Audiometry in Ossicular Reconstruction

Renee M. Banakis Hartl, MD, AuD

KEYWORDS

- Ossiculoplasty • Ossicular chain reconstruction • Hearing • Audiometry
- Immittance testing • Tympanometry • Wideband reflectance

KEY POINTS

- The most commonly used clinical metric of hearing improvement after ossiculoplasty is air–bone gap closure, with reduction to 20 dB or less accepted as good surgical outcome.
- While tympanometry is a more readily available measure, wideband reflectance may provide a more detailed assessment of middle ear function before and after ossicular reconstruction.
- Postoperative hearing assessment is limited to a restricted frequency range (<4 kHz) due to the frequency response of clinically-available bone conduction transducers. Development of higher fidelity transducers is needed to more accurately characterize surgical outcomes.

INTRODUCTION

While the motivation to pursue middle ear surgery is frequently related to establishing a safe, dry ear due to the presence of chronic otitis media or cholesteatoma, a highly prioritized secondary outcome is improvement in hearing. When the ossicular chain requires reconstruction, ideal restoration of middle ear energy transformation to address the impedance mismatch between the conduction of acoustic signal through the air to the fluid-filled inner ear can be challenging. Compounding the task of precise recapitulation of middle ear mechanics is the accurate measurement of hearing changes before and after surgery. Here, we will review the basics of the audiometric assessment of ossicular chain function, summarize clinical audiometric outcomes associated with ossiculoplasty, and discuss the limitations of both the surgical technique and our ability to quantify ideal hearing outcomes.

AUDIOMETRIC ASSESSMENT OF THE OSSICULAR CHAIN

Critical to evaluating hearing outcomes for patients who undergo surgery on the ossicular chain is a high-level of understanding of the basic principles of clinical audiometry.

Department of Otolaryngology, University of Michigan, 1500 E. Medical Center Drive, Ann Arbor, MI 48109, USA
E-mail address: banakisr@med.umich.edu

Otolaryngol Clin N Am 59 (2026) 307–316
https://doi.org/10.1016/j.otc.2025.12.004 oto.theclinics.com
0030-6665/26/© 2025 Elsevier Inc. All rights are reserved, including those for text and data mining, AI training, and similar technologies.
Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

Abbreviations	
PORP	partial ossicular chain prosthesis
SRT	speech reception threshold
TORP	total ossicular chain prosthesis

For most patients undergoing surgical reconstruction of the middle ear, a minimal preoperative assessment of hearing and middle ear function would include puretone air-conduction and bone-conduction thresholds, speech audiometry, and immittance testing.

Puretone Testing

Puretone air-conduction can be performed in the clinic with either insert or supra-aural headphones reliably from 125 to 8000 Hz. Though the sensitivity for human hearing extends beyond this range (20–20,000 Hz), routine measurement of ultrahigh frequency thresholds has been historically sacrificed due to calibration challenges and need for efficient assessment of the frequencies that contribute the highest percentage of content to speech signals. Increasingly more research has focused on the possible importance of the ultrahigh frequencies to commonly experienced clinical problems, such as understanding speech clearly in the presence of background noise,[1,2] but routine clinical assessment remains focused on the more narrow range.

Bone-conduction thresholds are typically assessed with the use of a specialized transducer; the most common clinical device is manufactured by RadioEar (Middelfart, Denmark). Due to the need to generate high levels of force at a reliably consistent output, the frequency response of the transducer is restricted even more than air conduction, typically ranging from 125 or 250 to 4000 Hz. Calibration requirements also restrict transducer output limit to a maximum of between 50 and 90 dB HL, depending on frequency.

When considering middle ear pathology, which often results in conductive hearing impairment, the outcome metric of high interest is the air–bone gap. This value is calculated as the difference between the air-conducted and bone-conducted thresholds at a given frequency, reflects that magnitude of the pathologic effect on hearing, and quantifies the maximum benefit that can be gained from an optimal surgical outcome; resolution or closure of the air–bone gap is the goal of most ossicular chain procedures. Audiometric findings for a patient with conductive hearing loss due to ossicular discontinuity are illustrated in Fig. 1.

Speech Testing

Both threshold speech reception and suprathreshold speech discrimination testing is typically completed as part of a comprehensive audiometric evaluation of any patient planning to undergo middle ear surgery. The speech reception threshold (SRT) should be consistent with the puretone average of air-conduction thresholds measured at 500, 1000, and 2000 Hz. The word recognition score is calculated as a percentage of correctly repeated monosyllabic words presented at an audible level, typically about 30 to 40 dB above an individual's SRT. For the vast majority of conductive pathology, as long as the stimuli are able to be presented at an audible level, discrimination remains highly preserved. Speech testing outcomes are reported clinically, but frequently not considered in research publications.

Immittance Battery

Consisting of a speaker, microphone, pressure pump, and manometer, the immittance probe has the ability to characterize several aspects of middle ear function. A

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

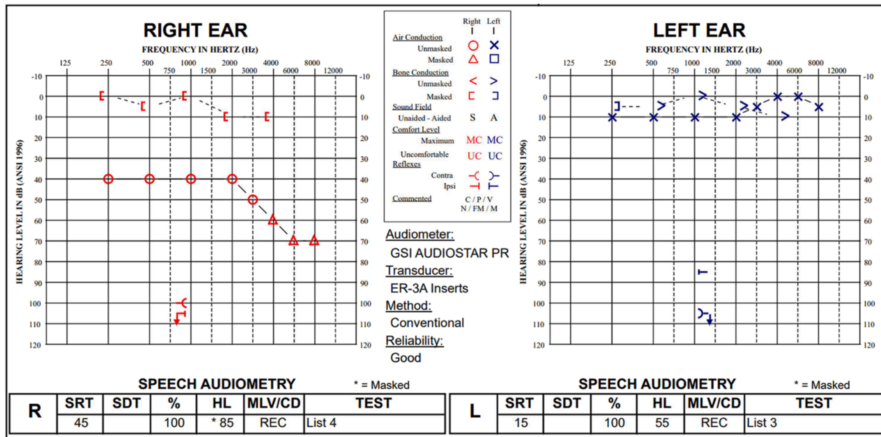

Fig. 1. Audiogram from a patient with absent lateral ossicular chain and intact tympanic membrane. There is a mild sloping to severe conductive hearing loss in the right ear and hearing sensitivity within normal limits in the left ear. The air–bone gap is apparent across frequency: 40 dB at 250 Hz, 35 dB at 500 Hz, 40 dB at 1000 Hz, 30 dB at 2000 Hz, and 50 dB at 4000 Hz.

tympanogram estimates static admittance of acoustic energy (226 Hz probe tone) to the middle ear as the ear canal is pressurized from −400 to +200 daPa. A normal (type A) pattern is characterized by the greatest amount of energy transmission through the middle ear near atmospheric pressure (0 daPa). If there is a significant accumulation of negative pressure in the middle ear, the tympanogram will reflect the shift in point of highest efficiency of acoustic energy transmission with a peak below −150 daPa (type C). When there is no change in admittance across pressure, the pattern is flat and labeled as type B.

Ear canal volume is also estimated during tympanometry. When the ear canal is pressurized to +200 daPa, it is assumed that the middle ear system is infinitely stiff and the tympanic membrane reflects all presented acoustic energy, with resulting immittance attributed to the volume of air in the ear canal alone. For a probe tone of 226 Hz, a static admittance of 1 mmho is considered equal to about 1 cc of air, so the volume of air in the ear canal between the probe and the eardrum is estimated as the static admittance measured at +200 daPa. When coupled with the tympanogram, the ear canal volume can provide meaningful information regarding the etiology of conductive impairment. If a type B tympanogram is accompanied by a normal ear canal volume, the tympanic membrane is assumed to be intact. A lower than anticipated volume can suggest an obstruction in the external meatus, such as impacted cerumen, while a higher than anticipated volumes imply a perforation in the tympanic membrane or otherwise surgically enlarged ear canal.

Acoustic reflexes and reflex decay can also be measured with the immittance bridge. To measure an acoustic reflex, the ear canal is pressurized to the level at which the peak admittance was observed on tympanometry. A second, high-intensity tone (or broadband noise stimulus) is presented, and an acoustic reflex is observed with a decrease in peak admittance of at least 0.2 mmho. The lowest stimulus to elicit this change is recorded as the reflex threshold. Reflexes can be elicited in an ipsilateral configuration (stimuli presentation and admittance measurement made in the same ear) or a contralateral configuration (stimuli presentation in one ear and admittance

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

measurement made in the other). Reflex decay measures the ability of the middle ear to sustain decreased admittance over time. A 10 second high-intensity stimulus tone is played above the established acoustic reflex threshold, and the admittance change is monitored over time. Reduction of change from baseline to less than 50% before 5 seconds is considered positive for reflex decay. While acoustic reflexes have historically been considered in the assessment of retrocochlear pathology, reflex patterns can also provide important adjuvant information in the assessment of conductive hearing loss. Specifically, increasing attention has been paid to the use of acoustic reflex testing in differentiating between otosclerosis and superior semicircular canal dehiscence—both pathologies that can result in conductive hearing impairment with normal tympanometric findings with absent reflexes in the former and intact reflexes in the later.

Middle Ear Reflectance

Traditional tympanometry is limited as it measured the relative reflected energy at a single frequency only (226 Hz in adults, 1000 Hz in pediatrics). Broadband stimuli, such as acoustic clicks, can be employed to measure wideband reflectance, which allows for characterization of middle ear function across the frequency spectrum.[3,4] Wideband measures highlight the influence of middle ear pathology on energy transmission across the audiometric frequency spectrum. Single-frequency tympanometry might demonstrate subtle changes between causes of conductive hearing loss, but the wideband measures have the opportunity to reinforce and explain the audiometric shifts seen as a result of the underlying pathology[5] (**Fig. 2**). As clinical use of wideband testing expands, the opportunity for a more detailed and nuanced understanding of normal changes to acoustic transmission during typical development as well as the impact of various pathology has the potential to advance our assessment of both ossicular disease and our operative repairs.

AUDIOMETRIC OUTCOMES IN OSSICULOPLASTY

The most commonly reported audiologic metric employed to evaluate the effectiveness of ossicular chain reconstructive surgery is degree of closure of the air–bone gap. Based on limitations of audiometric testing and test–retest reliability, improvement of the air-conduction threshold to less than or equal to 10 dB of the bone-conduction threshold would reflect improvement that is clinically indistinguishable from normal hearing sensitivity, even if a small sensitivity difference remains. Given the test–retest tolerance, much of the literature considers a persistent air–bone gap of 15 to 20 dB following ossicular chain reconstruction or stapedectomy to be a good surgical outcome.

When evaluating hearing outcomes for middle ear reconstructive surgery, several factors should be considered when establishing expectations for audiometric outcomes. A nuanced understanding of middle ear mechanics is critical for predicting the energy transmission changes across frequency. A surgical reconstruction that requires greater manipulation of normal anatomic structures would be less likely to result in complete normalization of hearing in the affected ear. For example, both institution-level investigations and meta-analyses support the greater likelihood of air–bone gap closure when using a partial compared to a total prosthesis.[6–8]

Bone Cement Ossiculoplasty

In specific cases, chronic retraction or a small cholesteatoma may result in minimal bony erosion, frequently of the incudostapedial joint. For these presentations,

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

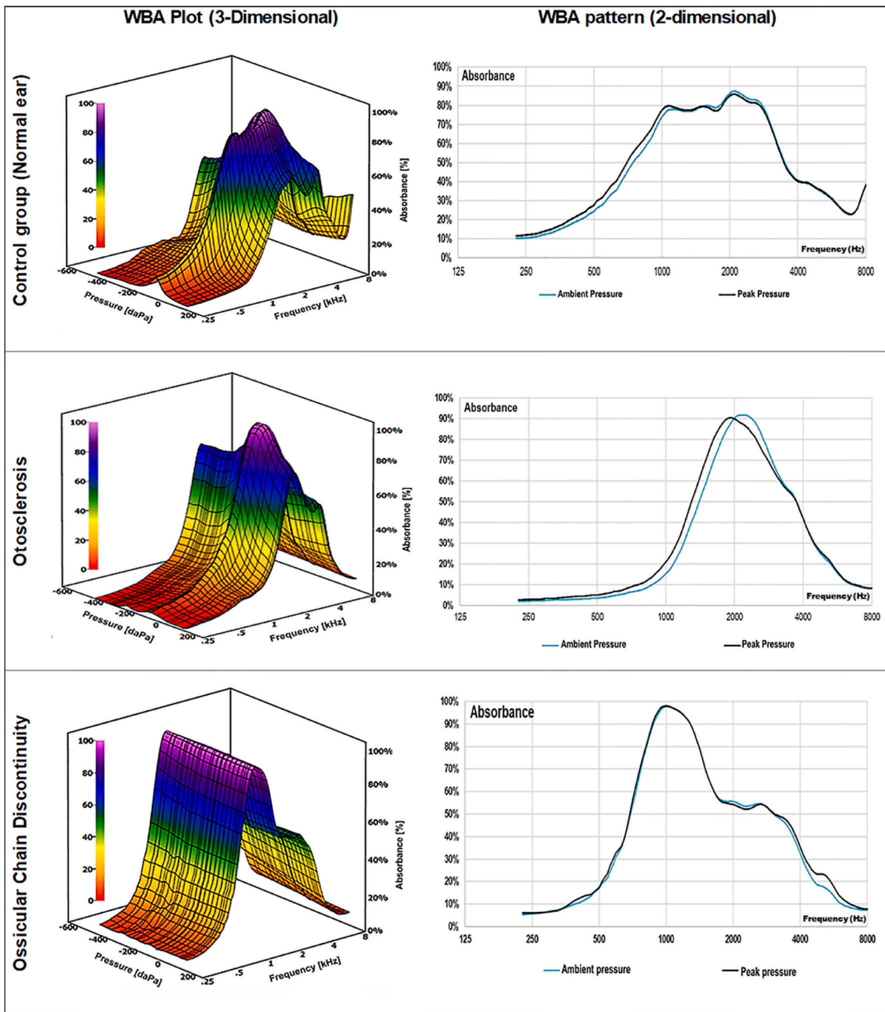

Fig. 2. Wideband absorbance pattern (3 dimensional and 2 dimensional plot) of one of the participants in each group (control, otosclerosis, and ossicular chain discontinuity). (*From* Karuppannan A, Barman A. Wideband absorbance pattern in adults with otosclerosis and ossicular chain discontinuity. Auris Nasus Larynx 2021;48(4):583–89. https://doi.org/10.1016/j.anl.2020.10.019. Epub 2020 Nov 11. PMID: 33187789.)

re-establishment of ossicular continuity has been achieved with the local placement of bone cement over the affected joint (Fig. 3). For patients undergoing incudostapedial rebridging ossiculoplasty with cement, a review of 40 patients at a single institution revealed an average reduction in air–bone gap from 27.65 dB to 19.65 dB.[9] Other studies have shown successful results (air–bone gap closure to $\leq$ 20 dB) in 60% to 94% of patients undergoing bone cement repair of the incudostapedial joint,[10–13] supporting its reliability for this indication.

Bone cement has also been successfully employed in revision stapes surgery to address incus erosion resulting in suboptimal couple of the prosthesis to the lateral chain. While one systematic review and meta-analysis suggested a slight benefit of

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

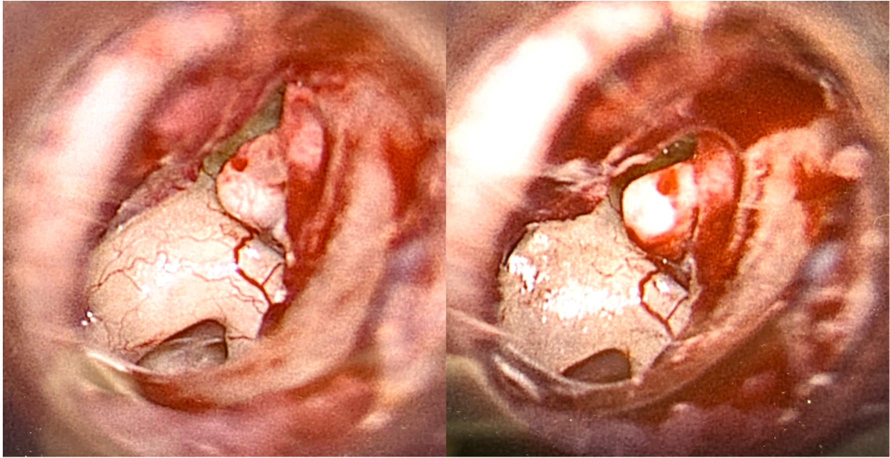

Fig. 3. Intraoperative photo from bone cement ossiculoplasty. Erosion of the incus long process is visible on the left panel. Reconstitution of the incudostapedial joint with bone cement can be seen on the right panel.

bone cement techniques over autologous grafts and prostheses with an odds ratio of 2.81 and a wide confidence interval of 1.04 to 7.61,[14] a similar review found no statistically significant benefit of bone cement over other techniques for both ossicular chain reconstruction and stapes revision surgery.[15] Though both investigations admit a high likelihood of bias in retrospective review, particularly with regards to patients selected for one intervention over the other, bone cement ossiculoplasty is likely at least non-inferior for audiometric outcomes when compared with other techniques.

Nonprosthetic Reconstruction

Autologous graft material used for ossiculoplasty may include a variety of materials, including calvarial bone, repurposed ossicles, cartilage, perichondrium, temporalis fascia, or fat. These materials may be used in isolation, or to support a synthetic prosthesis, such as a cartilage cap over a titanium prosthetic head. Most investigation of audiometric outcomes for these materials consider the use of autologous material alone versus synthetic prosthetics or a combination of synthetic materials supported by autografts. Some individual retrospective investigations have concluded superiority of air–bone gap closure with the use of autologous incus interposition compared with titanium prosthesis, with a greater percentage of patients achieving air–bone gap closure for autograft[16,17]; however, most larger studies show similar outcomes for both graft types for patients with chronic otitis media,[8,18,19] cholesteatoma,[19] or history of temporal bone fracture.[20] Regardless of audiometric outcome, multiple studies discuss the superiority of autograft material with regards to decreased post-operative complication and prosthetic extrusion.[16,17,19]

Ossicular Chain Reconstruction with Synthetic Materials

Synthetic prostheses for ossicular chain reconstruction fall into 2 broad categories: partial ossicular chain prosthesis (PORP) or total ossicular chain prosthesis (TORP). While several different variations in structure have been designed over the ears and different materials have been utilized (including titanium, Teflon, hydroxyapatite, and alloys such as nickel-titanium or nitinol), most studies reporting audiometric outcomes

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

group synthetic prostheses into these 2 broad groups. Several meta-analyses have demonstrated greater improvement in air–bone gaps with PORP compared to TORP, suggesting that the status of stapes superstructure is crucial in predicting hearing outcome.[6,7,21] In a larger review, these differences remained significant, even when surgery type (canal wall intact vs canal wall down), prosthesis material, and follow-up time were considered.[21] Smaller studies have investigated other factors, such as the use of a footplate shoe to improve coupling to the stapes footplate[22] or the use of a TORP with an intact stapes superstructure with otherwise challenging anatomy precluding use of a PORP.[23] Results contradict the generalized findings of the larger meta-analyses, suggesting there may be methods to further optimize audiometric outcomes when a TORP is indicated. Indeed, closer examination of human ossicular morphology reveals substantial differences not only between individual patients but also within individuals between ears, suggesting the possible opportunity to further optimize hearing outcomes with individually customized prosthetics in the future.[24]

AUDIOMETRIC OUTCOME LIMITATIONS

Mechanical Limitations

A crucial limitation when considering the optimization of ossiculoplasty is the challenge of recreating the complex mechanics of middle ear sounds transmission. While low-frequency vibration of the tympanic membrane, ossicular chain, and oval window is able to be characterized primarily by piston-like energy transmission, above 2 kHz, this simple, single-dimensional model begins to break down. Research has demonstrated the complex vibratory patterns of the tympanic membrane, during which high-frequency stimulation results in complex modal motion, rather than the synchronized, piston-like movement observed at low frequencies. Additionally, the movement of the stapes footplate includes both piston-like and rocking movement patterns with higher frequency stimulation.[25]

Commercially available stapes prostheses rely on a wire or piston (compared with the much broader footplate) to transmit lateral ossicular vibration to the inner ear, and the more complex rocking motion of the footplate is sacrificed.[26,27] Lateral ossicular chain reconstruction will forgo the level mechanism of the malleus and incus; ultimately impacting the stiffness of the transmission system.[28] These types of changes impact the frequency response of the ossicular transformation function and result in complex changes to hearing sensitivity, even under ideal surgical conditions. When the ultimate goal of ossiculoplasty is restoration of normal or preoperative hearing, the challenge of this goal becomes more broadly apparent when the mechanical factors are taken into consideration.

Assessment Limitations

Re-establishment of normal acoustic transmission through the middle ear and normal hearing is further constrained by limitations in standard clinical audiometry. Ultrahigh frequency air-conduction thresholds (above 8 kHz) are not routinely assessed despite hearing sensitivity extending up to 20 kHz. Though the most crucial frequencies for understanding human speech fall within the range of standard clinical tests, data have suggested its importance in optimizing understanding of speech in the presence of background noise.[1,2]

Perhaps even more importantly, conventional testing equipment limits bone conduction testing to a maximum of only 4 kHz.[29,30] The presence of persistent air–bone gaps following ossicular chain reconstructive surgery can only be assessed

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

reliably for the low-frequency and midfrequency range, and as a result, any postoperative changes in air-conduction sensitivity from 6 to 8 kHz cannot be clearly delineated as conductive or sensorineural in nature on standard audiometry. Though the use is limited primarily to research settings, bone conduction testing above 4 kHz has been investigated to better evaluate the audiometric outcomes of middle ear surgery.[31–33] High-frequency (≥ 4 kHz) conductive hearing loss and its subsequent recovery after bone cement ossiculoplasty has been documented in a small cohort of patients,[34] demonstrating the potential for future improvement in audiometric assessment of patients undergoing ossicular chain reconstructive surgery.

SUMMARY

When evaluating hearing outcomes following surgery on the ossicular chain, the most commonly cited metric of improvement is closure of the air-bone gap; general consensus throughout the literature suggests that reduction to 20 dB or less is considered a successful procedure. It is crucial to keep in mind the limitations of ossiculoplasty in our current capability to truly restore normal middle ear mechanics and the resulting transmission of sound energy to the inner ear, as well as our inability to characterize air–bone gaps at frequencies above 4 kHz. Moving into the future, critical evaluation and research development in these areas has the potential to allow further optimization of hearing after ossicular chain surgery.

CLINICS CARE POINTS

- The most widely accepted clinical goal in audiometric outcomes for successful ossiculoplasty is an air–bone gap closure of 15 or less to 20 dB.
- Better characterization of high-frequency (<4000 Hz) air–bone gap may help clinicians better understand the functional outcomes and limitations of surgery.
- Autologous and prosthetic materials have not been shown to have significantly different outcomes with regards to postoperative air–bone gap closure; however, autograft materials may be associated with fewer complications.
- A nuanced understanding of the complex impact of ossiculoplasty on middle ear mechanics is critical to inform patients regarding the practical expected benefits and limitations of postoperative hearing restoration.

REFERENCES

1. Polspoel S, Kramer SE, van Dijk B, et al. The importance of extended high-frequency speech information in the recognition of digits, words, and sentences in quiet and noise. Ear Hear 2022;43(3):913–20.
2. Motlagh Zadeh L, Silbert NH, Sternasty K, et al. Extended high-frequency hearing enhances speech perception in noise. Proc Natl Acad Sci U S A 2019;116(47):23753–9.
3. Merchant GR, Siegel JH, Neely ST, et al. Effect of middle-ear pathology on high-frequency ear canal reflectance measurements in the frequency and time domains. J Assoc Res Otolaryngol 2019;20(6):529–52.
4. Feeney MP, Keefe DH, Hunter LL, et al. Normative wideband reflectance, equivalent admittance at the tympanic membrane, and acoustic stapedius reflex threshold in adults. Ear Hear 2017;38(3):e142–60.

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

5. Karuppannan A, Barman A. Wideband absorbance pattern in adults with otosclerosis and ossicular chain discontinuity. Auris Nasus Larynx 2021;48(4):583–9.
6. Kortebein S, Russomando AC, Greda D, et al. Ossicular chain reconstruction with titanium prostheses: a systematic review and meta-analysis. Otol Neurotol 2023;44(2):107–14.
7. Omar M, McCoy JL, Kitsko DJ, et al. PORP vs. TORP in children: a systematic review and meta-analysis. Am J Otolaryngol 2023;44(1):103658.
8. Olaison S, Berglund M, Taj T, et al. Hearing outcomes after ossiculoplasty with bone or titanium prostheses—A nationwide register-based study. Clin Otolaryngol 2024;49(5):660–9.
9. Demir B, Binnetoglu A, Sahin A, et al. Long-term outcomes of ossiculoplasty using bone cement. J Laryngol Otol 2019;133(8):658–61.
10. Baglam T, Karatas E, Durucu C, et al. Incudostapedial rebridging ossiculoplasty with bone cement. Otolaryngol Head Neck Surg 2009;141(2):243–6.
11. Celenk F, Baglam T, Baysal E, et al. Management of incus long process defects: incus interposition versus incudostapedial rebridging with bone cement. J Laryngol Otol 2013;127(9):842–7.
12. Babu S, Seidman MD. Ossicular reconstruction using bone cement. Otol Neurotol 2004;25(2):98–101.
13. Ozer E, Bayazit YA, Kanlikama M, et al. Incudostapedial rebridging ossiculoplasty with bone cement. Otol Neurotol 2002;23(5):643–6.
14. Reis LR, Gani K, Pereira AS, et al. Bone cement in ossicular chain reconstruction: systematic review and meta-analysis. Acta Otorrinolaringol Esp 2024;75(5):316–23.
15. Wegner I, van den Berg JW, Smit AL, et al. Systematic review of the use of bone cement in ossicular chain reconstruction and revision stapes surgery. Laryngoscope 2015;125(1):227–33.
16. Sharma MO, Pareek Y, Sehra R, et al. Hearing outcome in ossiculoplasty with autologous incus and teflon prosthesis in chronic otitis media: a comparative study. Indian J Otolaryngol Head Neck Surg 2022;74(Suppl 1):345–50.
17. Amith N, Rs M. Autologous incus versus titanium partial ossicular replacement prosthesis in reconstruction of Austin type A ossicular defects: a prospective randomised clinical trial. J Laryngol Otol 2017;131(5):391–8.
18. Gopishankar S, Shah KD, Joshi AA, et al. Optimizing hearing outcomes in middle ear surgery: a comparative analysis of titanium (PORP) against autologous incus in type IIb tympanoplasty. Indian J Otolaryngol Head Neck Surg 2025;77(3):1354–9.
19. Orfao T, Julio S, Ramos JF, et al. Audiometric outcome comparison between titanium prosthesis and molded autologous material. Otolaryngol Head Neck Surg 2014;151(2):315–20.
20. Zhao L, Li J, Gong S. Comparison of the application of artificial ossicles and autologous ossicles in the reconstruction of a damaged ossicular chain. J Laryngol Otol 2018;132(10):885–90.
21. Yu H, He Y, Ni Y, et al. PORP vs. TORP: a meta-analysis. Eur Arch Otorhinolaryngol 2013;270(12):3005–17.
22. Faramarzi M, Roosta S, Faramarzi A, et al. Comparison of partial vs. total ossicular chain reconstruction using titanium prosthesis: a retrospective cohort study. Eur Arch Otorhinolaryngol 2023;280(8):3567–75.
23. Baker AB, O'Connell BP, Nguyen SA, et al. Ossiculoplasty with titanium prostheses in patients with intact stapes: Comparison of TORP versus PORP. Otol Neurotol 2015;36(10):1676–82.

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.

24. Kamrava B, Roehm PC. Systematic review of ossicular chain anatomy: strategic planning for development of novel middle ear prostheses. Otolaryngol Head Neck Surg 2017;157(2):190–200.
25. Hato N, Stenfelt S, Goode RL. Three-dimensional stapes footplate motion in human temporal bones. Audiol Neurootol 2003;8(3):140–52.
26. Kwacz M, Marek P, Borkowski P, et al. Effect of different stapes prostheses on the passive vibration of the basilar membrane. Hear Res 2014;310:13–26.
27. Rosowski JJ, Mehta RP, Merchant SN. Diagnostic utility of laser-Doppler vibrometry in conductive hearing loss with normal tympanic membrane. Otol Neurotol 2003;24(2):165–75.
28. Ferris P, Prendergast PJ. Middle-ear dynamics before and after ossicular replacement. J Biomech 2000;33(5):581–90.
29. Roychowdhury P, Polanik MD, Kempfle JS, et al. Does stapedotomy improve high frequency conductive hearing? Laryngoscope Investig Otolaryngol 2021;6(4):824–31.
30. Polanik MD, Trakimas DR, Castillo-Bustamante M, et al. Do high-frequency air-bone gaps persist after ossiculoplasty? Laryngoscope Investig Otolaryngol 2020;5(4):734–42.
31. Remenschneider AK, Cheng JT, Herrmann BS, et al. Characterization and clinical use of bone conduction transducers at extended high frequencies. Hear Res 2023;429:108688.
32. Rhebergen KS. Extended high-frequency bone conduction audiometry calibration of bone conductor transducers in the conventional and extended high-frequency range. Int J Audiol 2023;62(2):182–91.
33. Popelka GR, Telukuntla G, Puria S. Middle-ear function at high frequencies quantified with advanced bone-conduction measures. Hear Res 2010;263(1–2):85–92.
34. Fallon K, Inuzuka Y, Cheng JT, et al. Restoration of high-frequency middle ear function in partial ossicular discontinuity: a basic science and clinical correlation. Otol Neurotol 2025. https://doi.org/10.1097/MAO.0000000000004657.

Descargado para Lucia Angulo (lu.maru26@gmail.com) en National Library of Health and Social Security de ClinicalKey.es por Elsevier en abril 13, 2026. Para uso personal exclusivamente. No se permiten otros usos sin autorización. Copyright ©2026. Elsevier Inc. Todos los derechos reservados.