s and 2 min and is known as "alternobaric vertigo" (AV) [35].

Table 3 summarises studies focusing on epidemiology of vertigo in divers. The prevalence of AV is ranging from 30 to 84% of vertigo cases. A common theme among those with AV can be previous middle ear dysfunctions, such as equalisation difficulties, barotrauma, otitis media, Eustachian Tube Dysfunction (ETD) or diving with a cold. The studies have used a wide range of audiometric and vestibular testing, including the sharpened Romberg test.

The factors of diving experience and gender apparently affect the risk of AV. With a ratio of 1:2.7, there has been a significantly larger incidence reported for AV in females than males. However as a previously male-dominated activity, it is difficult to compare the accuracy of these findings to previous studies available on AV, since females are rarer in older studies.

The statistically significant finding of $P < 0.001$ (8/17) for the number of divers with AV having equalisation problems indicates the correlation between the prevalence of equalisation difficulties and women, found in previous studies, which is apparently quite high [25]. The gender ratio in study by Klingmann et al. [35] could be a fair representation of divers, except that the retrospective aspect of the study relies solely on remembering the incidences.

Inner Ear Barotrauma

If a diver reports symptoms of sensorineural hearing loss, tinnitus, and vertigo with no sign of decompression sickness then inner ear barotrauma (IEB) should be suspected [21]. There is variance in the onset of symptoms and injuries can be attributed to the cochlear &/or the vestibular apparatus. IEB is predominantly a shallow water (<30 m) diving injury and can occur following MEB.

Two theories exist for how IEB develops, firstly it is thought that an increase in cerebrospinal fluid (CSF) transferred to the cochlea causes rupturing or dislocation of intra-cochlear membranes [39]. Alternatively, a more popular theory is of a round/oval window rupture of either an implosive or explosive nature, provoking a probable perilymph fistula. The rim of the oval window is said to be the weakest part of the cochlea, especially in divers with otosclerosis [40]. The implosive and explosive factors can be attributed to performing the Valsalva manoeuvre (which increases MEP) or when inadequate (negative) MEP is maintained on descent in relation to intralabyrinth pressure.

The decrease in pressure within the perilymphatic system and imbalance of electrolytes affect the neural elements of the hearing and VS, causing damage if not corrected. The leaking of perilymph may cause the initial hearing loss observed but immediate bed rest with head elevation will help replenish the perilymph, also restoring ionic gradients, and hearing in the frequencies that are not anatomically damaged [10]. Due to the displacement of perilymph, exerting pressure on the EAC should develop a nystagmus known as the "Hennerberg sign".

Although symptoms may diminish as adaptation occurs, there is the concern that the lesion can progress further towards the destruction of the VS, so VS testing is highly recommended [10]. Vestibular positional testing may demonstrate rotary nystagmus which is consistent with previous studies of perilymph fistula [41, 42]. Positional

Table 3 Studies looking at alternobaric vertigo

Paper	Sample size	Study design	Method	Country of origin	Prevalence: vertigo/total cases (%)	AV in vertigo cases	Study conclusions
Lundgren [36]	354 sports divers	Cross sectional postal study	Questionnaire sent to 550 club members	Sweden	92 (26)	28 (30%)	The frequency of AV proved statistically significant; need for further research
Molvaer & Albreksen [37]	193 professional divers	Retrospective cohort study	Interviewed, examined and auditory tested	Norway	76 (39)	64 (84%)	Contributing variables were found, such as history of BT and diving with cold
Kossowski et al. [38]	333 navy divers	Cross sectional study	Questionnaire to naval divers over 3 months	France	45 (13.5) 0.06 incidence	19 (42%)	Wide variety of causes of dizziness recorded, AV the most common
Klingmann et al. [35]	63 sports divers	Retrospective cohort study	Audiometry testing + MRI	Germany	17 (27)	Incidence 0.09–25% dives	Higher AV prevalence of women than men. Higher incidence of equalisation problems

audiometry may allow air to displace from the perilymph-leaking window, which may improve hearing by more than 10 dB at some frequencies. This involves the patient lying horizontally with the affected ear upwards for 30 min [10].

Few individual studies have investigated the epidemiology of IEB, however one report analysed 50 reported cases from 1970s and 1990s using an "EAR barotrauma protocol" in order to differentiate from MEB [43]. History taking revealed 88% had suffered MEB previously on descent, 80% suffered hearing loss, 86% suffered with tinnitus, 38% experienced vestibular problems and 6% had IEB before. This study sample represented the diving population with mixed-level divers, but surprisingly no divers reported they equalised before descending. This indicates training on equalisation techniques was poorly administered, it may be due to the period when the data was collected and local policies.

Inner Ear Decompression Sickness

On ascent to the surface from depths greater than 30 m, the diver must safely undertake decompression stops, remaining at each depth for a certain period in accordance with their regulatory diving table [44]. The risk of DCS is quantified using Henry's law:

> *At a given temperature the amount of gas that dissolves in a liquid with which it is in contact is proportional to the partial pressure of that gas*

[45]. Applied to diving, this means the body must be allowed to safely release the nitrogen gas that has dissolved to saturation point within the body's tissues. If a diver was to ascend too quickly, there would be too great a drop in ambient pressure than that required to keep the gas in solution. The gas would then begin to escape from body fluids too quickly, causing damaging bubbles to form in the tissues [46]. Symptoms such as joint pain, tingling in limbs or dizziness must be reported immediately and the diver would require a recompression chamber, which allows the diver to complete their decompression stops on land rather than underwater [44].

Ear problems due to DCS are treated with secondary importance in comparison to those of the central nervous system [47]. It is not widely recognised that inner ear disorders resulting from decompression sickness are a serious hazard in diving, although they are present in 26% of all severe DCS cases [48, 49]. When the concentration or solubility of a dissolved gas exceeds ambient pressure within the inner ear during ascent, this can develop into inner ear decompression sickness (IEDCS). Bubbles are known to form in the inner ear, although the exact location and circumstances where this occurs are unclear and usually only hypothesised [47]. Theories suggest formation within the micro-vessels and otic fluids or within the osteoclast cells of the inner ear bony lining, causing it to rupture due to pressure elevation, forcing it into the otic fluid spaces [10].

An animal experimental model of DCS using squirrel monkeys has been used to investigate the damage to the inner ear [48]. Monkeys were sorted into groups of varying severity of symptoms. The study found granulated precipitated material within all otic fluid spaces with rupturing of blood vessels along the semi-circular canals. In the group of monkeys showing only vestibular problems, new connective tissue and bone growth was found in damaged tissue areas contiguous to the bony walls of the semi-circular canals [48]. This may explain why the occurrence of vertigo alone in IEB was reported as only 10%, whereas in IEDCS it is seen more frequently [10].

A different possibility is suggested by the theory of super-saturation. Either counter-diffusion through round and oval windows causing IEDCS at the interface of middle and inner ear, or gas osmosis transfer of the fluid between endolymph (perfused with blood) and perilymph (saturated with gas) could result in vestibular damage [10]. Doolette & Mitchell [47] used a physiological compartmental model to investigate the diffusion of gases across the membranous labyrinth. The model was able to demonstrate super-saturation in the early stages of decompression with a diffusion time through the membrane of 8.8 min, allowing considerable super-saturation and bubble formation. A more recent study developed a similar model that also looked at the brain. It analysed the nitrogen release difference, finding a 1.2 min half time for the brain, concluding a comparative difference of an extra 7.5 min for the inner ear [50]. This demonstrates that the inner ear remains super-saturated with nitrogen longer than the brain once the diver has surfaced, causing higher residual damage.

The auditory symptoms of IEDCS can be difficult to differentiate from IEB, although being a subclass of DCS, only IEDCS may present other symptoms such as joint pain and numbness. The diver's history is also important, previous MEB or equalisation problems may indicate IEB and can occur on ascent or descent, whereas IEDCS only occurs on ascent and is more common after dives over 30 m deep, whereas IEB is more prevalent under 30 m. If any doubts arise, treating the diver for IEDCS is recommended, due to the higher severity of the condition [51]. The prevalence of IEDCS is generally unknown and has only been addressed in one study in Hawaii, where the condition was found in 29 of 1,376 patients' records of recreational divers (3% of all cases of DCS treated at a hyperbaric chamber). Hearing loss was stated at 13.6% and tinnitus at 20.6% in addition to vestibular symptoms, with also 34.4% still suffering from residual side-effects at the time of discharge. This study demonstrates that following the established decompression guidelines is essential; otherwise, IEDCS may cause permanent damage to the auditory system [52].

IEDCS is common in occupational divers due to the depths reached and transfer between mixtures of gases, which increases the risk of DCS. "Remote operated vehicles" ROV's can now undertake occupational duties at such depths to reduce the risk to employees.

Tinnitus

Tinnitus is a perception of spontaneous noises within the head or ears with no external source. Apparently generated within the individual's auditory pathway, its precise cause is unknown [54]. Although tinnitus is one of the symptoms that can be found in divers, little research specifically investigates tinnitus associated with diving, except for some examination of navy divers [53]. It is largely recognised as a referral symptom of both IEB and IEDCS. Among divers, the symptom is normally intertwined with hearing loss and vertigo. Tinnitus due to IEB or IEDCS is said to improve over a 6 to 12 month period, as damaged sensory endings within the cochlea either die or repair themselves [10].

Discussion and Conclusion

This review has highlighted a number of clinical points regarding diving. Firstly, although some auditory disorders are presented as uncommon, they may involve a great safety risk to the diver. Trying to cope with such symptoms as dizziness, nausea, vomiting, or excruciating pain whilst underwater can be very distressing and dangerous. Therefore encouraging and enforcing the right preventative methods will avoid a minor problem from growing into a larger more life-threatening one. It will help with disorders where prevalence is much higher, such as MEB and ETD. Longer surface duration between dives has shown a reduction in the risk of MEB. Also, simple advice on the correct equalisation techniques provided by the audiologist/clinician as well as the diving instructors during training will further empower the diver to use the information effectively. The frequency of divers at the Otolaryngology clinic in Germany shows a ratio of 5:1 for check-ups compared to consultations for auditory problems. Strict rules for regular checks come into play there, however, low incidence of those complaining of problems could be due to these clinicians' knowledge of diving medicine, enabling them to give appropriate advice in a previous visit.

A high incidence of otitis externa was found among both diving and non-diving populations, and hearing loss and tinnitus showed similar results. Diving was found not to be a statistically significant cause of hearing loss. The largest source of hearing loss in divers is in fact noise, and there is also an interesting correlation between hearing loss and divers who smoke. As for age, the majority of divers ranged between 29 and 39, except in the USA most appear from these data to be over 40 [55, 56]. The ratio is still male-dominated. A number of studies have demonstrated a link between females and equalisation problems and also with AV.

Searching the literature has revealed that not all the investigations included a sample of recreational divers, especially those investigating hearing loss or exostoses. Therefore, the other studies of free-divers and occupational divers must be used to estimate the possible risks to recreational divers. For some disorders, limited or no studies of any divers were found, presenting a gap in the literature when investigating the epidemiology of otitis externa, and only one study investigating the prevalence of IEDCS and IEB. Therefore, this review inevitably benefitted through using a mixture of both large-scale and individual studies. Without the large-scale population studies, no statistics for the most severe auditory conditions of divers would be present for discussion, and without the individual studies, it would not be possible to distinguish the prevalence of AV from general vertigo.

The medical problems associated with diving are seen in the literature as a worldwide concern. The different pre-medical requirements among different countries have shown no immediate factors influencing the frequency of conditions. However, the lack of studies (other than the BSAC incidence report) covering the incidence of auditory or even ENT diving problems causes concern that the UK diving population is not correctly represented. The incidences reported by the DAN and BSAC do not correlate with those of medical studies, which would predict higher reporting of auditory problems given the small population of divers. Therefore, the channels for reporting a diving incident in the UK are either not accessible enough to the divers, or they are only encouraged to report those they themselves consider serious.

Education and training are the only ways to prevent these auditory problems from happening. More can be done, especially in a country where no medical examination or check-ups are required before learning to dive. Barotrauma problems will only reach the hospital department once they become serious, such as TM perforation or round window rupture. Even in such cases, additional tests not habitually used in audiology such as the "Teed classification" and positional audiometry would be useful. A recommended referral for Eustachian tube testing when equalisation problems become apparent in dive training, would identify ETD and prevent development of MEB or TM perforation underwater, which cause a serious safety risk to the diver. Further preventive measures such as increasing awareness in the divers themselves, by means of a detailed leaflet or poster available at both audiology clinics and diving centres for the information of all divers, could be helpful.

Recommendations for Future Research

One recommendation for future research would be to undertake a cross sectional survey among ENT departments, of how many divers attend and for what reasons. This would help pinpoint the auditory problems of divers and provide descriptive epidemiological data and the geographic locations of highest prevalence, where increased knowledge and attention from clinicians are most needed.

A further recommendation would be research that looked at alternative middle ear measures to assess if there is any possibility to predict auditory problems, especially of the middle ear, in the diving population.

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