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Occupational Noise Exposure in Hyperbaric Oxygen Therapy Centers: A Nationwide Study on the Sound Levels and Audiometric Impact on Operators in Türkiye

Hiperbarik Oksijen Tedavi Merkezlerinde Mesleki Gürültü Maruziyeti: Türkiye Genelinde Ses Düzeyleri ve Operatörler Üzerindeki Odyometrik Etkilerin Değerlendirilmesi

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ABSTRACT Objective: This study aimed to measure noise levels in hyperbaric oxygen therapy (HBOT) centers across Türkiye and to evaluate their potential impact on the hearing thresholds of hyperbaric chamber operators. **Material and Methods:** Between November-December 2021, sound intensity measurements were conducted in 41 HBOT centers. Noise levels were recorded during the 4 operational phases using a calibrated sound level meter. Audiometric data from 28 eligible operators were retrospectively analyzed. Hearing thresholds were corrected for age and sex according to the European norm International Standart of Organization 7029:2017 standard to isolate occupational effects. **Results:** The maximum equivalent continuous sound level [Leq decibel (dB) (A)] was recorded as 81.9 dB(A), and the highest peak noise level [Lpeak dB(C)] was recorded as 114.5 dB(C). In 63.4% of the centers, the 70 dB(A) limit was exceeded during the treatment depth when the ventilation was on. A statistically significant hearing threshold shift at 4,000 Hz was observed in the right ear (p=0.039). No operator met the clinical criteria for noise-induced hearing loss (NIHL); however, the findings were suggestive of early cochlear involvement. **Conclusion:** Although no clinical NIHL was detected among the hyperbaric chamber operators, the significant threshold shift at 4,000 Hz, the frequency often first affected by noise exposure, indicates the early auditory effects of occupational noise exposure. In centers where noise levels exceed 70 dB(A), regular noise monitoring, routine audiometric evaluations, the use of hearing protection, and the implementation of engineering controls are recommended. These findings highlight the need for updated national regulations specifically tailored to HBOT centers.

Keywords: Hyperbaric oxygenation; occupational noise; noise induced hearing loss

ÖZET Amaç: Bu çalışma, Türkiye genelindeki hiperbarik oksijen tedavi (HBOT) merkezlerinde gürültü düzeylerini ölçmeyi basınç odası operatörlerinin işitme eşiklerine olan olası etkilerini değerlendirmeyi amaçlamıştır. **Gereç ve Yöntemler:** Kasım-Aralık 2021 tarihleri arasında 41 HBOT merkezinde ses şiddeti ölçümleri gerçekleştirildi. Gürültü düzeyleri, kalibre edilmiş ses seviyesi ölçer cihaz kullanılarak 4 operasyonel aşamada kaydedildi. Yirmi sekiz uygun operatöre ait odyometrik veriler retrospektif olarak analiz edildi. İşitme eşikleri, mesleki etkileri izole edebilmek amacıyla yaş ve cinsiyete göre Avrupa normu Uluslararası Standartlar Örgütü 7029:2017 standardı kullanılarak düzeltildi. **Bulgular:** Maksimum eşdeğer sürekli ses seviyesi [Leq (desibel) dB(A)] 81,9 dB(A), en yüksek tepe gürültü seviyesi [Lpeak dB(C)] ise 114,5 dB(C) olarak kaydedildi. Merkezlerin %63,4'ünde, tedavi derinliğinde ventilasyon açıkken 70 dB(A) sınırı aşıldı. Sağ kulakta 4.000 Hz frekansında istatistiksel olarak anlamlı bir işitme eşiği değişimi gözlendi (p=0,039). Hiçbir operatörde klinik gürültüye bağlı işitme kaybı [noise-induced hearing loss (NIHL)] izlenmedi; ancak bulgular erken koklear etkilenim olabileceğini düşündürmektedir. **Sonuç:** Basınç odası operatörlerinde klinik düzeyde NIHL saptanmamış olmakla birlikte, 4.000 Hz'de anlamlı işitme eşiği değişimi-gürültüye bağlı işitme kaybında genellikle ilk etkilenen frekans-mesleki gürültü maruziyetinin erken işitsel etkilerini göstermektedir. Gürültü düzeyi 70 dB(A)'yı aşan merkezlerde düzenli gürültü izlemeleri, rutin odyometrik değerlendirmeler, işitme koruyucu aparat kullanımı ve mühendislik kontrollerinin uygulanması önerilmektedir. Bu bulgular, HBOT merkezlerine özgü güncellenmiş ulusal yeni yönetmeliğe duyulan ihtiyacı vurgulamaktadır.

Anahtar Kelimeler: Hiperbarik oksijenasyon; mesleki gürültü; gürültüye bağlı işitme kaybı

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Sound is a pressure wave created by a vibrating object and propagated by transferring energy through a medium. The most crucial parameter for understanding the impact of sound' is sound pressure, which is the deviation of a sound wave from the atmospheric pressure.[1] The human ear can detect sound pressures ranging from 20 μpascal to 100 pascals. Because this range spans over a million-fold difference, a linear scale is impractical. Therefore, the sound pressure level, a logarithmic ratio referenced to 20 μpascal, is used and expressed in decibels (dB).[2]

To mimic the human ear's' response, sound measurements often apply frequency weighting. The A-weighting filter approximates human hearing by de-emphasizing frequencies the ear is less sensitive to (very low and very high frequencies), while the C-weighting filter includes more extreme frequencies and is preferred for measuring peak sound levels.[3] These are reported as dB(A) and dB(C), respectively.[1]

The equivalent continuous sound level [Leq dB(A)] represents a constant sound level with the same acoustic energy as the fluctuating noise during a given period. Initially variable, Leq dB(A) stabilizes over time and is generally reported in dB(A). Another parameter, the peak noise level [Lpeak dB(C)], reflects the highest noise level at any instant, typically measured with C-weighting due to its broader frequency capture. Many countries cap Lpeak dB(C) at 135 or 140 dB(C).

Prolonged or sudden exposure to high-intensity noise can damage hearing, particularly in the 3,000 to 8,000 Hz range. Occupational noise exposure limits have been established to minimize the risk of hearing damage.[4] The World Health Organization (WHO) recommends a maximum of 85 dB(A) for hourly exposure and 70 dB(A) for daily exposure. In Türkiye, similar regulations apply, with mandatory protective measures above specific thresholds.[5] According to this regulation, the maximum sound levels allowed according to the exposure times are given in Table 1. Hospital environments can have multiple noise sources, including equipment and ventilation systems, alarms, and communication systems.[6] The WHO advises that sound levels in hospitals should not exceed 35 dB(A) during the day and 30 dB(A) at night. Similarly, according to the Environmental Protection Agency, the sound level should not exceed 45 dB (A) by day-night weighted Leq dB(A).[7]

Hyperbaric oxygen therapy (HBOT) centers are potential high-noise environments due to hyperbaric chamber operations. The European regulation for pressure vessels for human use [European norm (EN) 14931] recommends maximum levels of 70 dB(A) during treatment and up to 90 dB(A) during compression/decompression.[8] However, limited studies exist on the auditory impact of noise in hyperbaric chambers, particularly on healthcare staff.

The primary objective of this study was to measure noise levels during the operation of hyperbaric chambers in HBOT centers across Türkiye. The secondary objective was to evaluate the potential impact of noise on the auditory health of the chamber operators. To our knowledge, this is the first study focusing on the auditory functions of personnel in relation to noise exposure in HBOT centers.

MATERIAL AND METHODS

Noise intensity levels were measured at the HBOT centers in Türkiye between November-December 2021. Both public and private institutions with active chambers were included. Measurements captured A-weighted equivalent continuous levels [Leq dB(A)] and C-weighted peak levels [Lpeak dB(C)].

At each center, sound levels were measured during four stages: compression (approximately 15 min), at treatment depth with ventilation on (5 min), at treatment depth with ventilation off (5 min), and decompression (approximately 15 min). The total measurement duration per center was 40 min. All measurements were conducted using a calibrated Bruel and Kjaer Sound Level Meter Type 2,240 and a Sound Level Calibrator Type 4,231. Measurements were taken at the operator's' ear level, with the operator seated at the control desk, approximately 1 m from the hyperbaric chamber.

Noise measurements were conducted in 41 HBOT centers. Audiometric testing was available for operators in 28 centers, with data obtained from routine occupational health records. Audiometric data from 13 operators were excluded because of incomplete prior test results, employment duration of less than 1 year, or known pre-existing hearing loss. For eligible participants, the earliest and most recent audiograms, separated by at least 1 year, were analyzed to evaluate changes in hearing thresholds.

AUDIOMETRIC TESTING AND AGE CORRECTION PROCEDURE

Audiometric evaluations were conducted in accordance with the International Standart of Organization (ISO) 8253-1:2010 standard, using monaural headphone conditions within the frequency range of 250 Hz to 8,000 Hz. Hearing thresholds were measured in decibels (dB) for each operator at every test frequency.

To account for age-related physiological changes in hearing and to evaluate whether any hearing loss observed was specifically attributable to the hyperbaric chamber environment, the measured thresholds were corrected for age and sex according to the EN ISO 7029:2017 standard.[9] This standard provides statistical distributions of hearing threshold deviations related to age and sex in otologically normal individuals aged 18-80 years, across frequencies from 125 Hz to 8,000 Hz. The correction procedure was performed as follows:

1. For each operator, age- and sex-specific median hearing threshold deviations (ΔHmd,Y) were obtained from the EN ISO 7029:2017 standard. These values represent the expected deviation from the median hearing threshold of an otologically normal 18-year-old individual.

2. The measured hearing thresholds were adjusted by subtracting the age- and sex-specific median deviation values (ΔHmd,Y), as specified in the standard, using the following formula: **Corrected Hearing Threshold=Measured Hearing Threshold-ΔHmd, Y** where ΔHmd,Y represents the median deviation in the hearing threshold for the individual's age (Y) and sex.

3. These corrected hearing thresholds were used to assess hearing loss specifically attributable to the hyperbaric chamber environment. By isolating the effect of natural age-related hearing loss (presbycusis), this correction allowed for a more accurate analysis of occupational exposure-related hearing impairment among the operators.

Statistical analysis was performed using the Statistical analysis was performed using the Jamovi software version 2.3.28 (The Jamovi Project, Sydney, Australia). The Kolmogorov-Smirnov test assessed normality. Descriptive statistics included means, medians, and standard deviations. Paired comparisons were evaluated using the Wilcoxon test, whereas group comparisons used the Mann-Whitney U test and repeated measures analysis. A p value <0.05 was considered statistically significant.

This study was conducted in accordance with the principles of the Declaration of Helsinki. Ethics approval was granted by the Gülhane Scientific Research Ethics Committee (date: 17.06.2021; no: 2021/286)

RESULTS

Forty-one HBOT centers across 21 cities participated in the study (Figure 1). Twenty-eight operators (21 men and 7 women) were included, with a mean age of 36.7±7.7 years. None of the participants had chronic illnesses or used protective equipment. The mean working duration was 4.7±3.4 years (Table 2).

SOUND INTENSITY MEASUREMENTS

The maximum equivalent continuous sound level recorded was Leq dB(A) 81.9 dB(A), and the highest peak noise level was Lpeak dB(C) 114.5 dB(C) (Table 3). Noise levels were significantly higher when ventilation was on compared to when it was off (p<0.001). At the treatment depth with ventilation on, 26 of 41 centers (63.4%) exceeded the 70 dB(A) threshold. With ventilation off, only 1 center (2.4%) exceeded this limit. No center surpassed the 90 dB(A) limit during the compression or decompression phases (Table 4). Lpeak dB(C) values remained below the 135 dB(C) threshold in all centers. In 28 centers (68.2%), the primary noise source was located to the right of the operator's' position at the control desk.

HEARING MEASUREMENTS

The changes in the audiometric values measured in the operators were examined (Table 5). Hearing tests conducted at least 1 year apart showed a statistically

FIGURE 1: Geographic distribution of the 41 HBOT centers across 21 cities in Türkiye that participated in the study
HBOT: Hyperbaric oxygen therapy

TABLE 1: Maximum daily exposure time according to sound levels

Sound level (dB)	Maximum daily exposure time (Hours)
85	8
87	6
90	4
92	3
95	2
97	1.5
100	1
105	0.5
110	0.25

TABLE 2: Demographic characteristics of the participants

Characteristic	**Value**
Total participants	28
Sex	
Male, n (%)	21 (75.0%)
Female, n (%)	7 (25.0%)
Age (minimum-maximum)	36 (23-52)
Body mass index (minimum-maximum) (kg/m²)	25.2 (21.3-29.1)
Smoking status	
Non-smokers, n (%)	19 (67.9%)
Smokers and ex-smokers (%)	9 (32.1%)
Chronic disease, n (%)	0 (0%)
Medication use, n (%)	0 (0%)
Use of hearing protection, n (%)	0 (0%)

significant hearing threshold shift in the right ear at 4,000 Hz [mean change: 2.7 dB(A)] (p=0.039). No significant differences were observed in other frequency bands or between genders and body mass index (BMI) categories. A mean change of 6.1 dB(A) was observed in the left are at 4,000 Hz (p=0.057). The observed shift at 4,000 Hz in the right ear may be attributed to the operator's position relative to the main sound source.

DISCUSSION

This study demonstrated that hyperbaric chambers can produce sound levels that occasionally exceed international safety standards, particularly during the ventilation phases. According to EN 14931, the acceptable levels are 70 dB(A) during treatment and 90 dB(A) during compression and decompression. While our study found that none of the centers exceeded the 90 dB(A) threshold, 63.4% of the centers exceeded the 70 dB(A) treatment-phase threshold with ventilation on. This is consistent with the findings of Zaman et al. who also found elevated sound levels during HBOT sessions, particularly during the ventilation phases.[1]

Previous studies have reported high levels of noise within hyperbaric chambers, particularly in

TABLE 3: The highest and lowest sound intensity values measured during each stage				
Parameter	Compression (dB)	Treatment depth-vent on (dB)	Treatment depth-vent off (dB)	Decompression (dB)
Leq (dB A)				
Highest	80.4	81.9	71.7	76.1
Lowest	61.4	58.8	43.0	57.6
Lpeak (dB C)				
Highest	114.5	109.5	101.9	114.5
Lowest	88.9	83.8	80.9	89.3

dB: Decibel

TABLE 4: Average Leq values and distribution of centers exceeding noise limits						
Phase	Average Leq [dB(A)]	Limit [dB(A)]	Number of centers exceeding limit	70-74.9 dB(A) range	75-79.9 dB(A) range	80-85 dB(A) range
Compression	71.56	90	0	17	8	1
Decompression	68.44	90	0	13	1	0
Treatment depth-ventilation on	71.74	70	26	11	12	3
Treatment depth-ventilation off	59.83	70	1	1		

dB: Decibel

TABLE 5: Comparison of first and last audiometric measurements of operators				
Frequency (Hz)	Right ear-mean change (dB)	p value	Left ear-mean change (dB)	p value
250	0.8±7.8	0.187	0.0±6.3	0.373
500	0.4±7	0.567	0.2±5.9	0.543
1,000	0.8±4.6	0.518	-0.04±4.4	0.920
2,000	-0.0±5.5	0.916	-0.7±4.5	0.997
4,000	2.7±6.1	**0.039**	6.1±17.5	0.057
6,000	-1.1±6.5	0.931	-0.46±7.21	0.749
8,000	-1.1±7.6	0.825	-0.2±10.3	0.884
Pure-tone audiometry air	1.4±4.7	0.083	0.5±4.6	0.747

dB: Decibel

older designs or during aggressive ventilation. For instance, Parvin and Nedwell, as well as Nedwell et al. documented internal chamber noise levels exceeding 100 dB(A), raising concerns about potential auditory damage among both patients and personnel.[10,11] However, subsequent technological improvements-such as the use of metal mufflers-have significantly mitigated these risks. Summitt and Reimers demonstrated that the implementation of various mufflers in the Navy's test dive unit could reduce noise levels by up to 30 dB(A), underscoring the effectiveness of such modifications in minimizing acoustic exposure during chamber operations.[12] Today, with more modern infrastructure and enhanced noise control measures, hyperbaric chamber environments tend to produce considerably lower noise levels. In our study, although in-chamber measurements were not performed, operator zone assessments showed that peak noise values [Lpeak dB(C)] remained well below the critical threshold of 135 dB(C), indicating no immediate risk of acoustic trauma. Nonetheless, even moderate noise levels may contribute to long-term subclinical hearing changes through cumulative exposure, emphasizing the importance of sustained monitoring and preventive strategies in current practice.

While Leq dB(A) and Lpeak dB(C) values were measured at the operator ear level, the absence of personal dosimetry or continuous exposure tracking limits the ability to fully characterize cumulative noise exposure or establish precise dose–response relationships at 4,000 Hz in the right ear (p=0.039), which is consistent with the typical pattern of noise-induced hearing loss (NIHL). The 4,000 Hz frequency is often the first to be affected by noise exposure due to the anatomical and physiological characteristics of the cochlea. The organ of the Corti, particularly in the basal turn, is most sensitive to high-frequency sounds around 3,000-6,000 Hz, making it vulnerable to damage from prolonged or intense noise exposure.[13,14] This frequency range corresponds to the resonance of the outer ear canal, which amplifies sound energy and increases the risk of cochlear hair cell damage.

Although NIHL is typically considered symmetrical, Le et al. reported an asymmetry prevalence ranging from 4.7% to 36%, attributing it to factors such as the head shadow effect, proximity to the noise source, and possible differences in ear susceptibility.[15,16] In our study, a greater impact on the right ear was observed in the form of a statistically significant subclinical hearing threshold shift at 4000 Hz (p=0.039). This asymmetry is likely attributable to the noise source being positioned to the right of the control desk in the majority of the centers (68.2%), aligning with Le et al.'s assertion that proximity to the noise source may result in asymmetric NIHL. Although the mean threshold shift in the left ear was higher (6.1 dB), the greater inter-individual variability (SD: 17.5 dB) prevented the finding from reaching statistical significance (p=0.057). This underscores that statistical significance is influenced not only by the magnitude of change but also by the variability within the data. Notably, while only the right ear exhibited a statistically significant threshold shift, a similar trend was evident in the left ear. It is conceivable that with a larger sample size, the left ear may also have demonstrated significance, supporting the presence of the bilateral subclinical effects of noise exposure. Although the mean threshold shift in the left ear at 4,000 Hz was relatively higher (6.1 dB), statistical significance was not achieved (p=0.057). A "post hoc" power analysis based on the observed effect size (Cohen's d≈0.35) and the actual sample size (n=28) revealed a statistical power of only 42.8%. This indicates a high risk of Type II error, suggesting that the lack of statistical significance may be attributed to insufficient power rather than the absence of a true effect. Despite none of the participants meeting the criteria for clinical hearing loss, these early audiometric changes suggest the potential for cumulative auditory damage over time in the absence of effective protective measures. We also investigated variables such as gender and BMI. While the literature suggests hormonal and metabolic influences on auditory physiology-such as the protective effects of 17β-estradiol reported by Shuster et al.-our data did not reveal significant associations.[17] This may be due to the small sample size or short follow-up duration. Curhan et al. found that a higher BMI was linked to an increased hearing loss risk (Relative Risk [RR]: 1.25, 95% confidence interval: 1.14-1.37 for BMI ≥40), citing cochlear vascular damage.[18] Conversely, our study detected no such association. This may stem from Curhan et al.'s large cohort (68,421 women, 20 years) versus our smaller sample. Noise exposure in HBOT centers may have masked the BMI's effect.[18] The BMI-hearing loss link likely varies by population and study design, warranting broader research.

The limitations of our study include heterogeneity in the chamber architecture, reliance on retrospective audiograms, and lack of exact exposure durations. Future studies should incorporate real-time personal dosimetry, assess in-chamber personnel, and control for confounding variables such as age, comorbidities, and previous noise exposure.

CONCLUSION

Although no operator in our study met the clinical criteria for NIHL, a statistically significant hearing threshold shift at 4,000 Hz in the right ear-a frequency typically affected early by noise exposure-was identified. These findings may reflect early subclinical auditory changes associated with cumulative occupational noise exposure. To mitigate long-term auditory risks and ensure a safer work environment, we recommend regular noise assessments, age-adjusted audiometric monitoring, mandatory use of hearing protection when noise exceeds 70 dB(A), and engineering solutions to reduce the noise at its source. The development of national HBOT-specific regulations is also warranted.

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Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

***Idea/Concept:** Recep Özkan, Taylan Zaman; **Design:** Recep Özkan, Taylan Zaman; **Control/Supervision:** Recep Özkan, Levent Yücel, Osman Türkmen; **Data Collection and/or Processing:** Osman Türkmen, Recep Özkan; **Analysis and/or Interpretation:** Levent Yücel, Taylan Zaman, Osman Türkmen, Recep Özkan; **Literature Review:** Recep Özkan, Osman Türkmen, Taylan Zaman; **Writing the Article:** Recep Özkan, Taylan Zaman, Osman Türkmen, Levent Yücel; **Critical Review:** Recep Özkan, Taylan Zaman; **References and Fundings:** Recep Özkan, Taylan Zaman, Osman Türkmen.*

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