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Investigation of the Mechanics of Type III Stapes Columella Tympanoplasty Using Laser-Doppler Vibrometry

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Abstract

Objectives—To investigate the middle ear mechanics of Type III stapes columella tympanoplasty using laser-Doppler vibrometry (LDV) and to determine whether LDV was useful in the identification of structural factors responsible for poor hearing outcomes.

Background—The Type III stapes columella tympanoplasty procedure involves placing a tympanic membrane (TM) graft directly onto the stapes head. Postoperative hearing results vary widely, with air-bone gaps (ABGs) ranging from 10 to 60 dB.

Methods—Laser-Doppler vibrometry measurements were performed in 22 patients (23 ears) who underwent Type III stapes columella tympanoplasty. The measurements were made at three locations on the TM graft: over the stapes head, over the round window, and on the anterior TM. The LDV results were correlated with the clinical and audiologic findings.

Results—The 23 ears were divided into three groups: *Nonaerated ears* ($n = 2$). The ABGs were 30 to 60 dB. The TM velocities over all three locations were 20 to 40 dB lower than normal umbo velocity (in normally hearing subjects). *Fixed stapes with aerated middle ear* ($n = 2$). The ABGs were 40 to 60 dB, and TM velocities were equivalent to normal umbo velocity in one case and lower by 15 to 20 dB in another case. *Mobile stapes and aerated middle ear* ($n = 19$). There were two subgroups in this category: 1) small ABGs less than 25 dB ($n = 7$) and large gaps greater than or equal to 25 dB ($n = 12$). There were small differences in TM graft velocity at all three measurement locations between these two subgroups. However, these small differences did not explain the large difference in ABG between the two subgroups.

Conclusion—Nonaeration of the middle ear and stapes fixation lead to large residual conductive hearing losses after Type III tympanoplasty. Laser-Doppler vibrometry can aid in the diagnosis of nonaeration of the middle ear but does not readily diagnose stapes fixation. Postoperative results can vary even in cases of a mobile stapes and an aerated middle ear. We hypothesize that these variations may be the result of differences in the coupling between the TM graft and the stapes head. Measurements of TM velocities by means of LDV did not show clear differences between cases with good hearing and cases with poor hearing in ears with a mobile stapes and an aerated ear. Except for diagnosis of nonaeration of the middle ear, LDV seems to have limited clinical usefulness to identify causes of failure after Type III tympanoplasty.

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Keywords

Air-bone gap; Laser-Doppler vibrometry; Middle ear mechanics; Tympanoplasty

Tympanoplasty describes a group of surgical procedures used to repair the ossicular chain and the tympanic membrane (TM). The modern era of tympanoplasty was established by Zollner and Wullstein (1–2), who separated tympanoplasty into subtypes on the basis of the relationship between the TM and the ossicles or cochlear windows. Type III tympanoplasty is a commonly used surgical procedure for reestablishing the continuity between the TM and the inner ear when the ossicles are diseased. Type III tympanoplasty is subdivided into three different types based on the Nadol-Schuknecht modification (3) of the original Wullstein classification: 1) stapes columella tympanoplasty, which consists of placing a TM graft (usually made of fascia) directly onto the stapes head (Fig. 1A); 2) minor columella tympanoplasty, which consists of placing a strut or prosthesis between the stapes head and the TM graft; and 3) major columella tympanoplasty, which consists of placing a strut or prosthesis between the stapes footplate and the TM graft.

The postoperative hearing results after tympanoplasty, in general, and after Type III stapes columella tympanoplasty, in particular, are variable, with air-bone gaps (ABGs) ranging from 10 to 60 dB (1–11). Some reasons for poor hearing outcomes include nonaeration of the middle ear cavity, stapes fixation, and poor coupling between the TM graft and stapes (11). In the present study, we examined the postoperative hearing outcomes in 22 patients (23 ears) who underwent Type III stapes columella tympanoplasty. All patients also underwent measurement of TM motion by means of laser-Doppler vibrometry (LDV). The LDV measurements were correlated with the postoperative hearing results to determine whether LDV was useful in identifying the determinants of the hearing outcomes in these patients.

METHODS

A prospective longitudinal study was performed after approval by our institutional review board. Twenty-two patients (23 ears) who had previously undergone Type III stapes columella tympanoplasty were enrolled into the study. The mean age was 50 years, with a range of 28 to 69 years. The following information was obtained from each patient: otologic history, findings at otomicroscopy and pneumatic otoscopy, and a postoperative audiogram. In some patients, postoperative temporal bone computed tomographic (CT) scans were also obtained.

All patients underwent velocity measurements of the grafted TM by means of LDV. The LDV test was performed after healing was completed, with the mean interval between surgery and LDV test being 4.2 years (SD, ± 4.1 years). The technique of LDV has been described in detail previously (12–14). Briefly, the patient lay in a supine position on an examination table. An otologic speculum was placed in the external auditory canal. The operated ear was examined using an operating microscope. Because the grafted TM was no longer sensate, we were able to place small pieces of reflective tapes (with dimensions of approximately 0.25×0.25 mm) on the TM without needing topical anesthesia. The reflective tape significantly enhanced the signal-to-noise ratio of the measurements. Measurements of TM motion were performed in each ear at three locations (Fig. 1B): posterosuperiorly (over the stapes head), posteroinferiorly (over the round window [RW]), and anteriorly (over the anterior TM). A glass-back sound coupler containing an earphone and a probe-tube microphone was coupled to the otologic speculum. A laser-Doppler interferometer (Polytech HLV-1000; Polytec PI, CA, USA), mounted on the operating microscope, measured the sound-induced velocity at these 3 locations in response to a nine-tone sound stimulus containing frequencies of 300, 500, 700, 1,000, 1,500, 2,000, 3,000, 4,000, and 6,000 Hz. Sound pressure in the external auditory canal

was also measured, and the measured velocities were divided by the sound pressure so as to *normalize* the velocity measurements by the stimulus pressure.

The LDV findings were correlated with the clinical findings. The 23 ears were divided into 3 groups:

Postoperative nonaerated middle ear (n = 2)

Determined by the lack of motion on pneumatic otoscopy and the lack of aeration on postoperative temporal bone CT scan.

Fixed stapes with postoperative middle ear aeration (n = 2)

Stapes fixation was determined by means of intraoperative observation, and postoperative middle ear aeration was determined by means of pneumatic otoscopy, by using the motion of TM on autoinflation, or by means of postoperative CT scan.

Mobile stapes with postoperative middle ear aeration (n = 19)

The determination of stapes mobility and aeration status was similar to that in Group 2. The third group was further subdivided into two subgroups: 1) small, postoperative ABGs (pure-tone average [PTA] ABG < 25 dB [n = 7]; PTA ABG is defined as the average ABG at 500, 1,000, and 2,000 Hz) and 2) large, postoperative ABGs (PTA ABG ≥ 25 dB [n = 12]).

Because the *normal* TM graft velocity in patients who underwent Type III stapes columella tympanoplasty is not known, the mean normal umbo velocity from a study by Whittemore et al. (14) (measurements from 56 normally hearing subjects) was used as a reference for comparison (the numbering of the cases in this study refers to the patient identification number assigned when they were evaluated in our laboratory rather than a numbering scheme related to the present study).

RESULTS

Nonaerated Middle Ear After Type III Tympanoplasty

There were two ears in this category. In the first case (Patient 11), the middle ear was filled with fluid on otomicroscopic examination, and a postoperative temporal bone computed tomography showed complete opacification of the middle ear. In the second case (Patient 280), the TM was completely atelectatic on otomicroscopy. Pneumatic otoscopy revealed no TM motion in both cases. The postoperative ABG averaged for 250 to 4,000 Hz was 30 dB for Patient 11 and 49 dB for Patient 280. The LDV in both cases showed little to no measurable motion (Fig. 2) at all measured locations.

Stapes Fixation With Aerated Middle Ear

There were two ears with stapes fixation as determined by intraoperative palpation. In one case (Patient 2), the stapes was fixed by otosclerosis, and the middle ear was aerated postoperatively, as determined by means of pneumatic otoscopy and autoinflation. In the other case (Patient 245), the stapes was fixed by tympano-sclerosis, and the anterior part of the middle ear was aerated postoperatively, as determined by means of a CT scan. Both of these patients had large ABGs, averaging 47 dB for Patient 2 and 52 dB for Patient 245. In Patient 2, the TM graft velocity over the stapes was close to the normal umbo velocity but was lower than the velocities over the RW and anterior TM (Fig. 3). In Patient 245, the TM graft velocities over the stapes and RW were both much lower than the normal umbo velocity and were also lower than the velocity over the anterior TM (Fig. 3).

The low graft velocity over the stapes with a large velocity in the anterior TM in Patient 245 is consistent with stapes fixation being the cause of the residual hearing loss. However, in Patient 2, we saw large motions of the graft over the stapes despite the observed fixation. We hypothesize that there was poor coupling of the TM graft to the stapes head in Patient 2, which obscured the decreased stapes mobility. Therefore, diagnosis of stapes fixation in Type III tympanoplasty can be complicated by variations in coupling between the TM graft and the stapes head.

Mobile Stapes With Aerated Middle Ear

There were 19 ears in this category. The stapes was mobile in each case. The middle ear was aerated post-operatively in each case, as determined by means of pneumatic otoscopy, autoinflation, and, in some cases, by means of CT scans. There were two subgroups: those with small ABGs (<25 dB [$n = 7$]) and those with large ABGs (≥ 25 dB [$n = 12$]). Figure 4A compares the average ABGs between the two subgroups. Figure 4B shows the velocity measurements over stapes, RW, and anterior TM in the small ABG subgroup compared with normal umbo velocity. Figure 4C shows the velocity measurements over the same locations in the large ABG subgroup compared with normal umbo velocity. In cases of good hearing outcomes after Type III tympanoplasty (Fig. 4B), TM graft velocities at all locations were lower than the normal umbo velocity. The velocity over the anterior TM was higher than the velocity over the RW, which, in turn, was higher than that over the stapes. A similar pattern was also observed in cases with poor hearing outcomes (Fig. 4C).

Comparisons of the TM velocity measurements over the stapes, RW, and anterior TM between the small and large ABG subgroups are shown in Figure 5, A to C. The TM graft velocities at all 3 locations were similar at low frequencies, and the small ABG subgroup was found to have slightly higher velocities at all 3 locations at higher frequencies. In general, the measured velocities were similar between the two subgroups. Small differences were observed for selected frequencies. However, these small differences in measured graft velocities did not account for the large difference in ABGs between patients with good hearing outcome and patients with poor hearing outcome.

DISCUSSION

Tympanoplasty has been widely used to reconstruct the ossicular chain and the TM, after middle ear disease is surgically eradicated. Despite its wide application, the postoperative hearing results after tympanoplasty vary widely. The etiologies for poor hearing outcomes after Type III stapes columella tympanoplasty have been postulated in several studies (1–11) and include nonaeration of the middle ear cavity, stapes fixation, and poor coupling between the TM graft and stapes. However, it remains difficult to pinpoint the culprit for a poor hearing outcome in a particular patient without surgical reexploration. In the present study of 23 ears that underwent Type III stapes columella tympanoplasty, we also found a wide range of ABGs. We performed measurements of TM motion with LDV in all 23 ears and attempted to correlate the LDV results with the postoperative hearing outcomes.

Laser-Doppler Vibrometry Is Capable of Diagnosing Patients With Complete Middle Ear Nonaeration

We found very low TM graft mobility at all 3 measurement locations in both ears that were nonaerated; in fact, the measured velocities in Patient 11 were so low that most of them were in the noise range. This suggests that LDV is capable of detecting middle ear nonaeration after tympanoplasty.

Laser-Doppler Vibrometry Is Not Useful in the Diagnosis of Stapes Fixation as a Cause of Failure of Type III Tympanoplasty

There were 2 ears with stapes fixation. The surgical goal in these 2 *staged* cases was eradication of middle ear disease and not restoration of hearing because stapedectomy is contraindicated in the presence of middle ear disease (3,4). As expected, both cases had large 30-to 60-dB ABGs. However, the TM graft velocity over the stapes was near the level of normal umbo velocity in one case (Patient 2) and low in the other case (Patient 245). The variability observed in TM graft velocity over the stapes suggests that LDV is not very sensitive in determining stapes fixation after tympanoplasty. Possible problems include 1) poor coupling between the stapes head and the TM graft would mask stapes fixation by permitting large velocities of the graft over the stapes despite a decrease in stapes motion; and 2) inaccurate estimation of stapes location, given the fact that the grafted TM can be thickened and is opaque, making identification of the stapes head challenging.

Patients With a Mobile Stapes and an Aerated Middle Ear After Type III Tympanoplasty Had a Wide Range of Hearing Results. The Small Differences in TM Graft Velocities Did Not Account for the Large Difference in ABGs Between Ears With Good Hearing Outcome and Ears With Poor Hearing Outcome

When the mean TM graft velocities over the stapes, RW, and anterior TM were compared between the two subgroups, we found that the velocities at low frequencies at all locations were similar in magnitude. There were small differences in TM graft velocity at higher frequencies (>1–2 kHz) between the subgroups, with the velocities in the small ABG subgroup being larger than the velocities in the large ABG subgroup. The cause of this difference is unclear. The small differences in TM graft velocities did not account for the large difference in ABGs between these two subgroups of patients (Fig. 4A). Again, poor coupling between the TM graft and the stapes head may help to explain the large difference in ABGs and the lack of difference in TM velocities between these two subgroups.

CONCLUSION

Postoperative hearing results after Type III stapes columella tympanoplasty procedures are variable. We found that middle ear nonaeration or stapes fixation can result in 30- to 60-dB ABGs. Laser-Doppler vibrometry can aid in the diagnosis of complete middle ear nonaeration because all locations on the TM graft are unresponsive to sound. However, LDV does not readily distinguish stapes fixation as a cause of failure after Type III tympanoplasty. Postoperative hearing results can vary even when the stapes is mobile and the middle ear is aerated. These variations in hearing results may be caused by differences in the coupling between the TM graft and the stapes head. Laser-Doppler vibrometry measurements did not reveal clear differences in TM motion between cases with good hearing and cases with poor hearing in the group with a mobile stapes and an aerated middle ear. Except in cases of nonaeration of the middle ear, LDV seems to have limited clinical usefulness in determining the causes of failure after Type III tympanoplasty.

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REFERENCES

1. Zollner F. The principles of plastic surgery of the sound-conducting apparatus. *J Laryngol Otol* 1955;69:637–652. [PubMed: 13263770]
2. Wullstein H. The restoration of the function of the middle ear, in chronic otitis media. *Ann Otol Rhinol Laryngol* 1956;65:1020–1041.
3. Nadol, JB.; McKenna, MJ. *Surgery of the Ear and Temporal Bone*. 2nd ed.. New York, NY: Raven Press; 2005.
4. Glasscock, ME.; Gulya, AJ. *Surgery of the Ear*. 5th ed.. Philadelphia, PA: W.B. Saunders Co; 2002.
5. Juers AL. Myringostapedioplasty. *Arch Otolaryngol* 1960;71:376–379.
6. Wullstein H. Results of tympanoplasty. *Arch Otolaryngol* 1960;72:478–485.
7. Proctor B. What happens in Type III tympanoplasty. *Laryngoscope* 1965;75:1307–1319. [PubMed: 14341784]
8. Pennington CL III. Fascia graft myringostapedioplasty. *Laryngoscope* 1966;75:1459–1476. [PubMed: 5927126]
9. Lee K, Schuknecht HF. Results of tympanoplasty and mastoidectomy at the Massachusetts Eye and Ear Infirmary. *Laryngoscope* 1971;81:529–543. [PubMed: 4928558]
10. Merchant SN, McKenna MJ, Mehta RP, Ravicz ME, Rosowski JJ. Middle ear mechanics of Type III tympanoplasty (stapes columella), II: clinical studies. *Otol Neurotol* 2003;24:186–194. [PubMed: 12621330]
11. Mehta RP, Ravicz ME, Rosowski JJ, Merchant SN. Middle-ear mechanics of Type III tympanoplasty (stapes columella), I: experimental studies. *Otol Neurotol* 2003;24:176–185. [PubMed: 12621329]
12. Merchant, SN.; Whittemore, KR.; Poon, B.; Lee, C-Y.; Rosowski, JJ. Clinical measurements of tympanic membrane velocity using laser Doppler vibrometry: preliminary results, methodological issues and potential applications. In: Rosowski, JJ.; Merchant, SN., editors. *The Function and Mechanics of Normal, Diseased and Reconstructed Ears*. The Hague, Netherlands: Kugler; 2000. p. 367–382.
13. Rosowski JJ, Mehta RP, Merchant SN. Diagnostic utility of laser-Doppler vibrometry in conductive hearing loss with normal tympanic membrane. *Otol Neurotol* 2003;24:165–175. [PubMed: 12621328]
14. Whittemore KR Jr, Merchant SN, Poon BB, Rosowski JJ. A normative study of tympanic membrane motion in humans using a laser Doppler vibrometer (LDV). *Hear Res* 2004;187:85–104. [PubMed: 14698090]

FIG. 1. Schematic diagrams showing (A) Type III stapes columella tympanoplasty, illustrating the TM graft coupled to the head of stapes, and (B) LDV measurement locations on the TM graft: 1) over stapes head, 2) over RW, and 3) over anterior TM.

FIG. 2.

Illustration showing LDV measurements over TM graft in the 2 cases with complete middle ear nonaeration. All measurements in Patient 11, except at 2,000 Hz, were within the noise and are not shown. The mean umbo velocity in 56 healthy subjects from Whittemore et al. (14) and its SD and range are shown for comparison.

FIG. 3. Illustration showing the laser-Doppler vibrometry measurements over TM graft in the 2 ears with stapes fixation. The mean umbo velocity in 56 healthy subjects from Whittemore et al. (14) and its SD and range are shown for comparison.

FIG. 4.

Illustrations showing (A) mean ABGs in patients with middle ear aeration and mobile stapes. These patients were divided into 2 subgroups: patients with good hearing outcomes (<25 dB [$n = 7$; solid black line with open circles]) and patients with poor hearing outcomes (>25 dB [$n = 12$; solid black line with open squares]). The respective SDs are also shown as shading around the mean. (B), Mean TM graft velocities over stapes (*square*), RW (*pointed-up triangle*), and anterior TM (*pointed-down triangle*) in patients with small ABGs. The mean normal umbo velocity from Whittemore et al. (14) and its SD and range are shown for comparison. (C), Mean TM graft velocities over stapes (*square*), RW (*pointed-up triangle*),

and anterior TM (*pointed-down triangle*) in patients with large ABGs. The mean normal umbo velocity from Whittemore et al. (14) and its SD and range are shown for comparison.

FIG. 5.

Illustrations showing the (A) mean TM graft velocity over stapes in 12 patients with aerated middle ear and mobile stapes but large ABGs, with its 95% confidence intervals (*solid black line with open circles + shaded areas*), compared with the mean TM graft velocity over stapes in 7 patients with aerated middle ear and mobile stapes but small ABGs (*solid black line with open squares*). (B), Comparison of the TM graft velocities over RW between small and large ABG groups. (C), Comparison of the TM graft velocities over anterior TM between small and large ABG groups.