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ORIGINAL RESEARCH

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Do high-frequency air-bone gaps persist after ossiculoplasty?

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Abstract

Objectives: Conventional reporting of postoperative hearing outcomes utilizes a pure-tone averaged air-bone gap (ABG) that is biased toward low frequencies. Consequently, a high-frequency ABG after otologic surgery may go unnoticed. In this study, we evaluate changes in low- and high-frequency ABG following ossiculoplasty.

Study design: Retrospective review.

Subjects and setting: Consecutive series of patients who underwent ossiculoplasty at a single tertiary care center. Patients with pre- and postoperative audiograms were included.

Methods: Low-frequency ABG was calculated as the mean ABG at 250, 500, and 1000 Hz. High-frequency ABG was calculated at 4 kHz. Pre- and postoperative ABGs were compared.

Results: Thirty-seven consecutive patients were included. Mean age at surgery was 38 years (range, 7-77 years). Reconstruction materials included: cartilage (N = 4), hydroxyapatite cement (N = 5), and partial or total ossicular replacement prostheses (N = 20 and N = 8, respectively). Postoperatively, the mean low-frequency ABG improved by 11.9 ± 15.1 dB ($P < .0001$) and the mean high-frequency ABG improved by 5.9 ± 16.0 dB ($P = .030$). Low-frequency ABG closure was significantly larger than high-frequency ABG closure ($P = .007$). Mean postoperative persistent high-frequency ABG was 22.0 ± 13.8 dB.

Conclusion: In this series, ossiculoplasty improved ABG across all frequencies, but greater improvements were observed at low frequencies when compared to high frequency. Current reporting standards may not identify persistent high-frequency ABG. Additional study of the mechanisms of high-frequency sound conduction in reconstructed middle ears is needed to improve high-frequency hearing outcomes in ossiculoplasty.

Level of evidence: Level 4.

KEYWORDS

conductive hearing loss, hearing loss, high-frequency hearing loss, middle ear reconstruction, ossiculoplasty

1 | INTRODUCTION

The ossicular chain is a vital mechanical pathway for coupling sound-induced motion of the tympanic membrane (TM) to the inner ear.[1] In patients with conductive hearing loss, common pathology includes ossicular erosion secondary to chronic otitis media (COM), bone resorption from an expanding cholesteatoma, or acute disarticulation following temporal bone trauma.[2,3] Surgical reconstruction of the ossicular chain (ossiculoplasty) has been the primary approach taken by otologist to improve conductive hearing in affected patients. Since its popularization in the second half of the 20th century, the techniques and materials utilized in ossicular reconstruction has substantially expanded, with dozens of reconstructive materials and prostheses available to surgeons.[4]

Given the variety of procedures that can be broadly categorized as an ossiculoplasty, surgeons have long struggled to isolate factors that most significantly impact audiometric outcomes.[4,5] This has prompted numerous investigational studies into the selection of reconstruction materials[6,7] and development of classification schemes that incorporate key factors, such as perioperative status of the ossicular chain and condition of the surrounding mucosa.[8-11]

Considering the goal of ossiculoplasty is to improve middle ear sound transmission, it is important to analyze and report audiometric results from these investigational efforts in a meaningful manner. Traditionally, audiometric reporting is done according to the Hearing Committee of the American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) recommendations of using a four-tone average air-bone gap (ABG) including 500, 1000, 2000, and 3000 Hz.[12,13] Despite collecting data from a wide spectrum of frequencies via pre- and postoperative multifrequency audiometry, condensing results in this manner leaves little room for reporting high-frequency hearing gain or loss following ossiculoplasty.

In this study, we assess hearing outcomes in patients having undergone ossiculoplasty with a specific focus on high-frequency conductive hearing. Our goal is to understand if current methods of ossiculoplasty correct both low and high-frequency conductive hearing loss. Frequency-specific changes in ABG are analyzed within subgroups arranged according to ossiculoplasty techniques and pathologic etiology. Improved knowledge of how reconstructed ossicular chains impact audiologic trends across a broad frequency range may influence future surgical techniques and outcome reporting.

2 | METHODS

2.1 | Subjects

The charts of a consecutive series of patients who underwent ossiculoplasty at a single tertiary care center were reviewed. Inclusion criteria were: patients that underwent ossiculoplasty with or without concurrent tympanoplasty, primary or revision procedure, and available pre- and postoperative audiograms. Exclusion criteria included: patients without TM perforation closure, stapedotomy, and canal wall down mastoidectomy. Patients that underwent canal wall up mastoidectomy were not excluded. Institutional review board approval was obtained from the Human Subjects Committee: approval # H00017444.

2.2 | Surgical technique

All ossicular reconstructions were performed by two surgeons at a single tertiary care Otolaryngology department with patients under general anesthesia. If required, any cholesteatoma was removed prior to a one-stage or two-stage reconstruction. Ossicular anatomy was assessed. Reconstruction material was chosen based on patient anatomy, condition of remnant ossicles, and history of concurrent infection. In each case, materials included one of the following: tragal cartilage graft as stapes type III major columella, hydroxyapatite cement for incudostapedial articulation, or placement of a synthetic partial ossicular replacement prosthesis (PORP; Kurz, Dusslingen, Germany) or total ossicular replacement prosthesis (TORP; Grace Medical, Memphis, Tennessee). Ossicular continuity and mobility were confirmed visually during reconstruction. If required, a synchronous tympanoplasty was then performed using a temporalis fascia or cartilage graft. Any exposed bony ear canal wall was lined with split thickness skin grafts prior to placement of packing material.[14]

2.3 | Audiometric evaluation

All audiometric data were extracted from pre- and postoperative standard pure-tone air and bone conduction threshold audiometry exams performed closest to the date of surgery. Pure-tone thresholds for air and bone conduction at 250, 500, 1000, 2000, 3000, and 4000 Hz were recorded; with an additional air conduction recording at 8000 Hz. Frequency-specific ABG was calculated as the difference between the pure-tone air conduction and the pure-tone bone conduction. Low-frequency ABG was defined as the mean ABG at 250, 500, and 1000 Hz. High-frequency ABG was defined as the ABG at 4000 Hz.

In accordance with AAO-HNS recommendations,[12] hearing results were also depicted in a scattergram format relating the average ABG pure-tone threshold to the word recognition score (WRS). Pure-tone averages (PTAs) were calculated for both air conduction and bone conduction by averaging the patient's thresholds at 500, 1000, 2000, 3000 Hz. In cases where 3000 Hz was unavailable, this value was substituted by averaging the 2000 and 4000 Hz thresholds.[12] The pure-tone average ABG (PTA-ABG) was then calculated as the difference between the air conduction PTA and the bone conduction PTA. Patients without tested discrimination scores (due to non-English or non-Spanish primary language) were excluded.

Pre- and postoperative ABG were summarized in bins constructed as follows: normal (0-10 dB), mild (11-20 dB), moderate (21-30 dB), and severe (>30 dB).

2.4 | Statistical analysis

All audiometric values are reported as the mean and SD (SD). Student *t* test (two-tailed, paired) was used to compare measurements between low- and high-frequency ABG for all within-group analyses. Kolmogorov-Smirnov normality test was used to confirm that all continuous variables planned for statistical significance testing were normally distributed. For between-group analyses, student *t* test (independent, equal variance) was used to compare the magnitudes of low- and high-frequency ABG improvement for the following two subgroups: presence of cholesteatoma and presence of concurrent tympanoplasty. Single factor analysis of variance was used to assess the same measure for subgroup analysis by reconstructive material: cartilage, hydroxyapatite cement, PORP, and TORP. Significance was set at $P < .05$ for all statistical tests.

3 | RESULTS

Forty-eight patients were identified during the specified period. Of these, 11 were excluded for missing pre- or postoperative audiograms. Each of the remaining 37 patients (Table 1) met inclusion criteria. Age of patients ranged from 7 to 77 years old, with a mean age of 38 years. Nineteen patients (51%) were female and 16 (43%) were right ears. Middle ear pathology included trauma (14%), COM without cholesteatoma (38%), or COM with cholesteatoma (48%). Average time from surgery to postoperative audiogram was 4.5 months, with a range of 1.4 to 18.9 months.

3.1 | Hearing results

Pre- and postoperative ABGs were compared for all patients. The preoperative mean low-frequency ABG (30.4 ± 13.1 dB) was not significantly larger than the mean high-frequency ABG (28.0 ± 12.5 dB, P = .310). Postoperatively, the mean low-frequency ABG was 18.5 ± 11.1 dB and the mean high-frequency ABG was 22.0 ± 13.8 dB. The mean low-frequency ABG was significantly improved by 11.9 ± 15.1 dB ($P < .0001$). The mean high-frequency ABG was also significantly improved by 5.9 ± 16.0 dB (P = .030). Low-frequency ABG closure was significantly larger than high-frequency ABG closure (P = .007). Air conduction was significantly improved at 2000 Hz ($P < .001$) and 4000 Hz (P = .004) but not 8000 Hz (P = .507). Representative audiograms from two patients are demonstrated in Figure 1.

Twenty-two patients (60%) experienced an improvement in high-frequency ABG whereas 12 other patients (32%) had a worsening of their high-frequency ABG; the remaining three (8%) experienced no change. In comparison, 29 patients (78%) experienced an improvement in low-frequency ABG, whereas the other 8 (22%) had a worsening of their low-frequency ABG. Pre- and postoperative ABG for high and low frequencies are summarized, according to stratification bins, for all patients (Figure 2).

TABLE 1 Patient demographics

Characteristic	N = 37	(%)
Age (years)		
Mean	38.4	
Range	7-77	
Gender		
Female	19	(51.4)
Male	18	(48.6)
Sidedness		
Left	21	(56.8)
Right	16	(43.2)
Middle ear pathology		
Trauma	5	(13.6)
COM without cholesteatoma	14	(37.9)
COM with cholesteatoma	18	(48.5)
Duration of hearing loss		
<1 year	7	(18.9)
1-5 years	13	(35.1)
>5 years	17	(45.9)
Ossiculoplasty material		
Cartilage	4	(10.8)
Hydroxyapatite cement	5	(13.5)
PORP	20	(54.1)
TORP	8	(21.6)
Procedures		
Ossiculoplasty alone	13	(35.1)
Ossiculoplasty + tympanoplasty	24	(64.9)

Abbreviations: COM, chronic otitis media; PORP, partial ossicular replacement prosthesis; TORP, total ossicular replacement prosthesis.

When reported in accordance with the AAO-HNS guidelines,[12] preoperative PTA-ABG was 23 ± 11 dB. Postoperatively, the PTA-ABG significantly improved to 14 ± 9 dB ($P < .001$). The change in ABG was 9 ± 14 dB. Pre- and postoperative PTA-ABG are summarized, according to stratification bins, for all patients (Figure 2). Results for the 35 patients with available WRS are mapped into pre- and post-treatment scattergram plots shown in Figure 3.

Between-group comparisons of selected subgroups (Table 2) found that type of ossiculoplasty material had no impact on the magnitude of low- or high-frequency ABG improvement (P = .292 and P = .349, respectively). Although not statistically significant, it was noted that TORP placement promoted the largest ABG improvement at both low and high frequencies. There was also no significant difference in the magnitude of low or high-frequency ABG improvement (P = .923 and P = .147, respectively) when comparing ossiculoplasty-alone patients to those who received a concurrent tympanoplasty. Although there was no significant difference in the magnitude of low-frequency ABG improvement (P = .224) when subgrouped according to the presence of cholesteatoma, patients with cholesteatoma, on average, experienced a widening of their high-

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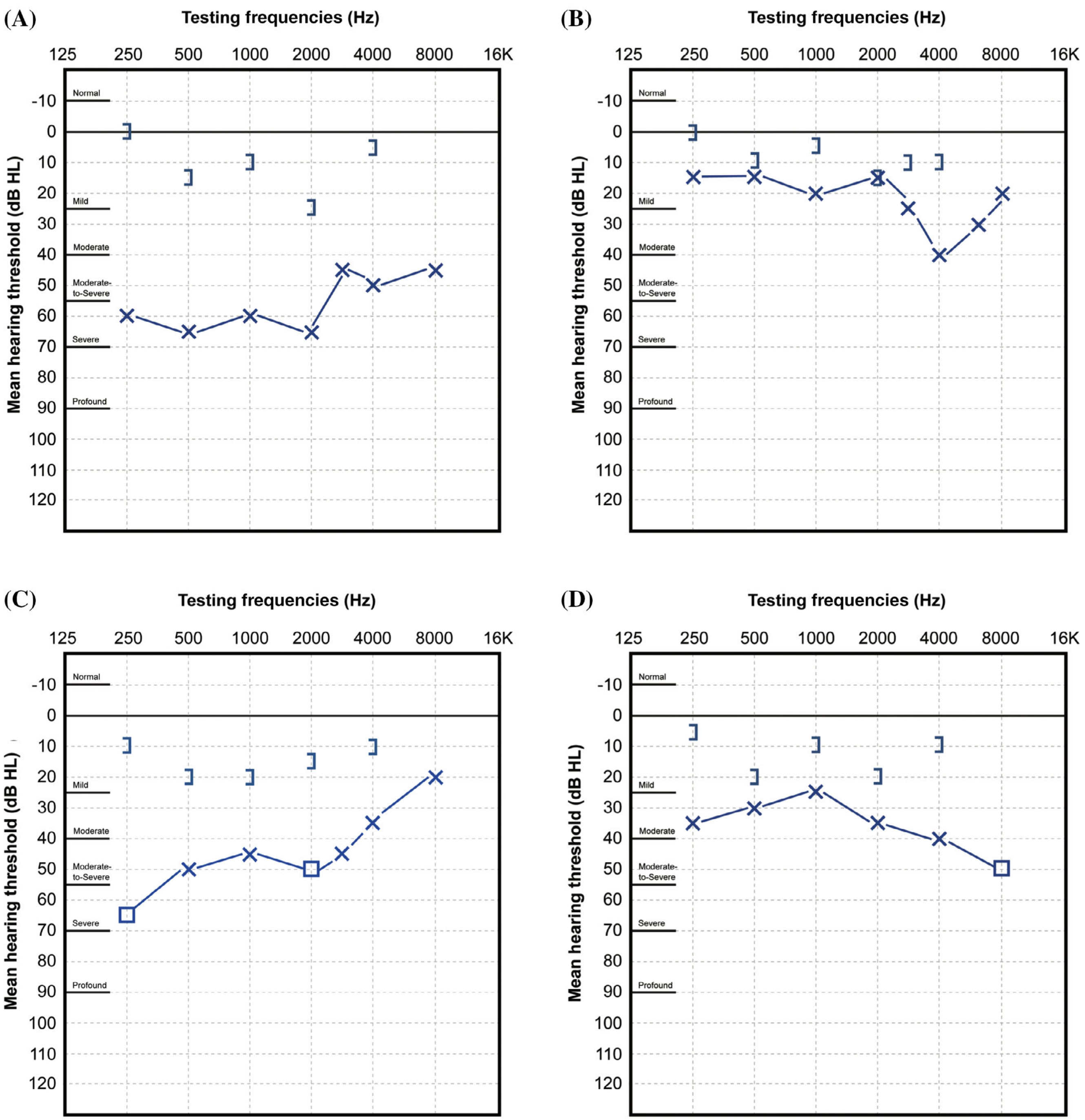

FIGURE 1 Representative audiograms demonstrating improved low-frequency air-bone gaps (ABG) but worsening high-frequency ABG (4000 Hz). Patient #1: left ear preoperative (A) and postoperative (B). Patient #2: eft ear preoperative (C) and postoperative (D)

frequency ABG (0.3 ± 15.9 dB) compared to those without cholesteatoma (−11.8 ± 14.1 dB, P = .019).

When comparing the magnitude of high- and low-frequency ABG changes within these selected subgroups, it was determined that ABG improvement was larger at low frequencies in patients with cholesteatoma (P = .002) and/or those undergoing ossiculoplasty with concurrent tympanoplasty (P = .003). A similar finding was not observed within other subgroups (Table 2 and Figure 4).

4 | DISCUSSION

This study is the first to our knowledge to quantitatively compare low-and high-frequency conductive hearing outcomes for patients undergoing ossiculoplasty. Although we find a significant improvement in hearing, as defined by the AAO-HNS guidelines, we determined that, when high-frequency hearing was isolated, a large persistent ABG exists. As such, changes in conductive hearing following ossiculoplasty appear to be frequency dependent, providing more

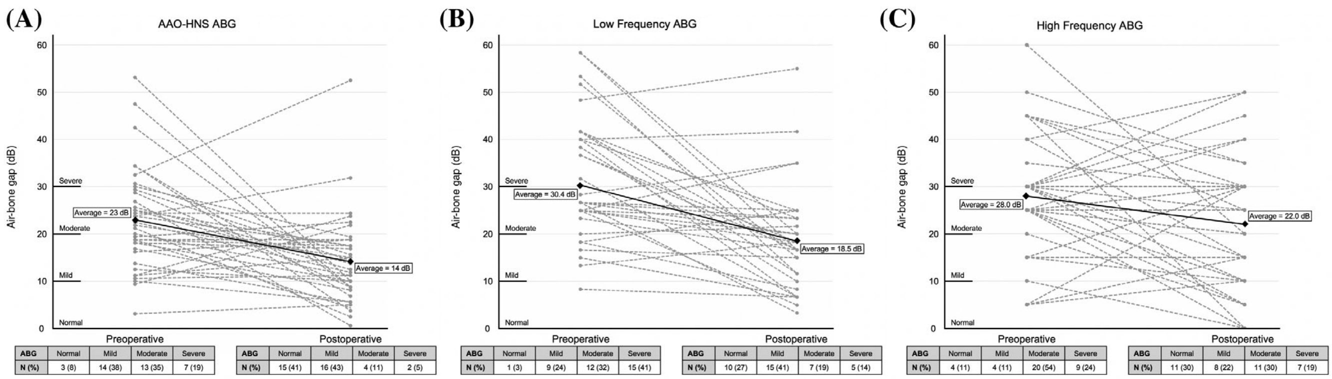

FIGURE 2 Pre- and postoperative air-bone gap (ABG) averages for all patients (N = 37), stratified by severity of ABG width. Results compared according to method of ABG calculation: American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) recommended four-tone average: 500, 1000, 2000, and 3000 Hz (A); low-frequency three-tone average: 250, 500, and 1000 Hz (B); and high-frequency tone: 4000 Hz (C). Normal (0-10 dB), mild (11-20 dB), moderate (21-30 dB), and severe (>30 dB)

(A) Word recognition score (%)

Pure tone average (dB HL)	100 - 90	89 - 80	79 - 70	69 - 60	59 - 50	49 - 40	39 - 30	29 - 20	19 - 10	9 - 0
0-10	2		1							
11-20	10	3								
21-30	7	3		2						
31-40	4									
41-50	1		1							
51-60				1						
61-70										
71-80										
81-90										
91-100										

(B) Word recognition score (post – pre, %)

← Improved … Worse →

Pure tone average (post - pre, dB) (↑ Improved / ↓ Worse)	>41	40 to 31	30 to 21	20 to 11	10 to 1	0	-1 to -10	-11 to -20	-21 to -30	-31 to -40	<-41
<-41			1								
-40 to -31				1			1				
-30 to -21						2					
-20 to -11				1	2	1	5				
-10 to -1				1	3	3	4				
0			1				1				
1 to 10					3		2				
11 to 20						2	1				
21 to 30											
31 to 40											
>41											

FIGURE 3 Scattergrams relating word recognition scores (WRS) and four-frequency pure-tone average air-bone gap (PTA-ABG) as per American Academy of Otolaryngology-Head and Neck Surgery (AAO-HNS) recommendations. Scattergrams for pretreatment (A) and postoperative changes (B) include the 35 patients with available WRS

benefit to low-frequency hearing. The frequency-specific difference in hearing results is only identified when independently analyzing low- and high-frequency conductive hearing outcomes. Although improvements in conductive hearing are significant at all frequencies, low-frequency ABG closure is significantly larger than ABG closure at 4 kHz. Current reporting standards for conductive hearing outcomes after surgery appear insufficient to address frequency-dependent hearing loss.

In this study population, surgery did little for those with severe high-frequency conductive deficits; as demonstrated by the mere 5% reduction in patients with a high-frequency ABG >30 dB, compared to the 27% reduction in patients with a low-frequency ABG >30 dB. However, when reported using traditional methods,[12] this observation is not apparent since our findings show that only 5% of patients maintained an ABG >30 dB in the postoperative period. It is important to note that, when reported using traditional methods, the postoperative PTA-ABG reported herein (14 dB) is similar to those reported in comparable studies of ossiculoplasty outcomes; for example, Kotzias et al and Mardassi et al reported postoperative PTA ABGs of 17.3 dB (N = 72 ears) and 17.1 dB (N = 70 ears), respectively.[15,16] Figure 2 demonstrates how traditional ABG reporting is biased toward low-frequency outcomes and overlooks frequency-dependent differences that exist within the same data set. By utilizing a low-frequency biased PTA calculation, traditional reporting methods do not recognize both the persistent high-frequency conductive deficits following osciculoplasty and the significantly different magnitude of ABG

TABLE 2 Audiometric outcomes by selected subgroups

	Mean low-frequency ABG[a]				Mean high-frequency ABG[b]				
Subgroup	PRE (±SD)	POST (±SD)	ΔABG (±SD)	ΔABG between subgroups (*P* value)	PRE (±SD)	POST (±SD)	ΔABG (±SD)	ΔABG between subgroups (*P* value)	Low versus high ΔABG (*P* value)
Cartilage (N = 4)	24.2 (11.6)	18.3 (8.3)	−5.8 (18.7)	.292	31.3 (9.5)	32.5 (11.9)	+1.3 (17.0)	.349	.146
Cement (N = 5)	26.7 (14.5)	12.7 (7.0)	−14.0 (15.9)		26.0 (16.0)	17.0 (14.8)	−9.0 (13.4)		.463
PORP (N = 20)	29.4 (12.1)	20.3 (13.3)	−9.2 (12.7)		25.3 (11.5)	21.8 (14.9)	−3.5 (16.9)		.077
TORP (N = 8)	38.1 (14.4)	17.9 (8.2)	nu 20.2 (18.0)		34.4 (13.5)	20.6 (10.5)	−13.8 (13.8)		.215
Cholesteatoma (N = 18)	31.4 (12.7)	22.7 (12.8)	−8.7 (15.5)	.224	24.7 (11.4)	25.0 (15.4)	+0.3 (15.9)	.019*	.002*
No Cholesteatoma (N = 19)	29.4 (13.8)	14.6 (7.8)	−14.8 (14.5)		31.1 (13.0)	19.2 (11.8)	−11.8 (14.1)		.357
Ossiculoplasty (N = 13)	27.6 (15.4)	15.4 (9.0)	−12.2 (16.2)	.923	33.1 (13.3)	21.9 (13.0)	−11.2 (16.0)	.147	.740
Ossiculoplasty and Tympanoplasty (N = 24)	31.9 (11.8)	20.2 (12.0)	−11.7 (14.9)		25.2 (11.4)	22.1 (14.5)	−3.1 (15.6)		.003*

Abbreviations: ABG, air-bone gap; ΔABG, postoperative change in ABG (negative values indicate less gap after treatment and positive values indicate worse gap); PORP, partial ossicular replacement prosthesis; POST, postoperative; PRE, preoperative; TORP, total ossicular replacement prosthesis.
[a]Low-frequency ABG is a three-tone average of 250, 500, and 1000 Hz.
[b]High-frequency ABG is measured at 4000 Hz.
*$P < .05$.

improvement between high and low frequencies. Likewise, published data of our own demonstrate similar discrepancies between traditional and frequency-specific reporting of audiometric outcomes in patients undergoing type 1 tympanoplasty.[17]

The inclusion of frequency-specific data is imperative as the clinical impact of high-frequency conductive hearing loss is multifold since a significant amount of environmental sounds and language occurs at and above 4 kHz. Impaired high-frequency hearing can hinder sound localization and language comprehension, which may result in poor word discrimination, especially in the presence of background noise or multiple sources of speech.[18,19] Those with a persistent high-frequency ABG following middle ear surgery may demonstrate these handicaps on secondary testing, such as speech understanding in noise.[20] Given the output limitations of traditional amplification and bone conduction hearing aids at high frequencies, it is critical that otologist determine the most effective methods of correcting high-frequency conductive deficits in patients with middle ear disease.[21-23]

Given the limitations in standard reporting practices, it is challenging to put our findings into the broader context of relevant literature as only one previous study reports frequency-specific conductive hearing outcomes for a comparable study population. Similar to this study, Choi and colleagues reported a significant ABG improvement across all frequencies, with the magnitude of ABG closure inversely related to an increase in frequency.[24] Furthermore, they found significant low-frequency ABG (below 2 kHz) improvement in PORP, TORP, cholesteatoma, and non-cholesteatoma subgroups. Whereas, significant high-frequency ABG improvement was limited to patients without cholesteatoma. However, no between-group comparisons were made regarding the magnitude of ABG improvement at high and low frequencies. Conversely, in an investigation limited to patients with cholesteatoma, Sevik Elicora et al reported no frequency-specific differences in conductive hearing gain between PORP and TORP groups.[25]

Although outside the scope of this study, the origin of the frequency-specific differences that we observe is challenging to isolate given the variability that exists between ossiculoplasty cases. However, it is important to remember that, at low frequencies, mechanical systems inherently demonstrate an inverse relationship between the magnitude of sound transfer and overall system stiffness. Previous mechanical studies investigating the impact of prosthesis length, and therefore middle ear stiffness, on stapes velocity in cadaveric temporal bones show improved transmission at frequencies >2.0 kHz in high tension systems but improved low-frequency performance in low tension systems.[26,27] Thus it is conceivable that low tension ossicular reconstruction contributes to the significantly larger ABG improvement at low frequencies. In regard to the significant differences in high-frequency ABG improvement between those with and without cholesteatoma, previous studies suggest that cholesteatoma patients are unable to achieve the same degree of improvement from middle ear reconstruction because their surgeries are often more extensive

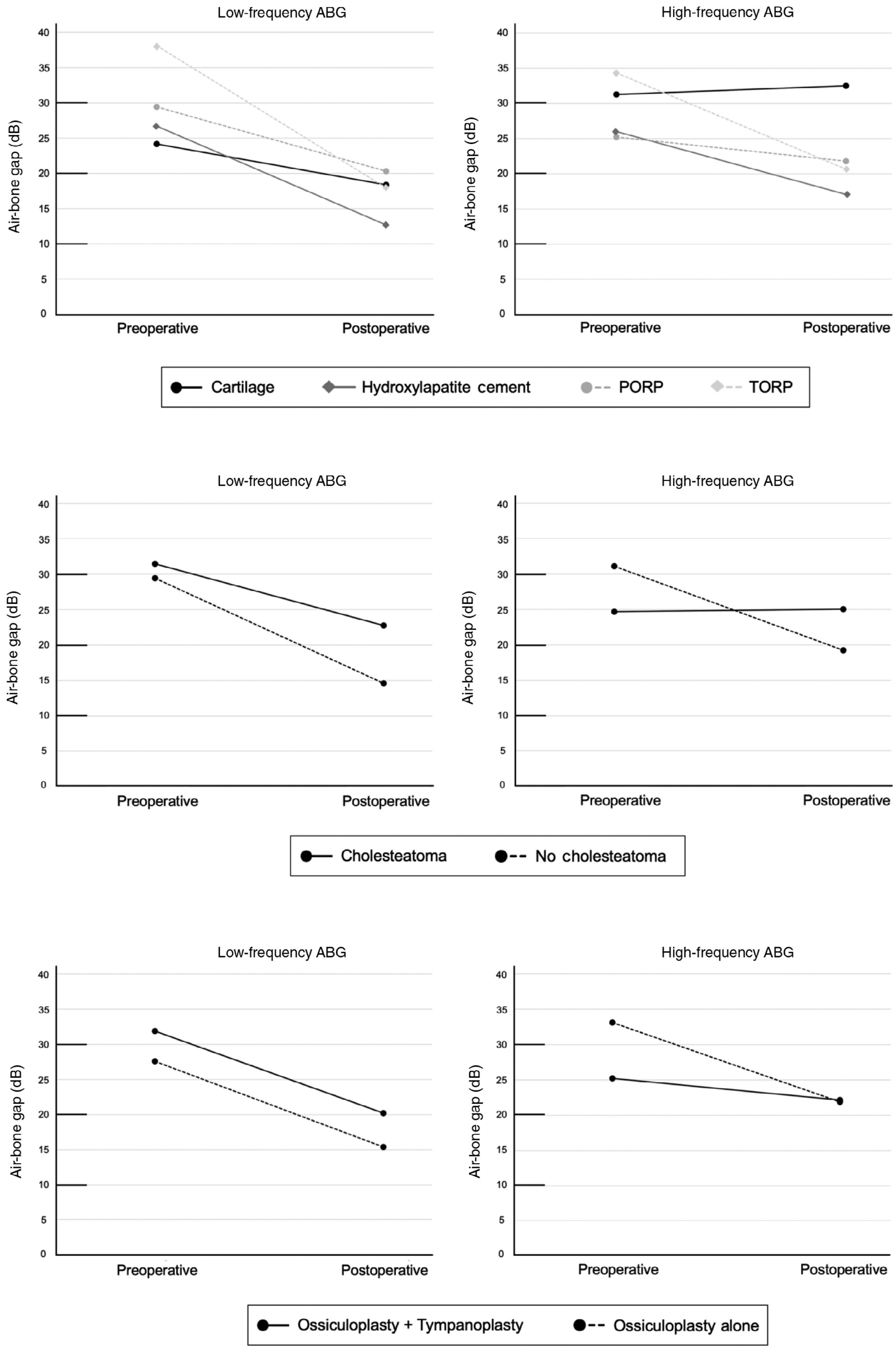

FIGURE 4 Legend on next page.

and necessitate a more aggressive manipulation of the ossicular chain as the priority is disease removal, not hearing improvement.[28,29] Although these may be contributing factors, the frequency-specific differences in ABG have not been previously addressed and any explanation in this study population is limited by the heterogeneous nature of the included reconstructions. Further investigation into the mechanisms of high-frequency sound conduction within reconstructed middle ears is needed to improve ossiculoplasty hearing outcomes.

It is common for investigators to claim that persistent high-frequency hearing losses following middle ear surgery are sensorineural in nature, a result of excessive ossicular manipulation and/or bony drilling.[30-32] However, we provide clear evidence of a conductive component as demonstrated by the significantly smaller ABG improvement at 4 kHz compared to that at low frequencies. Also important to this discussion is a consideration of hearing losses above 4 kHz. In light of the persistent ABG demonstrated at 4 kHz and the insignificantly changed air conduction at 8 kHz, we speculate that hearing losses above 4 kHz also contains a conductive component. Although bone conduction audiometry is currently performed only up to 4kHz, we hope new bone conduction transducers may permit evaluation of pre and post-operative conductive hearing losses above 4kHz. Identification of large post-operative ABGs above 4kHz would further indicate the need to develop new materials and techniques to improve high frequency hearing in ossiculoplasty.

This study is limited by the small sample size and retrospective nature of the review. Furthermore, challenging to any study of ossiculoplasty outcomes[33] is the variation in disease status and surgical approaches as this limits the strength of internal and external validity. However, a heterogeneous population was intentionally included to facilitate a broad investigation of audiometric outcomes from ossiculoplasty procedures as a whole. Despite including a small and heterogeneous study population, our post-operative ABG outcomes are similar to other published studies reporting hearing outcomes following ossiculoplasty,[15,16,24,34-36] thus it is reasonable to speculate that other ossiculoplasty patients also have a persistent post-operative high-frequency ABG. Similarly, we believe a larger patient cohort may delineate some of the small but statistically significant differences between low- and high-frequency conductive hearing outcomes demonstrated herein; this is an important direction for future research. Additionally, with this study, we were unable to accompany the audiometric outcomes with a detailed analysis of the preoperative middle ear environment. As this study focused on the overall frequency-specific hearing threshold changes after surgery, a detailed investigation of distinct pathological conditions and types of prostheses are left for further study. Specifically, studies that limit the inclusion criteria and include one of the various published middle ear risk indices[8-11] to contextualize the outcomes reported.[37] But for now, it is clear that when reported using conventional methods, our audiometric outcomes following ossiculoplasty appear satisfactory. However, differences between high- and low-frequency ABG reduction suggest current ossiculoplasty techniques and materials preferentially improve low-frequency conductive hearing. Given the impact of high-frequency hearing loss,[18,19] we call for future research to report audiometric outcomes with increased detail, so that superior surgical techniques, aimed at improving ABG across all frequencies of hearing, might be identified.

5 | CONCLUSION

In a series of patients undergoing ossiculoplasty, low-frequency conductive hearing gain was significantly larger than high-frequency hearing gain. Current reporting standards appear inadequate for the identification of frequency-dependent changes in conductive hearing following middle ear surgery.

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CONFLICTS OF INTEREST

The authors have no conflicts of interest.

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FIGURE 4 Pre- and postoperative air-bone gap (ABG) averages for selected subgroups: type of ossiculoplasty material (A), presence of cholesteatoma (B), and presence of concurrent tympanoplasty (C). Low-frequency ABG = three-tone average of 250, 500, and 1000 Hz. High-frequency ABG = 4000 Hz. PORP, partial ossicular replacement prosthesis; TORP, total ossicular replacement prosthesis

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