



Bone conduction threshold improvement after otosclerosis surgery

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ABSTRACT

Objective: To analyze the characteristics of bone conduction (BC) threshold changes after stapedotomy in patients with otosclerosis, and to explore the clinical significance and implications for the evaluation of surgical outcomes. **Methods:** It is a retrospective, single-center study. A total of 97 ears from patients with otosclerosis who underwent endoscopic stapedotomy (footplate fenestration with titanium piston implantation) between November 2015 and February 2025 were included. Pure tone audiometry (PTA) was performed preoperatively, and at 1 month and 6 months postoperatively. Air conduction (AC) thresholds were tested at 125–8000 Hz, and bone conduction (BC) thresholds at 250–4000 Hz. Pre- and postoperative changes in BC thresholds, AC thresholds, and air-bone gap (ABG) were documented, and the results were compared with findings from other studies. **Results:** The average postoperative BC threshold across 250–4000 Hz showed significant improvement, with a mean gain of 7.5 dB ($Z = -6.343$, $p < 0.001$). At individual frequencies, improvements were significant at 250, 500, 1000, 2000 Hz, with the most notable gain at 250 Hz (10 dB), followed by 500 Hz, 1000 Hz, and 2000 Hz (5 dB gain each) ($\text{all } p < 0.001$). No statistically significant improvement of BC threshold was observed at 4000 Hz ($Z = -0.368$, $p = 0.713$). AC thresholds also showed significant improvements across all tested frequencies (125–4000 Hz) ($\text{all } p < 0.001$), with a mean gain of 19 dB; the greatest improvement was observed at 1000 Hz (30 dB). Although the average ABG narrowed by 13 dB, the degree of closure underestimates the actual hearing improvement, as it fails to account for concurrent BC enhancement. Compared with those of other studies, the study cohort demonstrated more pronounced BC improvements. **Conclusion:** Stapedotomy not only effectively restores AC hearing but also significantly improves BC thresholds. This improvement in BC thresholds may be attributed to the restoration of bone conduction mechanisms following stapedotomy. Traditional evaluation methods for surgical outcomes that rely solely on ABG closure tend to underestimate overall surgical efficacy. For clinical implementation, we suggest a multidimensional framework can be applied by simultaneously evaluating postoperative air conduction gain, bone conduction gain, and air-bone gap closure at each frequency, rather than relying on ABG closure alone.

KEYWORDS

Otosclerosis, Stapes surgery, Stapes footplate fenestration, Bone conduction threshold, Air-bone gap (ABG).

1 Introduction

Otosclerosis is an osteodystrophic disorder of the temporal bone, characterized by disordered bone resorption and neof ormation in genetically predisposed individuals (Quesnel et al., 2018). Lesions involving the annular ligament of the stapes footplate lead to progressive conductive hearing loss. Currently, stapes surgery (including stapedotomy, total or partial stapedectomy, and artificial stapes prosthesis implantation) is the most effective treatment for conductive hearing loss caused by otosclerosis, and stapedotomy (with footplate fenestration as the core step) was adopted in this study. Its primary goal is to reconstruct the middle ear sound conduction pathway and significantly improve air conduction hearing levels (Kisilevsky et al., 2009; Xie et al., 2019).

Traditionally, surgical outcomes have been assessed based on postoperative air conduction threshold improvement and air-bone gap (ABG) closure (Saerens et al., 2021; Elsamnody et al., 2024). Extensive studies have demonstrated the stable and significant long-term efficacy of stapes surgery in reducing ABG and improving speech recognition (Vincent et al., 2006; Wiatr and Wiatr, 2020). However, clinical observations have identified an often-overlooked phenomenon: postoperative changes in bone conduction (BC) thresholds in some patients. First systematically described by Carhart in 1950, this condition is known as the classic "Carhart notch", characterized by a pseudo-dip in the preoperative BC thresholds at 0.5–4 kHz (most pronounced at 2 kHz). Fundamentally, it reflects a mechanical transmission impairment caused by stapes fixation rather than actual sensorineural damage. Post-

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operative disappearance or reduction of this notch is considered an indirect indicator of surgical success (Carhart, 1950). Although the overall efficacy of stapes surgery is well established, systematic studies on postoperative changes in BC thresholds remain limited. Two main shortcomings persist: first, dedicated studies are limited in number and have small sample sizes (typically 40–60 cases), failing to reflect population-wide trends; second, stratified analyses considering potential influencing factors such as age, disease stage (e.g., window type vs. cochlear type), and surgical technique are lacking, leading to an incomplete understanding of the mechanisms underlying postoperative BC threshold changes.

To address these gaps, this study retrospectively analyzed the clinical data of otosclerosis patients who underwent stapedotomy, systematically evaluating pre- and postoperative BC threshold characteristics. The findings are intended to provide a robust evidence-based foundation for clinical outcome assessment and postoperative follow-up strategies.

2 Patients and Methods

2.1 Patients

From November 2015 to February 2025, the patients were diagnosed with otosclerosis who underwent surgical treatment at the Department of Otorhinolaryngology, Eye & ENT Hospital Affiliated with Fudan University were enrolled in this study. Among the 97 ears included, a total of 82 patients were enrolled, of whom 15 patients underwent bilateral otosclerosis surgery and both ears were included in the analysis. Demographically, a mean age of 43.08 ± 11.07 years. Age distribution was as follows: ≤ 30 years, 13.4%; 31–50 years, 60.8%; and > 50 years, 25.8%. Normal CT findings were observed in 12.4% of cases, low-density lesions in the fenestra vestibuli were detected in 66% of cases, thickening of the stapedial footplate was observed in 7.2% of cases, and mixed-type lesions (abnormal cochlea, fenestra, and/or footplate thickening) were noted in 14.4% of cases.

This dataset provides foundational information for subsequent investigations into the disease characteristics and surgical outcomes of otosclerosis patients. This retrospective clinical study has obtained explicit approval from the Institutional Review Board (IRB) of Eye & ENT Hospital, Fudan University. The IRB approval number is Lun Shen Zi No. (2023157).

2.2 Methods

It is a retrospective, single-center study. According to the guidelines issued by the Hearing Committee of the American Academy of Otolaryngology-Head and Neck Surgery, all patients underwent pure tone audiometry (PTA) preoperatively. At our hospital, air conduction (AC) thresholds were tested at 125, 250, 500, 1000, 2000, 4000, and 8000 Hz. BC thresholds were tested at

the same frequencies except 125 and 8000 Hz. All patients underwent general anesthesia and stapedotomy which involved footplate fenestration and a piston implantation under endoscopic guidance. The prosthesis piston was made of titanium. All surgeries were performed by the same otologist. Postoperatively, patients received routine intravenous antibiotics for 1–2 days to prevent infection and were discharged approximately 1–2 days after surgery. Following discharge, they continued taking oral antibiotics for 5–7 days. At 1 and 6 months postoperatively, all patients underwent a PTA follow-up to evaluate hearing levels.

3 Statistical Analysis

Data analysis was performed using SPSS 27.0 software. For normally distributed quantitative data, results were expressed as mean $\pm$ standard deviation, and t-tests were applied for comparisons between groups. For non-normal distribution data, non-parametric tests were used instead, and results were presented as median $\pm$ interquartile range. For categorical data, inter-group comparisons were conducted using chi-square tests and Fisher's exact probability methods, as appropriate. A p-value < 0.05 was considered statistically significant.

4 Results

4.1 BC, AC improvement and ABG narrowing across frequencies

As shown in Table 1, the average BC threshold (250–4000 Hz) exhibited a statistically significant improvement before and after surgery, with an average gain of 7.5 dB. At individual frequencies, statistically significant BC improvements were observed at 250, 500, 1000, and 2000 Hz (all $p < 0.001$): a notable 10 dB gain was observed at 250 Hz, followed by a 5 dB gain at each of 500 Hz, 1000 Hz, and 2000 Hz. In contrast, although a slight numerical improvement was seen at 4000 Hz, this change did not reach statistical significance ($Z = -0.368$, $p = 0.713$).

Postoperative air conduction thresholds improved significantly across 125–4000 Hz (all $p < 0.001$), with an average gain of 19 dB. The most significant improvement occurred at 1000 Hz (30 dB). No significant change was observed at 8000 Hz ($p = 0.870$).

Postoperative ABG values were significantly narrowed across 250–4000 Hz (all $p < 0.001$), with a mean reduction of 13 dB.

4.2 Underestimation of ABG closure due to bone conduction improvement.

As illustrated in Figure 1, concurrent postoperative improvements in both BC and AC thresholds result in narrowing of the ABG, which may lead to underestimation of the true hearing gain achieved by stapedotomy. Figures 1A and 1B demonstrate significant improvements in BC and AC thresholds across frequencies

Table 1 Pre- and postoperative Bone conduction thresholds.

Bone Conduction	Preoperation	Postoperation	Z	P
Average(500-4000 HZ)	32.5(23.75~38.75)	25(19.38~31.25)	-6.343	<0.001
250 HZ	25(25~30)	15(10~20)	-6.203	<0.001
500 HZ	25(20~35)	20(15~25)	-6.511	<0.001
1000 HZ	30(25~40)	25(15~30)	-6.397	<0.001
2000 HZ	35(30~45)	30(20~37.5)	-5.547	<0.001
4000 HZ	30(20~45)	25(20~40)	-0.368	0.713

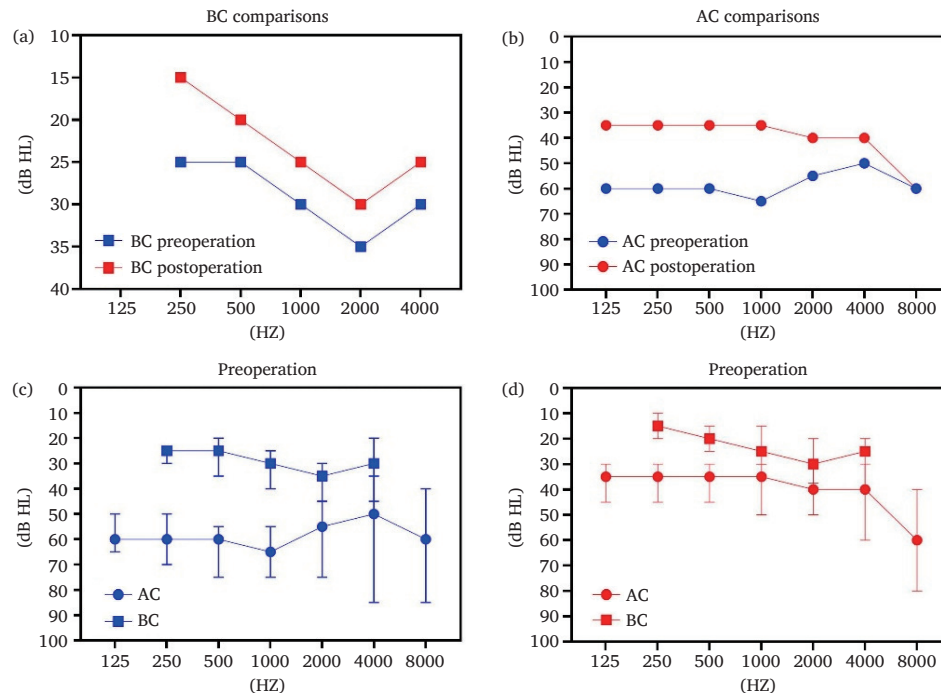


Figure 1 Underestimation of ABG closure due to bone conduction improvement.

blue indicates preoperative data, red denotes postoperative data, squares represent BC values, circles indicate AC values, and error bars depict the upper and lower quartiles. A: Significant Bone Conduction (BC) threshold improvement at 250–2000 Hz. B: Significant Air Conduction (AC) threshold improvement at 125–4000 Hz, peaking at 1000 Hz. C (Preoperation) & D (Postoperation): Preoperatively (C), large air-bone gaps (ABG) reflect conductive hearing loss. Postoperatively (D), while ABG narrows, concurrent bone conduction (BC) improvement means the actual hearing gain is underestimated by ABG narrowing alone.

pre- and postoperatively. Figures 1C and 1D follow the PTA data presentation format to illustrate the preoperative and postoperative distribution patterns of air conduction and bone conduction thresholds. Collectively, these results suggest that simultaneous improvements in BC and AC thresholds mean that the extent of ABG closure underestimates the actual surgical efficacy, thus underscoring the need for a multidimensional assessment framework integrating AC, BC, and ABG to comprehensively evaluate the outcomes of stapedotomy.

BC improvement in other studies employing stapedotomy
 Stapedotomy consistently improves bone conduction (BC) threshold levels, as evidenced by cross-study comparisons (Table 4). Our study achieved a notable mean BC improvement of 7.5 dB, whereas other previous studies reported mean gains of 2.1–5.7 dB: marked gains were observed across key frequencies: 10 dB at 250 Hz, stable 5 dB improvements at 500–2000 Hz, and a 5 dB gain at 4000 Hz—while most other studies reported no improvement or a decline at this frequency. All the studies

suggest that stapedotomy significantly enhances BC thresholds.

In addition, no significant differences in BC improvement among the three fenestration techniques (63.9% microdrill, 32% triangular needle, 4.1% laser) at different frequencies (250 Hz: $\chi^2 = 21.55$, $p = 0.66$; 500 Hz, $\chi^2 = 17.90$, $p = 0.93$; 1000 Hz: $\chi^2 = 18.19$, $p = 0.463$; 2000 Hz: $\chi^2 = 16.98$, $p = 0.89$; 4000 Hz: $\chi^2 = 23.39$, $p = 0.34$).

5 Discussion

This study analyzed audiological data from 97 ears following stapedotomy and found that patients exhibited significant improvements not only in AC hearing but also in BC thresholds. The average BC improvement was 7.5 dB, with the most prominent gain at 250 Hz (10 dB). These findings support the established consensus that stapedotomy improves BC hearing and highlight its advantages in both the magnitude and frequency-specific char-

Table 2 Pre- and postoperative Air conduction thresholds.

Air Conduction	Preoperation	Postoperation	Z	P
Average(500-4000 HZ)	58(50~70)	39(33~46)	-6.038	<0.001
125HZ	60(50~65)	35(30~45)	-5.662	<0.001
250 HZ	60(50~70)	35(30~45)	-6.303	<0.001
500 HZ	60(55~75)	35(30~45)	-6.365	<0.001
1000 HZ	65(55~75)	35(30~50)	-6.156	<0.001
2000 HZ	55(45~75)	40(30~50)	-5.708	<0.001
4000 HZ	50(35~85)	40(30~60)	-4.391	<0.001
8000 HZ	60(40~85)	60(40~80)	-.164	0.870

Table 3 Pre- and postoperative Air–bone gap.

ABG	Preoperation	Postoperation	Z	P
Average(500-4000 HZ)	28(20~35)	15(10~20)	−6.288	<0.001
250 HZ	35(30~45)	20(15~25)	−6.216	<0.001
500 HZ	35(30~45)	20(10~20)	−6.146	<0.001
1000 HZ	35(25~40)	15(10~20)	−6.281	<0.001
2000 HZ	20(10~25)	10(5~15)	−4.553	<0.001
4000 HZ	25(15~35)	15(10~25)	−4.054	<0.001

Table 4 Changes in bone conduction (BC) threshold after stapes surgery in other comparable studies.

	N	250 HZ	500 Hz	1000 Hz	2000 Hz	4000 Hz	Mean improvement	stapedotomy fenestration
Zuur, C.L. et al., (2003)	58	−0.3	+1.5	+2.27	+6.3	−1.7	+2.1	/
Kisilevsky et al., (2009)	1145		+1.9	+2.1	+4.7	−1.4	/	Triangular needle/laser
Brase et al. (2013)	280		+2.18	+1.92	+2.59	−2.89	/	laser
Iza et al., (2016)	116	/	+2.85	+3.45	+5.39	−3.28	+2.1	/
Hao, X.P.C., (2017)	56	+2.05	+1.51	+3.75	+3.93	−1.34	/	laser
Conway et al. (2022)	518	/	+2.99	+5.13	+8.34	−2.33	+3.54	laser
Conway et al. (2022)	70	/	+3.79	+5.86	+9.07	−2.07	+4.16	Micro drilling
Wiatr et al. (2020)	140	/	+8.24	+9.12	+10.05		+5.7	/
Molinari et al. (2023)	60	/	/	/	/		+2.15	Triangular needle
Darjazini Nahas et al. (2023)	38	+0.9	+2.5	+0.8	+1.6	+5.3	+2.1	laser
Our results	97	+10	+5	+5	+5	+5	+7.5	63.9% microdrill + 32%Triangular needle + 4.1% laser

> + indicates improvement; −, worsening; BC, bone conduction

acteristics of hearing improvement, providing new evidence for a more comprehensive evaluation of surgical efficacy.

Consistent with recent studies—such as Conway et al. (2022) who observed BC threshold improvement, and Wiatr and Wiatr (2020) who also reported significant low-frequency BC gains—our results are consistent with the core mechanism by which surgery alleviates mechanical obstruction of the bony labyrinth and restores the integrity of the bone conduction pathway. The bone conduction improvement across 250–2000 Hz observed in this study further underscores the universality of this mechanism in otosclerosis treatment.

The average BC improvement of 7.5 dB in this study was significantly higher than that reported by Molinari et al. (2023) and Darjazini Nahas et al. (2023) (+2.15 dB and +2.1 dB, respectively). This numerical difference is speculated to be related to multiple factors such as the technical details of stapes surgery and the baseline characteristics of the study population. Stapes footplate fenestration methods (e.g., laser, triangular needle, microdrill fenestration, etc.) are one of the core technical variables in stapes surgery. However, multiple existing high-quality studies have consistently confirmed that different fenestration methods have no significant impact on the changes in BC hearing thresholds before and after surgery. Brase et al. (2013) compared CO₂ laser "one-shot" fenestration with traditional manual perforation and found that the improvement trends of BC hearing thresholds in the two groups were highly consistent at different postoperative time points (1 day, 4 days, 1 month, and 1 year): the low-to-mid frequencies (0.5, 1 kHz) quickly recovered to the preoperative baseline level 4 days

after surgery, the 2 kHz hearing threshold exceeded the preoperative value 1 month after surgery, and although the 4 kHz hearing threshold showed a temporary decrease in the short term, it returned to the preoperative level 1 year after surgery. Moreover, there was no statistically significant difference in BC hearing thresholds between the two groups at all time points ($P>0.05$). Conway et al. (2022) further verified this conclusion in a specialized study on obliterative otosclerosis. Their results showed that the mean postoperative BC hearing threshold improvement amplitudes in the microdrill fenestration group and laser fenestration group were 4.16 dB and 3.54 dB, respectively, with no statistically significant difference between the groups ($P>0.05$). Additionally, the change trends of high-frequency BC hearing thresholds such as 4 kHz were completely consistent, suggesting that even in more complex subtypes of the disease, fenestration methods did not have a substantial impact on BC hearing threshold improvement. Moneir et al. (2023) compared the classic technique and reversal technique in endoscopic stapes surgery (the core difference lies in the order of fenestration and ossicular chain management) and similarly found no significant difference in BC hearing thresholds between the two groups before and after surgery ($P=0.66$), with comparable air–bone gap (ABG) closure rates (76.67% vs 80%). This further indicates that technical details related to fenestration are not the key factors affecting the improvement of BC hearing thresholds.

From an operational perspective, the improvement in BC threshold across the low-frequency range (250–1000 Hz) may be attributed to the mechanical characteristics of low-frequency

sound waves and the pathway of bone conduction transmission. Low-frequency sounds, with longer wavelengths, are more sensitive to changes in mechanical conditions; reduced impedance after surgery results in more efficient vibratory transmission. The improvement or no decline of BC threshold in the high-frequency range (2000-4000 Hz) reflects the safety of the surgical procedure, indicating that the micro-drill, triangular needle, or laser technique can accurately remove lesions while avoiding damage to the cochlear structure and simultaneously relieving mechanical compression and metabolic interference caused by the pathology.

This study also revealed significant improvements in air conduction thresholds across the full frequency range (125-4000 Hz), with an average gain of 19 dB. The most notable improvement occurred at 1000 Hz (30 dB), which is consistent with previous reports (García-Iza et al., 2016; Molinari et al., 2023; Warhade et al., 2024). Notably, the air conduction improvement at 1000 Hz is closely associated with the elimination of the Carhart notch, confirming that removal of stapes fixation, disappearance of the "third window" effect, and normalization of middle ear impedance are key mechanisms underlying hearing improvement.

Furthermore, although the average ABG narrowed by 13 dB, the simultaneous improvement in both air and bone conduction indicates that ABG closure underestimates the total hearing benefit. This may challenge the conventional use of ABG closure as the primary outcome measure for middle ear surgery (Vincent et al., 2006; Elsamnody et al., 2024; Tomasoni et al., 2025). Relying exclusively on ABG reduction may fail to capture the comprehensive functional improvements in the auditory pathway reflected by enhanced bone conduction, leading to an underestimation of surgical efficacy. Therefore, we recommend adopting a multidimensional assessment framework that integrates air conduction improvement, bone conduction enhancement, and ABG reduction (Conway et al., 2023; Sun et al., 2024). This approach better reflects dual improvement in middle ear sound transmission and inner ear sensory function, while providing a more scientific basis for optimizing surgical techniques (e.g., prosthesis selection and fenestration size) and long-term follow-up strategies.

Several limitations of this study should be noted. First, this is a retrospective single-center study with a long inclusion period (November 2015–February 2025); despite strict inclusion/exclusion criteria, potential selection bias cannot be excluded, and the single-center design limits the generalizability of the results. Second, although the importance of long-term follow-up (>1 year) has been emphasized in previous studies, the follow-up period in this study was only 6 months. This represents a similar methodological shortcoming, and the durability and stability of the observed bone conduction improvement remain unknown. Third, 15 patients underwent bilateral otosclerosis surgery, and both ears were included in the analysis. This may introduce potential non-independence of data from the same individual, which represents a limitation of the present study. Future large-scale, multi-center, prospective studies with long-term follow-up are needed to address these limitations and further validate our findings.

6 Conclusion

Endoscopic stapedotomy effectively treats otosclerosis, improving average AC threshold by a mean of 19 dB (maximum 30 dB at 1000 Hz) and average BC threshold by a gain of 7.5 dB (250–4000) Hz. Notably, while the average ABG narrowed by 13 dB (mainly due to AC improvement), concurrent BC improvement weakens this narrowing, making ABG alone an underestimate of

the actual hearing benefit. Thus, a multidimensional assessment framework integrating AC, BC, and ABG is necessary, which accounts for the weakening effect of BC on ABG narrowing in postoperative evaluation.

Our study supplements the existing literature but has limitations (retrospective single-center design, 6-month follow-up period). Future multi-center prospective studies with a follow-up > 1 year are needed to validate the long-term efficacy of the procedure and the proposed multidimensional assessment framework.

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Data Availability Statement

The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Ethics Approval

This retrospective clinical study has obtained explicit approval from the Institutional Review Board (IRB) of Eye & ENT Hospital, Fudan University. The IRB approval number is Lun Shen Zi No. (2023157).

The study was conducted in accordance with the Declaration of Helsinki (2013).

All procedures involving human subjects were performed with informed consent.

Informed Consent Statement

Written informed consent was obtained from all patients for publication of identifying information and any accompanying images during hospital admission.

Conflicts of Interest

No conflicts of interest exist.

Author contributions

Nina Chen: Conceptualization, Methodology, Writing - Original Draft Te Li: Data Curation, Formal Analysis, image process Yue-Lin Hsieh: Data Curation, Formal Analysis, Jingji Yuan: Data Curation, Formal Analysis, Xianqiong Ma: Formal Analysis, Wuqing Wang: Supervision, Project Administration - Review & Editing Yi-Bo Huang: Supervision, Project Administration, Writing - Review & Editing All authors have approved the final version and agree to be accountable for all aspects of the work.

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