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Hyperbaric oxygen therapy and contralateral ear hearing thresholds in unilateral sudden sensorineural hearing loss

Taylan Zaman [a,*], Recep Ozkan [b], Kubra Ozgok Kangal [a], Osman Turkmen [c], Levent Yucel [d]

[a] University of Health Sciences, Gulhane Training and Research Hospital, Department of Undersea and Hyperbaric Medicine, Ankara, Türkiye
[b] University of Health Sciences, Van Training and Research Hospital, Department of Undersea and Hyperbaric Medicine, Van, Türkiye
[c] Samsun Training and Research Hospital, Department of Undersea and Hyperbaric Medicine, Samsun, Türkiye
[d] University of Health Sciences, Gülhane Training and Research Hospital, Department of Otorhinolaryngology, Ankara, Türkiye
*Corresponding author: taylanzaman@gmail.com (Taylan Zaman)

MAIN POINTS

- Hyperbaric oxygen therapy (HBOT) is widely used as an adjunctive treatment for idiopathic sudden sensorineural hearing loss (SSNHL) and is generally considered safe.
- This study uniquely evaluated the contralateral, clinically unaffected ears of 101 SSNHL patients undergoing HBOT.
- Hearing thresholds remained stable across 250 Hz–8 kHz, supporting the otologic safety of HBOT.
- A subtle but significant deterioration at 6 kHz (+1.98 dB, p = 0.0049) suggests chamber noise as a possible contributor.
- Findings highlight the need for high-frequency monitoring and noise-control measures in HBOT practice.

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ABSTRACT

Aim: To evaluate changes in hearing thresholds of the clinically unaffected contralateral ear before and after hyperbaric oxygen therapy (HBOT) in patients treated for unilateral idiopathic sudden sensorineural hearing loss (ISSNHL).

Materials and Methods: In this single-center retrospective observational study, pure-tone audiograms (250 Hz–8 kHz) of the contralateral ears of 101 patients who underwent HBOT were compared before and after treatment. Each session lasted approximately 120 minutes at 2.4 ATA, including compression, oxygen exposure, and decompression phases. Thresholds were age-corrected according to ISO 7029:2017. Depending on distributional assumptions, Wilcoxon signed-rank test were used for paired comparisons (α=0.05). The median number of sessions was 20 (IQR: 10–20).

Results: No significant changes were observed across most frequencies. Only at 6000 Hz, a minimal but statistically significant difference was detected (p=0.0049). The hearing thresholds at other frequencies remained stable.

Conclusion: Overall, HBOT was not associated with substantial changes in contralateral hearing thresholds. The minor threshold shift observed at 6 kHz may suggest noise exposure during treatment sessions rather than oxidative stress. This highlights the importance of monitoring high-frequency hearing and emphasizes the need for noise control measures during therapy. These findings confirm that HBOT is generally safe for the unaffected ear.

Keywords: Hyperbaric oxygen treatment, Sensorineural hearing loss, Occupational noise, Alternative therapies

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INTRODUCTION

Sudden sensorineural hearing loss (SSNHL) is an acute-onset condition, typically unilateral, defined as a hearing loss of ≥30 dB affecting at least three consecutive frequencies within a 72-hour window [1]. Although its etiology remains predominantly idiopathic, proposed mechanisms include viral infections, vascular compromise, autoimmune responses, and membrane ruptures. Given the risk of permanent auditory deficit, SSNHL necessitates prompt diagnosis and intervention [2].

Hyperbaric oxygen therapy (HBOT) has emerged as a critical adjunctive treatment for SSNHL. It functions by increasing arterial partial oxygen pressure, thereby facilitating oxygen diffusion to the cochlea and mitigating hypoxic injury. Cochlear hair cells—particularly the outer hair cells—are highly sensitive to oxidative stress, mechanical trauma, barometric fluctuations, and ototoxic agents [3-5]. Because these cells lack regenerative capacity in the mammalian cochlea, any significant damage typically results in permanent hearing loss.

Significant physiological effects on various organ systems, in-

cluding the auditory system, can be induced by changes in ambient pressure, whether at high altitudes or under hyperbaric conditions [6,7]. During HBOT, elevated ambient pressure and increased oxygen partial pressure may alter gas exchange, blood flow distribution, and cochlear microcirculation. Beyond pressure fluctuations, hyperbaric chambers are also significant sources of mechanical noise. A multicenter study conducted in Türkiye reported that noise levels within HBOT chambers can occasionally exceed international safety standards, particularly during the ventilation phase at treatment pressure [8]. Cochlea's dual sensitivity to pressure changes and acoustic stress highlights the need for a rigorous evaluation of the hyperbaric environment's impact on the auditory system [9].

The generation of reactive oxygen species (ROS), oxidative stress, and mitochondrial dysfunction are central to the pathophysiology of cochlear injury [4,5]. Noise exposure further exacerbates ROS production in cochlear cells, triggering DNA damage, lipid peroxidation, and apoptotic pathways. When combined with the disruption of mitochondrial membrane potential and reduced energy production, these factors can culminate in permanent sensorineural hearing loss. Consequently, strategies to prevent noise-induced hearing loss—such as reducing exposure time, utilizing protective devices, and implementing pharmacological interventions targeting oxidative stress—are essential [10]. Hyperbaric environments, where multiple stressors like pressure and noise coexist, must be managed with robust protective and monitoring protocols.

The aim of this study is to evaluate whether the noise and pressure fluctuations inherent in the hyperbaric environment induce auditory changes in the contralateral ear—which is considered clinically unaffected—in patients undergoing HBOT for unilateral SSNHL. By comparing pre- and post-treatment audiometric data, this study seeks to determine the risk of functional impairment in the healthy ear, thereby providing evidence to optimize the safety and efficacy of clinical HBOT protocols.

MATERIALS AND METHODS

Study design and participants

This retrospective cohort study was conducted at the Department of Underwater and Hyperbaric Medicine in University of Health Sciences Gülhane Training and Research Hospital. Medical records of patients who underwent HBOT for unilateral idiopathic SSNHL between February 1, 2017 and February 1, 2022 were reviewed.

Inclusion criteria were as follows: (1) diagnosis of unilateral SSNHL confirmed by pure-tone audiometry, (2) receipt of at least five HBOT sessions, and (3) availability of both baseline and post-treatment audiometric data for the contralateral (clinically unaffected) ear. Exclusion criteria included bilateral hearing loss, a history of chronic otologic disease, previous ear surgery, recent acoustic trauma, use of known ototoxic drugs within the past three months, and incomplete medical records.

Each HBOT session was conducted at 2.4 ATA for a total duration of 120 minutes, partitioned into 15 minutes of compression, 90 minutes of oxygen inhalation, and 15 minutes of decompression.

Audiological assessment

Pure-tone air-conduction thresholds dB (A) at 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, 6 kHz, and 8 kHz were measured for both ears in a soundproof booth using supra-aural headphones, in accordance with ISO 8253-1:2010. Audiometric evaluations were performed before hyperbaric oxygen therapy (pre-HBOT, baseline) and after treatment (post-HBOT, follow-up).

To control for the confounding effects of age-related hearing loss (presbycusis), thresholds were adjusted according to ISO 7029:2017 standard reference equations. These equations estimate median hearing thresholds for otologically normal individuals based on age and sex, utilizing the 18-year-old median as the 0 dB reference point [11]. For each frequency, the age-adjusted value was calculated by subtracting the predicted median threshold from the observed measured threshold.

The expected (age-adjusted) thresholds were then used to calculate correction values as follows:

ΔPre=Pre-HBOT – Expected

ΔPost=Post-HBOT – Expected

Change = ΔPost - ΔPre

Here, pre-HBOT and post-HBOT represent the hearing thresholds measured before and after treatment, respectively. In this way, the ISO 7029-adjusted hearing change for each patient was determined.

Reference noise level data

The noise data used in this study were obtained from measurements previously performed by our research team in the same multiplace hyperbaric chamber evaluated in the present study [8]. These measurements were carried out using a Brüel & Kjær Sound Level Meter Type 2240 and a Type 4231 Sound Level Calibrator under identical chamber conditions and operational protocols. Measurements were taken at a height of 130 cm above the floor and at least 1 m away from the chamber walls, corresponding to the ear level of a seated patient. The mean noise levels were 78.7 dB during compression, 84.2 dB during treatment with ventilation open, 76.0 dB with ventilation closed, and 79.1 dB during decompression. These values were used for the contextual analysis of potential noise exposure during HBOT in the present study. Although the data were cited from our previous publication, they represent the same environment and equipment used in this study.

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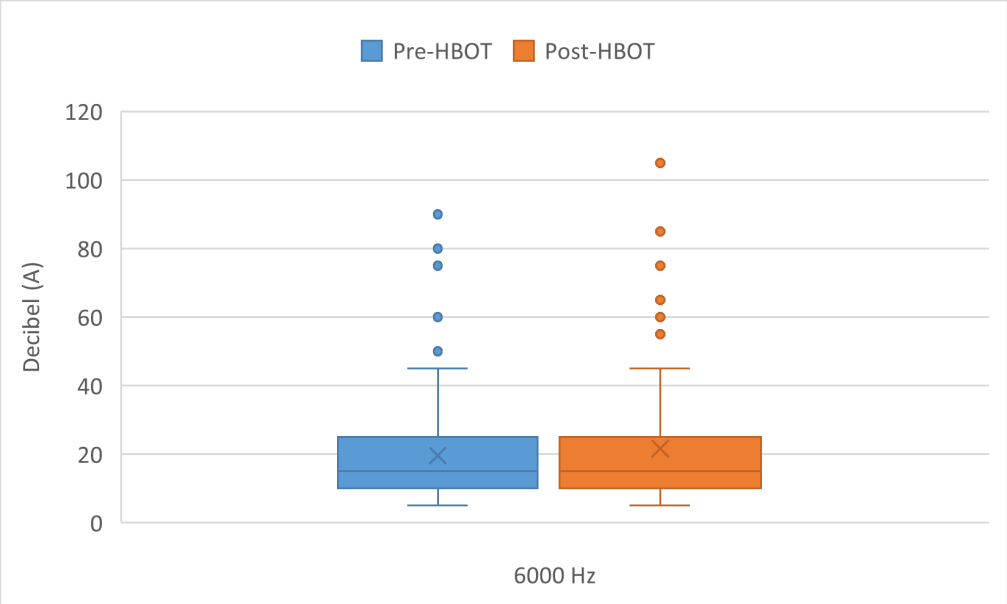

Figure 1. Change in 6 kHz pure-tone thresholds of the unaffected ear before and after HBOT.

Statistical analysis

All statistical analyses were performed using JAMOVI software, version 2.3.28 (The JAMOVI Project, Sydney, Australia). Descriptive statistics were presented as mean ± standard deviation (SD) for normally distributed variables, and as median (interquartile range, IQR) for non-normally distributed variables. Normal distribution of continuous variables was assessed by Kolmogorov–Smirnov test. The difference between present audiogram (baseline and follow-up) and age-adjusted ISO 7029:2017 standards were calculated. These differences were used in statistical analyses. The Wilcoxon signed rank test was used for analyzing the change before HBOT and after HBOT. A p-value <0.05 was considered statistically significant.

A post-hoc power analysis was conducted after study completion, based on a total sample size of N=101, an effect size of d=0.5, and a significance level of p=0.05. The analysis demonstrated a statistical power of 0.99.

Table 1. Demographic characteristics and laterality of the unaffected ear in patients with unilateral idiopathic sudden sensorineural hearing loss (ISSNHL).

Characteristic	n (%) or Median [IQR]
Sex	
Male	58 (57.4)
Female	43 (42.6)
Age (years)	42 [29--51]
Side of unaffected ear	
Right	54 (53.5)
Left	47 (46.5)
HBOT sessions	20 [10-20]

Note: Age is presented as median [Interquartile Range (IQR)]. Categorical variables are presented as absolute numbers and percentages.

RESULTS

A total of 101 patients diagnosed with unilateral idiopathic SSNHL who met the inclusion criteria were included in the analysis. The cohort consisted of 58 (57.4%) males and 43 42.6%) females, with a median age of 42 years (IQR: 29–51). The unaffected ear was the right ear in 54 patients (53.5%) and the left ear in 47 patients (46.5%). The median number of HBOT sessions completed was 20 (IQR: 10–20) (Table 1).

The pure-tone thresholds of the unaffected ear before and after HBOT, alongside the ISO 7029:2017 age-adjusted reference values, are detailed in Table 2. Across the majority of the tested frequencies (250Hz-8 kHz), both pre- and post-treatment median thresholds remained within the normal hearing range. The age-adjusted reference values were generally lower than the observed thresholds, suggesting the presence of subtle, subclinical variations in some individuals.

No statistically or clinically significant threshold shifts were observed in the contralateral (unaffected) ear at most tested frequencies, including 250 Hz, 500 Hz, 1 kHz, 2 kHz, 4 kHz, and 8 kHz. However, a minor but statistically significant change was detected at 6 kHz (p = 0.0049). This isolated high-frequency shift may reflect subtle exposure to hyperbaric chamber noise rather than the barometric or oxidative effects of HBOT (Figure 1, Table 2). This finding suggests a potential susceptibility of the unaffected ear to high-frequency environmental factors during HBOT sessions.

DISCUSSION

This study investigated whether HBOT in patients with unilateral idiopathic SSNHL induces measurable auditory changes in the contralateral ear considered clinically unaffected. Our analyses showed no significant post-treatment

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Table 2. Comparison of pre- and post-HBOT pure-tone and age-adjusted thresholds in the unaffected ear.

Frequency (Hz)	Pre-HBOT Median (IQR) (dB)	Age-adjusted Pre-HBOT Median (IQR) (dB)	Post-HBOT Median (IQR) (dB)	Age-adjusted Post-HBOT Median (IQR) (dB)	Change Median (IQR) (dB)	P-value
250	15 (10-20)	10.46 (8.29-17.08)	15 (10-17.5)	12.73 (8.45-15)	0 (-5-5)	0.9921
500	10 (10-15)	8.54 (4.75-11.73)	10 (5-15)	6.98 (4.01-10)	0 (-5-0)	0.2426
1000	10 (5-10)	4.94 (3.71-8.16)	10 (5-10)	4.91 (3.16-9.58)	0 (0-0)	0.1729
2000	5 (5-10)	4.51 (1.76-7.77)	5 (5-10)	4.45 (1.42-5)	0 (-5-0)	0.6231
4000	10 (5-20)	4.99 (1.80-13.43)	10 (5-20)	4.81 (-0.21-13.43)	0 (-5-0)	0.1099
6000	15 (10-25)	9.27 (4.19-14.92)	15 (10-25)	9.94 (4.06-19.27)	0 (0-5)	0.0049*
8000	15 (10-25)	7.53 (2.84-12.50)	15 (10-23.75)	8.02 (0.87-15.17)	0 (0-0)	0.9483

Note: Values are expressed as median (interquartile range, 25^{th}–75^{th} percentiles). Age-adjusted medians are calculated according to ISO 7029:2017 reference equations. p-values were obtained using Wilcoxon signed-rank test due to non-normal data distribution. *$p < 0.05$ indicates statistical significance.

threshold shifts at most frequencies, although a small but statistically significant deterioration was observed at 6 kHz. The magnitude of this change was minimal; however, its statistical significance and occurrence at one of the frequencies commonly affected by noise-induced damage is noteworthy.

During HBOT, patients are exposed to increased ambient pressure and partial oxygen pressure, which may influence inner ear physiology through alterations in gas diffusion, vascular perfusion, and oxidative metabolism. HBOT is known to enhance oxygen delivery to the cochlea, thereby supporting recovery in the affected ear. However, in addition to pressure fluctuations, patients are also exposed to chamber noise generated by mechanical systems, ventilation cycles, and gas flow adjustments. A multicenter study from Türkiye reported that chamber noise levels at treatment pressure varied between 100.4 and 40.5 dB(A), reaching particularly higher values during ventilation [8]. In our clinic, noise levels during treatment depth were observed to range between 76–84.2 dB(A), and during decompression, brief peaks up to 92.3 dB(A) were recorded. Although these levels remain below most occupational exposure limits, repeated exposure across multiple sessions may exert subtle auditory effects, particularly in vulnerable frequency regions.

In noise-induced hearing loss (NIHL), the earliest audiometric finding is typically a notch at high frequencies, most often at 3, 4, or 6 kHz. The frequency at which this notch first appears varies among individuals. Initially confined to a single frequency, the notch gradually spreads to adjacent frequencies with continued noise exposure [12-14]. This vulnerability results from the combined influence of external ear canal resonance, middle ear transmission characteristics, and the tonotopic organization of the cochlea. The basal turn of the organ of Corti, which processes frequencies in the 3,000–6,000 Hz range, is particularly susceptible to mechanical and metabolic stress and thus vulnerable to injury from prolonged or intense noise exposure [12,13]. Moreover, resonance of the external auditory canal further amplifies acoustic energy in this range, increasing the risk of hair cell damage. The finding of a significant change exclusively at 6 kHz in our cohort suggests that chamber noise exposure during HBOT may produce subtle but measurable effects at higher frequencies.

The relationship between HBOT and oxidative stress is dual: while hyperoxia can transiently increase ROS production, repeated sessions may induce antioxidant responses and mitochondrial adaptation, thereby counterbalancing the net effect [15,16]. Improved cochlear oxygenation, enhanced microcirculation, and suppression of inflammation are among the proposed mechanisms underlying HBOT's therapeutic benefits [17,18]. In our cohort, the only significant difference was detected at 6 kHz, where the median change in age-adjusted threshold was 0 dB (IQR 0–5 dB), although the mean increased slightly from 19.65 dB pre-HBOT to 21.63 dB post-HBOT (Δ = +1.98 dB; $p = 0.0049$). Although this difference reached statistical significance, both the median and mean shifts remained within the clinically negligible range, indicating that no meaningful alteration in hearing function occurred. Thus, this minimal shift should be interpreted as subclinical rather than indicative of noise-induced hearing loss. We believe this minor change is more consistent with potential chamber noise exposure during treatment rather than attributable to oxidative stress itself. HBOT is generally regarded as a safe therapy; the most frequent adverse event is middle ear barotrauma, while serious complications remain rare [19,20]. Monitoring of high frequencies during treatment and implementation of in-session noise control are therefore advisable.

There are few studies evaluating contralateral ear changes in SSNHL patients undergoing HBOT. Most of the available literature has focused on functional recovery in the affected ear, while potential auditory effects on the unaffected ear have largely been overlooked. Our findings are consistent with previous studies reporting that HBOT is overall safe from an otologic standpoint. The small but statistically significant change observed at 6 kHz, although clinically minimal, aligns with known NIHL patterns and underscores the importance of monitoring the contralateral ear in HBOT protocols. Engineering measures—such as optimization of ventilation systems, maintenance of silencers, and regulation of gas flow rates—may help reduce acoustic exposure during HBOT.

The retrospective, single-center design of this study limits causal inference and generalizability. Another limitation of

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this study is that direct in-chamber noise measurements were not performed during the HBOT sessions. Although previously collected reference data from the same HBOT unit were used, the lack of real-time measurements may limit the precision of the noise exposure assessment. The relatively short follow-up period also precluded assessment of possible delayed auditory effects. Future prospective studies should incorporate detailed monitoring of chamber noise exposure, comprehensive auditory testing, and long-term follow-up.

CONCLUSION

In this study, no changes were detected in most frequencies between 250 Hz and 8 kHz. A minimal but statistically significant difference was found at 6000 Hz ($p = 0.0049$), with no clinically relevant shift in median values. These findings suggest that HBOT is not associated with significant auditory deterioration in the unaffected ear, and that the small-scale change observed at 6000 Hz may be attributable to noise exposure during treatment sessions. While HBOT remains a generally safe adjunctive therapy, attention should be paid to noise control during treatment and to the possibility that high frequencies may be affected by noise. Prospective multicenter studies incorporating in-session noise measurements are needed to confirm these observations and to clarify the clinical significance of potential threshold shifts.

Ethics Committee Approval: This study was approved by the Ethics Committee of the University of Health Sciences Gülhane Training and Research Hospital (protocol/decision no: 2023-286, date: 22.08.2023) and was conducted in accordance with the principles of the Declaration of Helsinki.

Informed Consent: The study was retrospective, informed consent was not required from the patient.

Peer-review: Externally peer-reviewed.

Conflict of Interest: The authors declare no conflicts of interest.

Author Contributions: TZ: Conceptualization, Investigation, Methodology, Supervision, Visualization, Writing – original draft, Writing – review & editing; RO: Data curation, Investigation, Writing – review & editing; KOK: Conceptualization, Formal analysis, Methodology, Supervision, Writing – review & editing; OT: Data curation, Investigation, Writing – original draft; LY: Supervision, Writing – review & editing.

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