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Article

Characteristics and Prognostic Analysis in Diving-Induced Ear Trauma and Sudden Hearing Loss

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Abstract

Background/Objectives: Diving exposure can cause auditory injury involving both middle and inner ear structures. Inner ear barotrauma (IEB) and inner ear decompression sickness (IEDCS) are the major inner ear disorders and frequently present with auditory and vestibular symptoms. This study examined how diving characteristics relate to patterns of auditory trauma. **Methods:** A retrospective chart review of 30 patients with 36 affected ears was performed. Diving depth, clinical manifestations, and treatment responses were analyzed to identify factors influencing relatively prognosis. **Results:** Diving depth was the important factor associated with symptom severity and type of injury. Dives deeper than 30 meters of sea water were linked to a higher incidence of sudden sensorineural hearing loss and vertigo. In contrast, transient symptoms with minimal objective abnormalities were typically observed in shallow dives. Patients with concomitant decompression sickness (DCS) showed poorer auditory and vestibular recovery following hyperbaric oxygen therapy, while those without DCS showed better hearing improvement. Vertigo was observed in 80% of IEB cases and 66.7% of IEDCS cases. Hearing recovery was more frequently observed in cases presenting with middle ear symptoms, suggesting a relatively favorable prognosis for IEB compared with IEDCS. **Conclusions:** Diving depth and DCS involvement may play a role in the severity and prognosis of diving-related inner ear injury. IEB generally demonstrates better auditory outcomes than IEDCS. Further studies with larger cohorts are needed to refine prognostic indicators and optimize management strategies.

Keywords: scuba diving; decompression sickness; hyperbaric oxygen; hearing loss; ear; barotrauma

1. Introduction

Self-Contained Underwater Breathing Apparatus diving (SCUBA diving) being a popular recreational activity; however, rapid ambient pressure changes, ascent rate, breathing gas composition, and repeated exposure may predispose individuals to auditory injury involving outer, middle, and inner ear [1–3]. These exposure variables may affect both middle and inner ear structures through barotrauma or inert gas bubble formation [2,4]. Inner ear barotrauma (IEB) and inner ear decompression sickness (IEDCS) represent two distinct forms of inner ear injuries with similar clinical manifestations [5]. Most affected individuals present with sudden hearing loss accompanied by tinnitus and vertigo [6]. According to the literature, IEB is commonly associated with middle ear findings such as hemorrhage, tympanic membrane (TM) perforation, and otorrhea, whereas IEDCS is more often accompanied by musculoskeletal pain, as well as cardiopulmonary and neurological symptoms [7,8]. Currently, no definitive clinical diagnostic method exists to reliably differentiate between the two conditions [5]. Consequently, without thorough and detailed history-taking,

establishing an accurate diagnosis based solely on clinical presentation remains challenging and may lead to delays in initiating appropriate treatment.

Previous studies investigating the prognosis of idiopathic sudden hearing loss have consistently reported a significant therapeutic benefit from hyperbaric oxygen therapy (HBOT) [9–11]. Initiation of HBOT treatment within 14 days of symptom onset is considered critical for optimizing outcomes [12,13]. HBOT has also demonstrated favorable efficacy in cases of post-diving sudden hearing loss; however, variability in recovery suggests that treatment response alone cannot fully explain prognosis [14–18]. These discrepancies highlight the need for further investigation. Several clinical features, including diving depth, presence of vertigo, systemic decompression symptoms, and timing of treatment initiation, have been suggested as potential prognostic determinants of hearing recovery. However, existing evidence remains limited and inconsistent. Most previous investigations primarily emphasized treatment efficacy rather than the correlation between exposure variables and prognostic outcomes. Consequently, the relationship between diving exposure characteristics and auditory prognosis remains incompletely understood.

The present study aims to examine the prognostic risk factors associated with traumatic hearing loss occurring during diving activities. Specifically, it seeks to analyze correlation between diving exposure and hearing impairment, compare the severity and patterns of hearing loss with various diving modes, and identify contributing factors that may predispose individuals to barotrauma or decompression sickness following diving-related sudden hearing loss.

2. Materials and Methods

This study included patients who presented to our hospital with auditory or vestibular symptoms following diving between January 1, 2010, and November 30, 2023, and who underwent comprehensive audiological evaluation. This study protocol was approved by the Institutional Review Board of Tri-Service General Hospital, Taipei, Taiwan (IRB No. B202405094). A total of 36 patients were initially identified. After excluding four patients with unverifiable diving dates, one patient with suspected noise-induced hearing loss, and one patient with incomplete examination data, 30 patients were enrolled. Six patients exhibited bilateral ear involvement and 24 had unilateral ear involvement, yielding a total of 36 ears for analysis.

Given the limited sample size, results are presented primarily using descriptive statistics. The 36 ears were classified according to three frameworks. First, ears were grouped by diving depth: ≤ 10 meters of seawater (msw; Group A), 11–20 msw (Group B), 21–30 msw (Group C), and 31–40 msw (Group D). Second, ears were categorized by diagnosis into five groups: normal hearing with intact TM (NH + intact TM), middle ear barotrauma with TM perforation (MEB + perforated TM), middle ear barotrauma with intact TM (MEB + intact TM), IEB, and IEDCS. Continuous variables are summarized as mean $\pm$ standard deviation, and categorical variables as counts and percentages. Observed differences among groups are described descriptively without formal hypothesis testing. Finally, in the subgroup with sudden hearing loss, seven patients who met the diagnostic criteria for sudden sensorineural hearing loss (SSNHL) were identified and analyzed separately. The following variables were collected: demographic data (age, sex), diving-related parameters (diving depth, interval from symptom onset to treatment initiation), clinical characteristics (affected ear, chief complaints, and diagnosis), and audiological and vestibular assessments, including pure-tone audiometry (PTA), videonystagmography (VNG), and caloric testing. Reported auditory and vestibular symptoms included tinnitus, vertigo, aural fullness, otalgia, and otorrhea. Additional decompression-related symptoms, such as headache, muscle weakness, joint pain, and cardiopulmonary dysfunction, were also documented. Treatment-related variables comprised HBOT protocol, number of HBOT sessions, cumulative HBOT duration, and number of intratympanic steroid injections (ITSI). Prognostic outcomes included hearing recovery measured in decibels (dB), degree of hearing recovery, and the presence of residual vestibular symptoms. Degree of prognosis was defined as no recovery (PTA improvement ≤ 10 dB HL), partial recovery (PTA improvement > 10

dB HL with a residual interaural difference >10 dB HL), or total recovery (PTA improvement >10 dB HL with a residual interaural difference ≤10 dB HL or a final hearing threshold ≤ 20 dB HL).

3. Results

The study included 30 patients with a mean age of 37.36 years, comprising 17 males and 13 females. The mean hearing threshold of the 36 affected ears was 28.34 dB HL.

3.1. Characteristics and Analysis of Different Diving Depth Groups

Characteristics of the four diving depth groups are summarized in Table 1. Mean PTA thresholds increased progressively with depth, from 15.5 dB HL in Group A (≤10 msw) to 66.25 dB HL in Group D (31–40 msw), indicating greater hearing loss at deeper exposures. The distribution of diagnoses also varied by depth. IEDCS was observed only in the 31–40 msw group, whereas normal hearing with an intact TM was more common at depths ≤20 msw. Vertigo was more frequently reported in the deepest group, while otalgia was limited to depths ≤20 msw. Tinnitus was observed across multiple depth categories. Notably, individuals in the ≤10 msw group more often presented with subjective symptoms without objective clinical findings, suggesting that auditory symptoms following shallow dives may be transient and not associated with structural ear injury.

Table 1. Characteristics and Analysis of Different Diving Depth Group.

Diving depth		Total	A (0–10 msw)	B (11–20 msw)	C (21–30 msw)	D (31–40 msw)
Variables		n	n	n	n	n
Total		29	10	12	4	3
PTA (dB HL)		28.34 ± 23.61	15.50 ± 6.38	23.35 ± 16.33	45.31 ± 28.05	66.25 ± 12.69
Age (year)		37.36 ± 9.92	38.20 ± 11.26	32.67 ± 7.13	41.75 ± 12.30	49.67 ± 11.59
Gender	Male	14	5	5	1	3
	Female	15	5	7	3	0
Affected ear	Right	18	7	7	2	2
	Left	11	3	5	2	1
Diagnosis						
NH+intact TM		11	6	5	0	0
MEB+perforated TM		3	1	1	1	0
MEB+intact TM		8	2	4	2	0
IEB		5	1	2	1	1
IEDCS		2	0	0	0	2
Tinnitus	Without	17	2	11	3	1
	With	12	8	1	1	2
Vertigo	Without	19	9	6	4	0
	With	10	1	6	0	3
Aural fullness	Without	10	3	5	1	1
	With	19	7	7	3	2
Otalgia	Without	21	9	5	4	3
	With	8	1	7	0	0

Diving depth information was available for 29 ears. Patient-level variables (age and gender) were repeated for bilateral cases.

Abbreviations: dB HL=decibels hearing level; NH=normal hearing; MEB=middle ear barotrauma; IEB=inner ear barotrauma;

IEDCS=inner ear decompression sickness; TM=tympani membrane; PTA=pure-tone average.

3.2. Analysis of Different Diagnostic Categories

Characteristic of the five diagnostic categories—normal hearing with intact TM (NH + intact TM), middle ear barotrauma with perforated TM (MEB + perforated TM), middle ear barotrauma with intact TM (MEB + intact TM), IEB, and IEDCS— are summarized descriptively in Table 2. Mean PTA thresholds varied across diagnostic groups. Greater hearing loss was observed in patients diagnosed with IEDCS and IEB compared with those with middle ear barotrauma or normal hearing. Vertigo was reported more frequently in patients with IEDCS and IEB than in other diagnostic groups.

Table 2. Characteristics and Analysis of Different Diagnostic Categories.

Diagnosis		Total	NH+intact	MEB+perforated	MEB+intact	IEB	IEDCS
			TM	TM	TM		
Variables		n	n	n	n	n	n
Total		36	16	4	8	5	3
PTA (dB HL)		28.34 ± 23.61	14.06 ± 6.28	25.94 ± 7.80	24.88 ± 6.47	52.50 ± 31.68	76.67 ± 23.76
Age (years)		37.36 ± 9.92	35.25 ± 7.88	41.50 ± 7.14	39.63 ± 11.06	31.20 ± 9.81	47.33 ± 15.01
Gen							
der	Male	19	7	2	4	3	3
	Femal						
	e	17	9	2	4	2	0
Affected							
ear	R	21	9	3	5	3	1
	L	15	7	1	3	2	2
Tinnitus	Witho						
	ut	21	10	2	6	2	1
	With	15	6	2	2	3	2
Vertigo	Witho						
	ut	26	12	4	8	1	1
	With	10	4	0	0	4	2
Aural	Witho						
fullness	ut	13	4	2	1	4	2
	With	23	12	2	7	1	1
Otalgia	Witho						
	ut	27	12	2	6	4	3
	With	9	4	2	2	1	0

Analyses were performed per affected ear (n = 36). Patient-level variables (age and gender) were repeated for bilateral cases. Abbreviations: dB HL=decibels hearing level; NH=normal hearing; IEB=inner ear barotrauma; IEDCS=inner ear decompression sickness; MEB=middle ear barotrauma; PTA=pure-tone average; TM=tympanic membrane.

3.3. Descriptive Analysis of Patients with SSNHL

Results for patients with SSNHL are presented descriptively in Table 3. Among the seven patients with SSNHL, five patients were male and two were female, with ages ranging from 21 to 62 years (mean age: 36.29 years). The most frequently reported symptoms were vertigo (n = 5), tinnitus (n = 4), and aural fullness (n = 3). Additional symptoms, including otalgia, otorrhea, headache, muscle weakness, joint pain, and cardiopulmonary dysfunction, were each reported by one patient. All seven patients were scuba divers, with a mean diving depth of 29.83 msw. Hearing loss was right-sided in three patients and left-sided in four patients, with a mean PTA threshold of 68.4 dB HL. Vestibular function testing was performed in four patients, all of whom demonstrated unilateral or bilateral caloric weakness; one patient also exhibited spontaneous nystagmus on VNG. The mean interval from symptom onset to initiation of treatment was 120 hours. In addition to pharmacological therapy, two patients received combined HBOT and ITSI, three patients received HBOT alone, and two received ITSI alone. Among the five patients treated with HBOT, three underwent standard HBOT (253 kPa [2.5 ATA] for 100 minutes), one received treatment according to the United States Navy Diving Manual, Revision 5 (USN-5; 284 kPa [2.8 ATA] for 138 minutes), and one underwent a combination of both protocols. The mean hearing improvement was 21.9 dB HL. Among the three patients diagnosed with IEDCS, two presented with additional decompression-related symptoms, including headache, musculoskeletal pain, and cardiopulmonary dysfunction; all these symptoms resolved following HBOT. Overall, complete hearing recovery was observed in two patients (28.5%), partial recovery in one patient (14.3%), and no recovery in four patients (57.1%). Hearing recovery categories were defined according to changes in PTA and interaural hearing thresholds, as detailed in Table 3. Persistent vestibular symptoms were reported in four patients (57.1%), including individuals with both complete and absent hearing recovery. Among patients who received HBOT, hearing recovery was achieved in three cases (60%), including two with complete and one with partial recovery.

Table 3. Characteristics and treatment outcomes of patients with sudden hearing loss after diving.

No.	Basic information				Examination results				Symptoms								HBOT		ITSI			Prognosis		
	Sex	Age	msw	Delay (hours)	Ear	PTA	VNG	Caloric test	T	V	F	O	Orrh	HA	MW	JP	CPD	kPa	Times	Minutes	Times			
1	M	39	40	48	R	68.8	–	+	+	+	+	–	–	–	–	–	–	284 253	1 3	138 300	0	15	partial	+
2	M	32	/	168	L	100	/	/	+	–	–	–	–	–	–	–	–	/	0	0	4	5	no	/
3	M	27	27	72	L	86.3	–	+	–	–	+	–	–	–	–	–	–	253	20	2000	10	66.3	total	/
4	F	21	20	120	L	22.5	–	+	+	+	–	–	–	–	–	–	–	/	0	0	5	-5	no	–
5	M	62	35	144	L	77.5	/	/	+	+	–	–	–	+	+	–	–	253	12	1200	3	3.75	no	+
6	F	25	20	120	R	71.3	/	/	–	+	–	+	+	–	–	–	–	284	3	414	0	58.8	total	+
7	M	48	37	168	R	52.5	+	+	–	+	+	–	–	–	–	+	+	253	11	1100	0	10	no	+

Abbreviations: dB HL=decibels hearing level; HBOT=hyperbaric oxygen therapy; ITSI=intratympanic steroid injections; kPa=kilopascals ; msw=meters of seawater; PTA=pure-tone average; delay=delay onset of treatment; T=tinnitus; V=vertigo; F=aural fullness; O=otalgia; Orrh=otorrhea; HA=headache; MW=muscle weakness; JP=joint pain; CPD=cardiopulmonary dysfunction; min=minutes; Ves=residual vestibular symptoms.

4. Discussion

Inner ear barotrauma (IEB) and inner ear decompression sickness (IEDCS) may be differentiated based on several key characteristics, including diving mode (scuba diving or free diving), breathing gas composition (pure oxygen or mixed gas), diving depth and duration, timing of symptom onset, and associated clinical manifestations. IEB may occur during either descent or ascent, whereas IEDCS occurs exclusively during ascent, with symptoms typically emerging minutes to hours after surfacing. Although both conditions can present with sudden hearing loss accompanied by tinnitus and vertigo, IEDCS is more frequently associated with vertigo (91.7%) and systemic decompression sickness symptoms, whereas IEB presents with vertigo less commonly (44.8%) and is not accompanied by systemic manifestations [5]. The use of mixed breathing gases, such as nitrogen or helium, is a major etiological factor for IEDCS; consequently, scuba divers are at greater risk than free divers. Previous studies have suggested that IEB is more likely to occur at depths <30 msw, while the incidence of IEDCS increases substantially beyond 30 msw [1]. In the present study, patients presenting with sudden hearing loss accompanied by middle ear symptoms and without systemic decompression-related manifestations were more likely to be classified as having IEB.

Our analysis of diving depth showed variations observed in hearing loss severity, diagnostic distribution, and predominant symptoms, including tinnitus, vertigo, and otalgia. Hearing loss tended to increase with diving depth, and a higher proportion of IEB and IEDCS was observed in the 31–40 msw group, which also showed a greater occurrence of vertigo. These findings suggest that diving depth may play a role in the severity of auditory and vestibular manifestations following diving. Shallow dives (0–10 msw) were frequently associated only with subjective symptoms, without objective abnormalities, possibly reflecting smaller pressure gradients and a lower risk of structural injury. In contrast, deeper dives may expose the inner ear to more substantial pressure changes during ascent, potentially increasing the risk of vestibular injury and IEDCS [19]. Tinnitus was observed in both shallow and deep diving, whereas otalgia was mainly reported in divers exposed to depths ≤ 20 msw (Table 1).

When comparing diagnostic categories, patients with IEB and IEDCS demonstrated greater hearing loss than those with middle ear barotrauma or normal findings. Vertigo appeared to be a distinguishing clinical feature and was observed more frequently in these groups (Table 2). These observations are consistent with both the depth-based analysis and prior reports [15].

Decompression sickness results from inert gas bubble formation following rapid reductions in ambient pressure. Type II decompression sickness frequently involves the inner ear, with approximately 26% of cases presenting as IEDCS, and over one-third experiencing persistent auditory or vestibular deficits despite treatment [2,5,21,22]. Early recompression and hyperbaric oxygen therapy (HBOT) remain the cornerstone of management, with established treatment protocols varying by severity and region [13]. In Taiwan, USN-5A (608 kPa [6.0 ATA] with 154 minutes) and USN-6A (608 kPa [6.0 ATA] with 319 minutes) protocols are commonly employed, followed by standard HBOT for residual symptoms, a strategy also applicable to sudden sensorineural hearing loss.

In the present cohort of patients with SSNHL, early initiation of HBOT was associated with better auditory outcomes, consistent with prior studies [7,23,24]. However, extended HBOT duration (>900 minutes) did not uniformly predict favorable prognosis, as some patients continued to experience persistent vestibular symptoms despite adequate treatment. Prognostic differences appeared to be influenced by diving depth, treatment delay, intratympanic steroid use, and the presence of systemic decompression sickness symptoms at onset. Patients with IEDCS often exhibited improvement in systemic symptoms following HBOT, yet auditory and vestibular recovery remained limited. In contrast, patients with hearing recovery more frequently demonstrated middle ear symptoms consistent with IEB, suggesting that sudden hearing loss associated with IEB may carry a relatively favorable prognosis than that associated with IEDCS. These findings align more closely with those

reported by Mason [15] than by Lindfors [5], highlighting ongoing controversy and the need for further investigation.

Regardless of pressure level 203 kPa (2.5 ATA) or 253 kPa (2.8 ATA), HBOT was beneficial for hearing recovery in patients without systemic decompression sickness symptoms. Nevertheless, vestibular symptoms showed limited responsiveness to treatment. Accurate differentiation between IEB and IEDCS is therefore essential and should incorporate diving mode, gas composition, symptom onset timing, and the presence of vertigo or systemic decompression symptoms. In cases where sudden hearing loss after diving is accompanied by systemic decompression manifestations, aggressive HBOT and early vestibular rehabilitation should be considered to optimize outcomes [25].

This study has several limitations. First, treatment modalities were not randomized because of the retrospective study design. The choice of HBOT, ITSI, or combined therapy was based on clinical severity, the presence of vestibular or systemic decompression symptoms, physician judgment, and patient preference, which may introduce selection bias. Second, each ear was analyzed as an independent unit, although bilateral involvement was uncommon; therefore, intra-patient correlation cannot be completely excluded. Third, the sample size was small and clinically heterogeneous, and comparisons between HBOT protocols were descriptive only. Finally, diagnostic classification of IEB and IEDCS relied on overall clinical assessment, which may introduce some diagnostic uncertainty.

5. Conclusions

This study analyzed 36 ears to examine diving-related auditory injury and HBOT prognosis. Diving depth was a potential role: shallow dives were mainly observed in transient auditory symptoms, whereas deeper dives showed higher rates of sudden hearing loss with vertigo and persistent vestibular symptoms. Treatment delay, number of ITSI, and systemic decompression sickness symptoms were potential prognostic factors. HBOT was more effective for hearing recovery in inner ear barotrauma or without systemic decompression symptoms, but showed limited benefit when systemic decompression sickness was present. Vestibular outcomes responded poorly. Larger prospective studies and multicenter studies are needed to clarify these findings such as diagnosis, treatment strategies, and prognostic differences.

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