

Hyperbaric Oxygen Therapy in Neurotologic Blast Injury - a Systematic Review and Meta-Analysis

Abstract

Background

Blast injury is a clinically and mechanistically distinct form of acute acoustic trauma. We aimed to compare the auditory effects of hyperbaric oxygen therapy (HBOT) with systemic glucocorticoids in blast-injured patients versus those exposed to gunfire.

Methods

Original, peer-reviewed studies published between January 1990 and March 2025 reporting gunshot or blast injuries in humans were included if they provided quantitative auditory outcomes, including pure-tone averages (PTA) and high-frequency pure-tone averages (hPTA), before and after therapy. Exposure definitions were harmonized: gunfire was defined as acute acoustic trauma from small arms fire (impulse noise), and blast injury as exposure to high-explosive detonations (e.g., IEDs, mortar, artillery) characterized by complex pressure waves. Qualitative studies, animal models, and studies lacking a sufficiently described exposure history were excluded. Studies reporting generic “acoustic trauma” or pooling blast and gunfire cohorts without extractable subgroup data were also excluded to prevent mechanism misclassification.

Results

Nine studies were included, five of which described blast-injured patients. Following completion of HBOT with steroids, PTA improvement was slightly greater in blast-injured patients (pooled Md 4.3 dB, 95% CI [1.6–7.0]) compared with gunfire-injured patients (pooled Md 3.75 dB, 95% CI [1.2–6.3]; $p = 0.019$). Improvement in hPTA was significantly greater in the gunfire group (19.3 dB, 95% CI [14.3–24.3]) than in the blast group (pooled Md 7.03 dB, 95% CI [3.1–10.9]; $p = 0.004$).

Conclusions

Neurotologic blast injuries demonstrate distinct patterns of damage and response to HBOT compared with gunfire-induced acute acoustic trauma, including greater low-frequency involvement and a more limited response at higher frequencies.

Keywords: Hyperbaric Oxygen, Acute Acoustic Trauma, Blast Injury.

Background

Sensorineural hearing loss (SNHL) is a type of hearing loss that results from damage to the inner ear or the auditory nerve. It is the most prevalent type of chronic hearing loss, accounting for approximately 90% of all reported cases, and is a major public health concern. (1) Globally, over 1.5 billion people (nearly 20% of the population) live with hearing loss, 430 million of whom have disabling hearing loss. (2) In Israel, approximately 24,500 adults aged 18 and older were registered with hearing

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impairments in 2020, representing a prevalence of 4.0 per 1,000 people. The rate was significantly higher in men (7.0 per 1,000) than in women (1.1 per 1,000). (3)

While etiology varies (e.g., presbycusis, genetic and congenital factors, toxins, autoimmune or idiopathic processes, and infections), the vast majority of new cases in young adults are due to noise exposure. (4) While occupational and recreational noise exposures are important etiologies worldwide, over two-thirds of the disease burden in service personnel results from acute, short, and intense noise exposure. Firearm exposure remains the leading offending agent; however, escalating conflicts and particularly large-scale land-based operations increase the relative proportion of another mechanism – high explosives resulting in blast injury. (5)

Blast injury is distinct from other mechanisms of acute acoustic trauma (AAT) in a few crucially important ways. (6) First, while other forms of harmful noise can be reliably quantified in terms of peak sound wave pressure, blast-generating explosions are characterised by complex and multiple sound pressure waves. In other words, the same peak pressure can be delivered over prolonged periods and over multiple positive and negative pressure waves. (7) Second, explosions generate multiple mechanisms of injury beyond the initial pressure wave. These include shrapnel (secondary blast injury), patient displacement or the rush of air returning to fill the low-pressure area created by the explosion (“blast wind”, all included under the general category of tertiary blast injury), and any ensuing thermal and kinetic injury (e.g., the collapse of the building, or quaternary blast injury). (6)

These important mechanistic differences are very likely to result in distinct natural histories, therapeutic options, and prognoses. (8) Currently, the administration of a combination of glucocorticoids and hyperbaric oxygen therapy (HBOT), consisting of pressurizing the patient in a hyperbaric chamber and breathing oxygen at partial pressures of 1.5-3.0 atmospheres absolute (ATA), is emerging as the accepted therapy for AAT. (9) We aimed to systematically review the available evidence concerning the response to combination therapy (i.e., HBOT with steroids) and auditory prognosis of blast-injured versus gunfire-exposed patients.

Methods

Search Strategy

A comprehensive and systematic literature search was conducted across the following databases: PubMed, Embase, Web of Science, Scopus, and the Cochrane Library. The search included articles published from January 1990 through March 2025. Keywords and MeSH terms included combinations of: “blast injury,” “acoustic trauma,” “explosion,” “sensorineural hearing loss,” “SNHL,” “cochlear damage,” “central auditory processing,” “cochlear synaptopathy,” “tinnitus,” “temporal bone injury,” “auditory dysfunction,” “hyperbaric oxygen,” “HBO” and “HBOT”.

Study Selection

Original, peer-reviewed studies reporting blast injuries in humans were included in this study, provided they reported quantitative data on auditory outcomes, including pure tone averages (PTA) and high-frequency pure tone averages (hPTA) before and after the therapeutic course, with pooled mechanism cohorts analyzed separately. Qualitative studies, animal models, and studies in which exposure history was not sufficiently described were excluded from this analysis.

Data Extraction

Two independent reviewers (IG and IMG) reviewed candidate studies and extracted data. Extracted data included study design, population characteristics, the mechanism of exposure, evaluation and treatment latency, type of treatment administered, and the hearing assessment methods (e.g., pure-tone audiometry, subjective symptoms, etc.). Risk of bias for human studies was assessed using the Newcastle-Ottawa Scale (NOS) for cohort and case-control studies. Disagreements between reviewers were discussed and resolved by consensus.

Statistical Analysis

Meta-analyses were performed using R (metafor package (41)). For continuous outcomes, mean differences (MD) in hearing thresholds (change scores) were calculated. When the standard deviation (SD) of the change score was not directly reported, it was calculated using the

pre- and post-treatment SDs, assuming a conservative correlation coefficient (r) of 0.5. A random-effects model (DerSimonian and Laird) was employed to account for between-study heterogeneity. Heterogeneity was assessed using the I^2 statistic, with I^2 values $>50\%$ considered substantial. Publication bias was evaluated using funnel plots and Egger's regression test. However, given the limited number of studies included ($n=9$), these results were interpreted with caution due to potential small-study effects.

Results

A total of 853 articles were identified through initial database searching. After removal of duplicates ($n=692$) and screening of abstracts, 189 full-text articles were assessed for eligibility. Ultimately, 35 studies met the inclusion criteria for qualitative synthesis, and 9 studies remained after excluding those with poorly defined exposure (14), purely animal models (2), and a lack of quantitative outcome (10). This selection process is presented in Figure 1.

The mean age across studies ranged from 18 to 34 (range

4-80) years, and the populations were predominantly male (54-100%), reflecting the overwhelmingly military cohorts studied. Hyperbaric oxygen therapy protocols ranged from 5 to 20 sessions, at maximal pressures of 2.0-2.5 ATA administered over 60-120 minutes, in addition to standard medical therapy that included systemic or intratympanic corticosteroids in all but one study.⁽¹⁰⁾ Reported pure tone averages allowed for a relatively simple calculation of the changes in pure-tone average (Δ PTA) and high-frequency pure-tone average (Δ hPTA) in the minority of cases where these figures were not directly reported (10-12). These studies are outlined in Table 1.

For gunfire-related acute acoustic trauma, HBOT with steroids was associated with a statistically significant improvement in hearing thresholds. The pooled mean difference in PTA was 3.75 dB (95% CI 1.2 to 6.3, $p < 0.001$) with relatively high heterogeneity ($I^2 = 90\%$). The pooled mean difference in hPTA was considerably more pronounced at 19.3 dB (95% CI 14.3 to 24.3, $p < 0.001$, $I^2 = 92\%$). Conversely, overall improvement was considerably less clinically or statistically significant

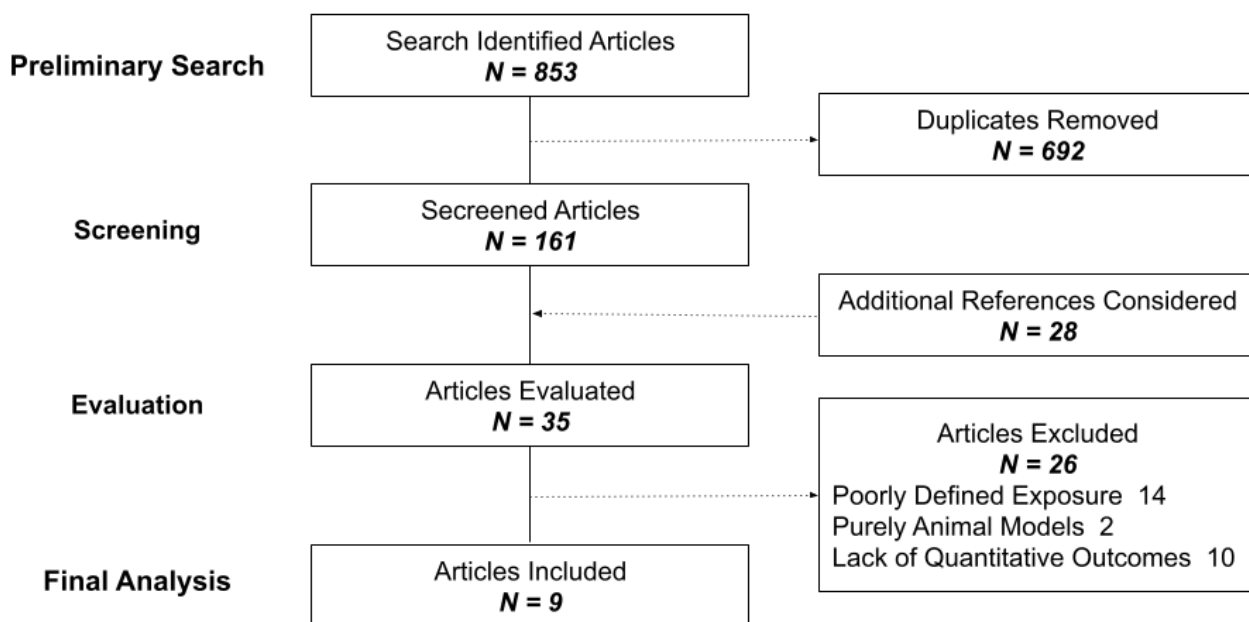


Figure 1 – The selection process is depicted in accordance with CONSORT guidelines. The search strategy yielded 853 initial articles; after removing duplicates and screening for eligibility criteria (human participants, quantitative auditory outcomes), 9 studies were included in the final meta-analysis. Reasons for exclusion, such as lack of quantitative data or insufficient exposure history, are detailed in the exclusion box.

Authors	Study Period	Country of Origin	Population	Exposure Type	Time from exposure to Tx	Treatment offered	N	Female	NOS
Holy et al. (2)	2014-2019	Czech Republic	military and civilian	Gunfire and Blast	< 7 days	HBOT + Systemic Steroids	68	2	5/9
Gutkovich et al. (3)	2016-2022	Israel	military	Gunfire and Blast	< 7 days	HBOT + Systemic Steroids	86	6	6/9
Van Haesendonck et al. (13)	2018	Belgium	civilian	Blast	Not Reported	HBOT + Systemic Steroids	21	10	7/9
Oya et al. (14)	1997-2017	Brazil	military	Gunfire and Blast	Mean 24.5 days	HBOT + Systemic Steroids	37	3	5/9
Salihoğlu et al. (15)	2011-2013	Turkey	military	Gunfire and Blast	< 10 days (Group A)	HBOT + Systemic Steroids	73	0	5/9
Lafère et al. (12)	2006-2008	Belgium	military	Gunfire	Not Reported	HBOT + Systemic Steroids	98	0	7/9
Bayoumy et al. (40)	2012-2017	Netherlands	military	Gunfire	2 days	HBOT + Systemic Steroids	53	0	5/9
Ylikoski et al. (11)	1993-1996	Finland	military	Gunfire	Not Reported	HBOT + Systemic Steroids	60	0	5/9
Vavrina and Müller (10)	1990-1992	Switzerland	military	Gunfire	Not Reported	HBOT Only	78	0	4/9

Table 1 – Studies included in this meta-analysis are presented below, including the critical appraisal (by way of Newcastle-Ottawa Scale (NOS)).

in blast-injured cohorts, with a modestly more pronounced improvement in PTA (pooled Md 4.3 dB (95% CI 1.6 to 7.0, $p = 0.019$) with low heterogeneity ($I^2 = 0.4\%$). The improvement in hPTA was significantly less pronounced, with pooled Md of 7.03 dB (95% CI 3.1 to 10.9, $p < 0.001$, $I^2 = 0.3\%$). These results are presented in Figure 2 and Figure 3.

The test for subgroup differences confirmed that the therapeutic effect of HBOT with steroids differed significantly between the two mechanisms of injury.

Improvements in hPTA were significantly greater in gunfire-related trauma compared with blast-related injury ($p = 0.004$). Improvement in PTA was slightly more pronounced in the blast-injured group ($p = 0.019$), although this difference was not clinically significant (Md 0.56 dB, 95% CI 0.04 to 0.83). Estimating publication bias by a funnel plot (Figure 4) revealed relatively low evidence of publication bias (Egger's regression $p = 0.47$) for hPTA, with a slightly higher risk of publication bias for PTA ($p = 0.16$).

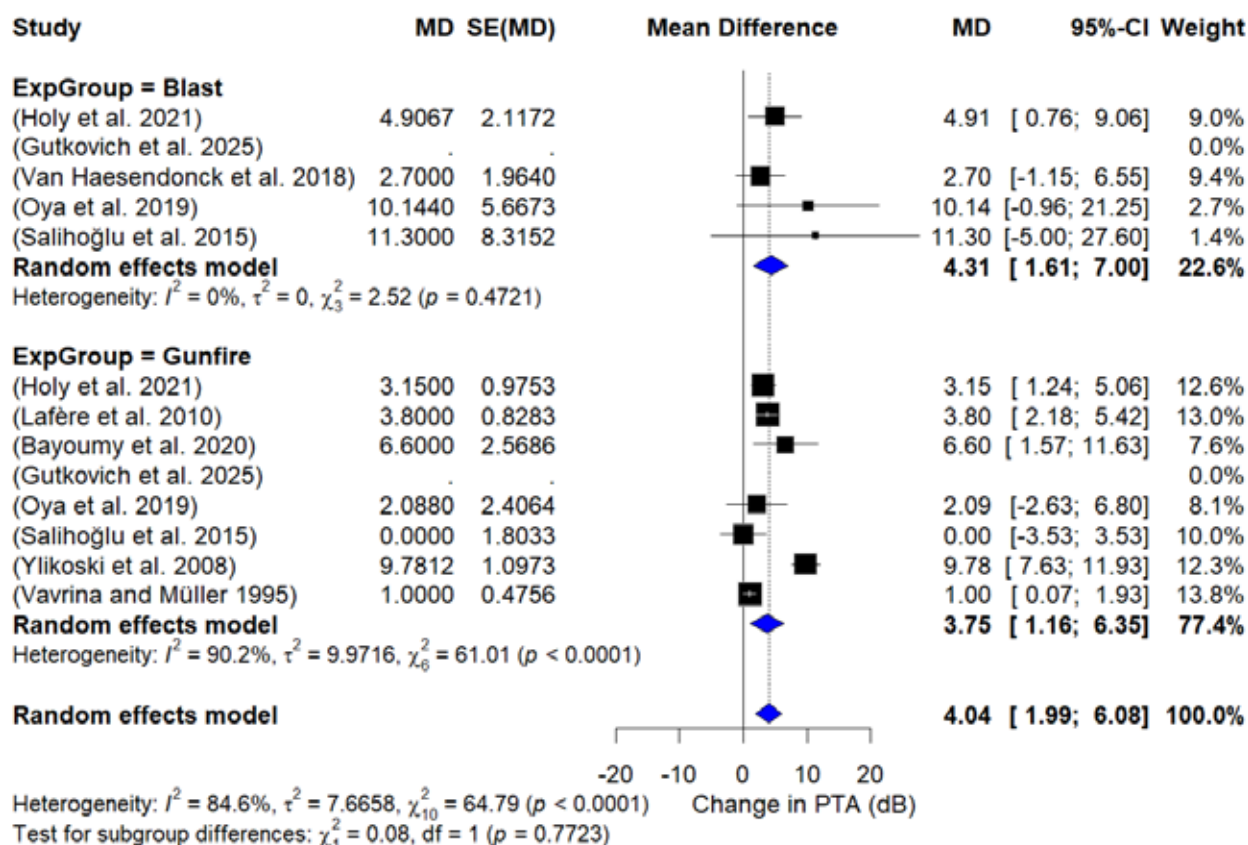


Figure 2 – Pure Tone Averages - This forest plot displays the mean difference (MD) in hearing thresholds following hyperbaric oxygen therapy (HBOT) combined with corticosteroids. PTA is defined as the average threshold at 0.5, 1, and 2 kHz. The analysis is stratified by injury mechanism: Blast (top) vs. Gunfire (bottom). Black squares represent the mean difference for each study, with horizontal lines indicating the 95% confidence intervals (CIs). The size of the square corresponds to the study's weight in the analysis. The blue diamonds represent the pooled effect sizes for each subgroup, calculated using a random-effects model. The vertical line at 0 dB indicates no effect; values to the right indicate hearing improvement.

Discussion

In this systematic review, we identified 9 human studies reporting pure-tone threshold averages following acute acoustic trauma. Only in five of these were any data reported concerning the auditory outcomes of blast injury.(2,3,13–15) This relative paucity of evidence could be the confluence of two factors. First, blast exposure used to be a relatively rare occurrence, restricted to active war zones and terror attacks, where HBO therapy with steroid availability is limited, and hearing restoration is not always the most pressing issue at hand. (16) Second, the complex nature of blast exposure, compared with impulse and impact noises, makes the quantification of the hazardous acoustic energy in each individual

exposure scenario extraordinarily complex. (17) For these reasons, several authors deemed the exposure history or even the initial audiogram insufficiently reliable to differentiate blast injury from other forms of AAT. (18,19)

A significant source of heterogeneity in this meta-analysis, particularly within the gunfire cohort ($I^2 > 90\%$), likely stems from the temporal and geographic variability across the included studies 444. The data span 30 years (1990–2022) and covers diverse medical settings across Europe, the Middle East, and South America (5). This diversity is reflected in the hyperbaric protocols employed, which ranged from 5 to 20 sessions and used pressures between 2.0 and 2.5ATA. While

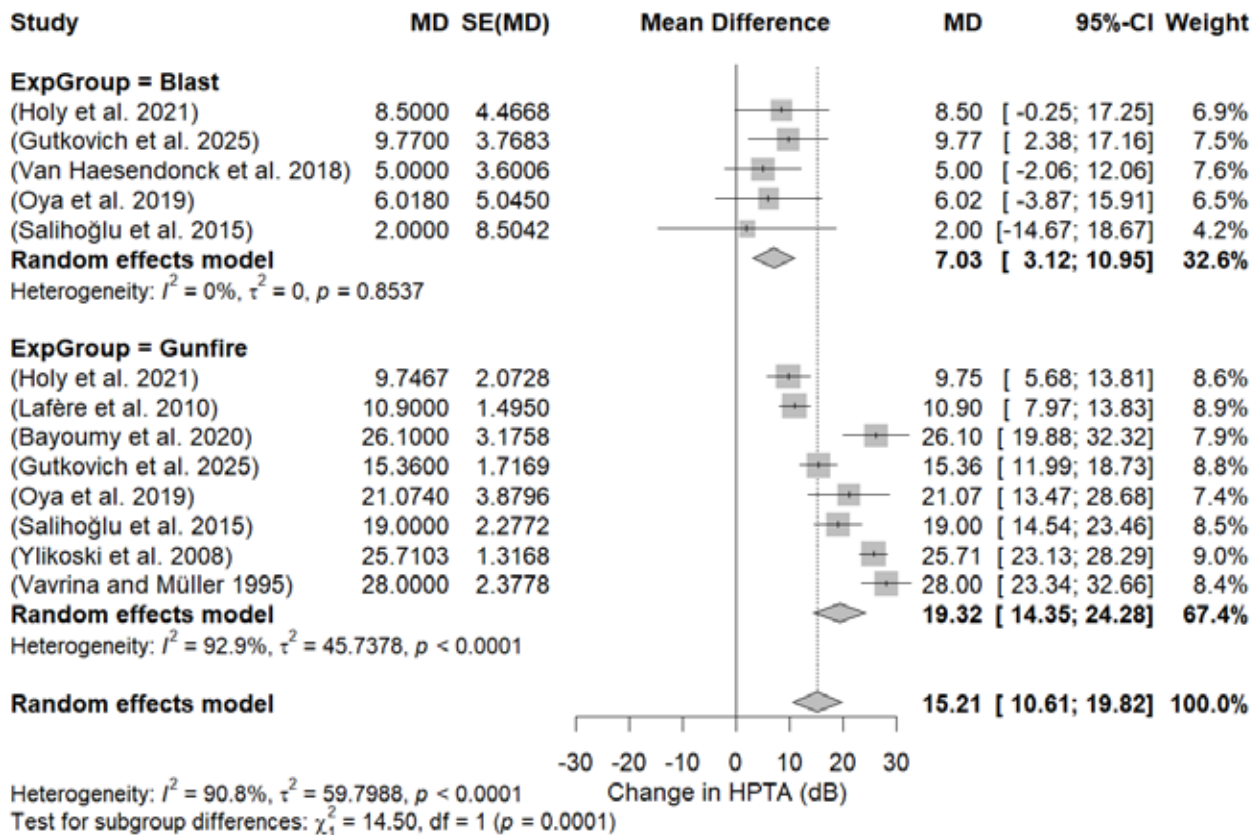


Figure 3 – High Pure Tone Averages - The mean effect of HBOT with corticosteroids on high-frequency thresholds is presented. hPTA is calculated as the average threshold at 3, 4, 6, and 8 kHz. The data is stratified by Blast and Gunfire subgroups. Black squares indicate individual study mean differences (MD) with 95% confidence intervals (CI), and blue diamonds represent the pooled estimate from a random-effects model. Note the significantly larger improvement in the Gunfire cohort (Pooled MD 19.32 dB) compared to the Blast cohort (Pooled MD 7.03 dB).

military protocols often strive for standardization, local logistical constraints and evolving clinical guidelines over three decades inevitably introduced variability in treatment intensity and timing. Notwithstanding these concerns, overwhelming evidence in animal studies (20–24) and the published evidence included in this review underline the distinct clinical and pathophysiological attributes of blast injury. Recent conflicts have resulted in a 3 to 20-fold increase in the prevalence of reported blast injuries (5,25–28), justifying the further inquiry into this neurologically distinct entity. Our analysis shows lower frequency impairment (as reflected by the PTA) to be more common, and shows a slightly

better response to HBOT with steroids, in blast injury compared with gunfire. This could be the result of the multifactorial nature of auditory damage resulting from blast injuries, distinguishing them from more localized and mechanistically straightforward acute acoustic trauma (AAT). (29) Both blast injuries and AAT can cause sensorineural hearing loss primarily through damage to the cochlear hair cells. (30) However, blast injuries exert a broader impact that includes damage to all other structures in the auditory system, (31) including synaptopathy, (32) spiral ganglion neuron loss, (33) cortical dysfunction, (7) altered neurotransmitter signaling, (34) and neuroinflammation. (35) Conversely, pure AAT resulting from short impulse

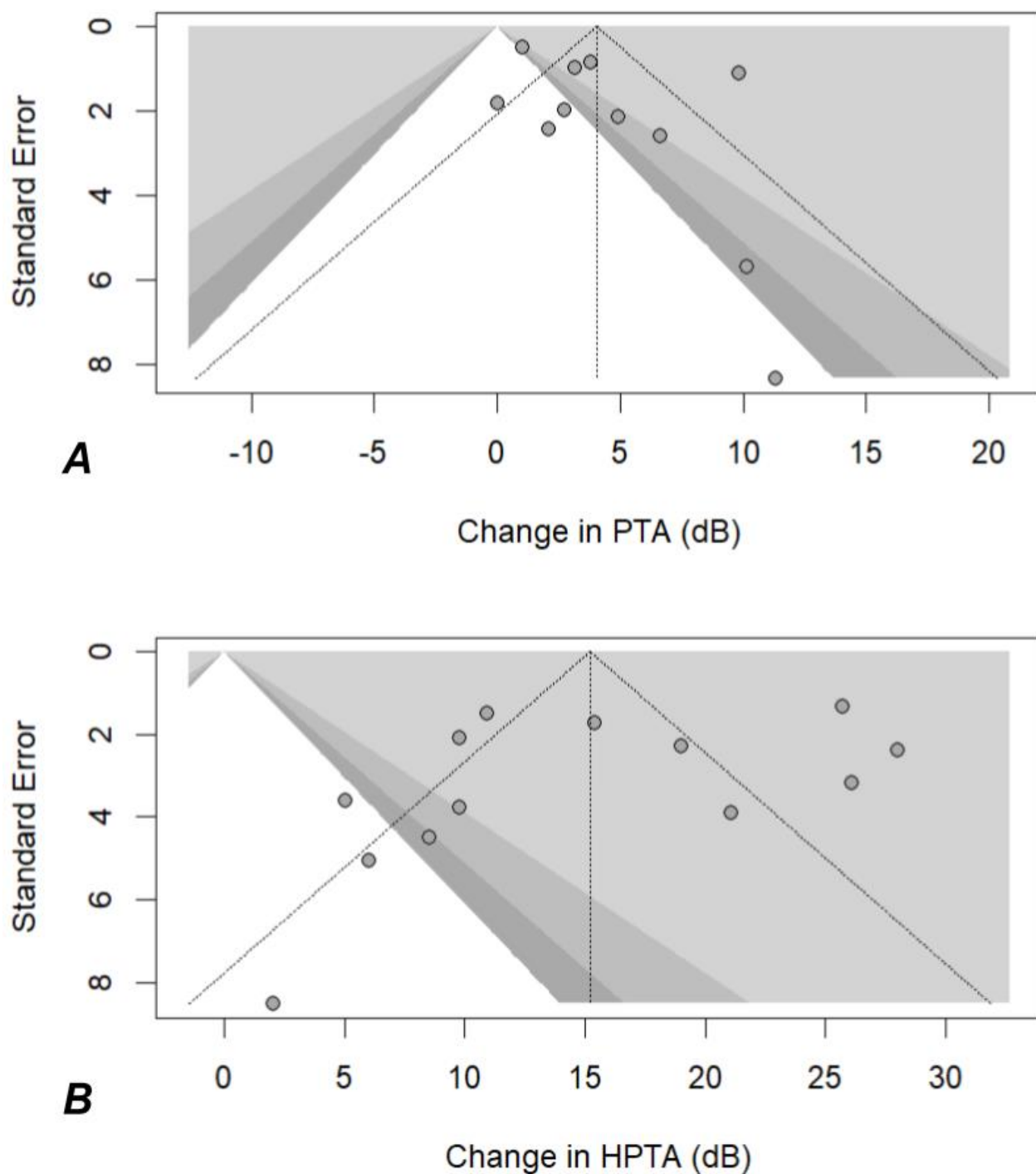


Figure 4 - Funnel plots assessing the risk of publication bias by plotting the effect size (Change in dB) against the standard error. (A) Pure Tone Average (PTA): Shows the distribution of studies for low-to-mid frequency outcomes. (B) High-Frequency Pure Tone Average (hPTA): Shows the distribution for high-frequency outcomes. The vertical dotted line represents the pooled effect estimate, and the diagonal dotted lines represent the pseudo-95% confidence limits. Asymmetry in the plot would suggest potential publication bias; Egger's regression tests indicated low evidence of bias for hPTA ($p=0.47$) and a slightly higher risk for PTA ($p=0.16$).

noise patterns such as gunfire tends to cause focused damage at the base structures in the cochlea and adjacent neural structures, resulting in significantly greater impairment at higher frequencies (as reflected by the hPTA). (36) The complex mechanisms resulting in long-term SNHL are believed to be an intricate synergy of neuroinflammatory mechanisms of damage (37). This notion is supported, amongst other evidence, by the improved therapeutic response to the combination of HBOT and systemic anti-inflammation compared to HBOT alone. (12,38,39)

For military health organizations such as the IDF Medical Corps, these findings hold immediate policy relevance. As modern conflicts increasingly involve high-explosive weaponry, distinguishing blast injury from standard acoustic trauma is critical for medical triage and force preservation. Our data confirm that while the combined HBOT and steroid protocol is effective for the lower frequencies often affected by blast, the high-frequency hearing loss in these patients is significantly more resistant to treatment compared to gunfire exposure. Operationally, this suggests that while the current aggressive treatment protocol should be maintained for all acute acoustic trauma, clinicians must adjust prognostic expectations for blast victims. These service members may experience lower rates of full auditory recovery and may require earlier referral to auditory rehabilitation to facilitate an effective return to duty.

Conclusion

Combined HBOT and systemic steroids appear effective in the treatment of acute acoustic trauma. Current evidence suggests that neurotologic blast injuries exhibit distinct patterns of damage and response to HBOT compared to gunfire-induced acute acoustic trauma, including more pronounced lower-frequency involvement and a more limited response at higher frequencies. Larger, prospective, and preferably long-term investigations directed specifically at blast-injured patients are imperative to improve our understanding and clinical outcomes for this injury mechanism, which is ever-increasing in prevalence. Such well-designed studies could also help isolate the relative contribution of HBO therapy compared with systemic steroids.

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None to declare

Contributorship

IG and GW conceptualized this study. IG and IMG conducted the search, independently assessed articles for eligibility, and completed the initial draft for this manuscript. IG performed the statistical analysis. All authors reviewed and approved the final version of this article.

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