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ORIGINAL RESEARCH

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Frequency-dependent hearing outcomes with or without preservation of intact ossicular articulations

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Abstract

Objective: To determine the frequency-specific benefits of ossicular chain preservation compared to performing disarticulations and reconstructions in transmastoid facial nerve decompression surgery in patients with an intact ossicular chain.

Methods: A retrospective chart review (January 2007 and June 2018) of patients undergoing transmastoid facial nerve decompression on the intact middle ear for severe facial palsy at a tertiary referral center. Surgery was performed with ossicular chain disarticulation on an as-needed basis using either ossicular chain preservation (without ossicular disarticulation), incudostapedial separation, or incus disarticulation technique. Hearing outcomes were assessed.

Results: The 108 patients were included in this study. Among these, 89 patients underwent ossicular chain preservation, 5 underwent incudostapedial separation and 14 underwent incus repositioning. The proportion of patients with a change in the 4-frequency air conduction pure-tone average of less than 10 dB was 91%, 60%, and 50%, respectively, for the three surgical techniques; these were significantly different (Fisher's exact test, $p < .001$). Frequency-specific analysis showed that air conduction was significantly better following the ossicular chain preservation technique compared with the incus repositioning technique at stimulation frequencies lower than 250 Hz and higher than 2000 Hz, and compared with the incudostapedial separation technique at 4000 Hz. Analysis of biometric measures determined on CT images suggested that the feasibility of the ossicular chain preservation technique correlates with incus body thickness on coronal CT images.

Conclusions: Ossicular chain preservation is an effective approach for hearing preservation in transmastoid facial nerve decompression or similar surgical procedures.

KEYWORDS

facial nerve decompression, hearing loss, ossicular chain preservation, ossiculoplasty, pure tone audiometry

Level of evidence: 3b.

1 | INTRODUCTION

Recent advances in endoscopic ear surgery enable us to approach the various parts in the tympanic cavity without disturbing the ossicular chain. However, a substantial number of middle ear surgeries still require ossicular chain disarticulation, which potentially induces hearing deterioration after surgery and impairs quality of life. This is especially the case when disarticulation of the intact ossicular chain is required to gain access to the surgical field underneath the ossicles. Once the articulations have been manipulated, reconstruction of the joints, typically by gluing, is required and thus physiological articulations will be lost, which leads to hearing deterioration through a reduction in the efficiency and stability of sound transmission in the middle ear.

Transmastoid facial nerve decompression is a typical example of surgery that still requires ossicular chain disarticulation. The standard procedure with incus removal was originally reported by Pulec in 1966.[1] To date, this approach is performed worldwide for decompression of the intratemporal facial nerve not only in severe facial palsy in Bell's palsy[2–8] and Ramsay Hunt syndrome,[9] but also in traumatic temporal bone fracture.[10,11] In addition, similar procedures with incus removal are frequently performed to approach a lesion involving the epitympanic cavity, such as a cholesteatoma, neuroma, or benign vascular tumor.

The most frequent complication accompanying transmastoid facial nerve decompression is auditory involvement[12]; indeed, it is reported that this standard procedure left a 15-dB or more air-bone conduction gap in 14% of patients.[12] To address this issue, we have performed transmastoid facial nerve decompression with ossicular chain disarticulation on an as-needed basis. A previous report demonstrated that both incudomalleolar and incudostapedial joints can be preserved in approximately 85% of cases with this approach, which is effective not only in improving facial outcome and but also to prevent hearing deterioration in severe Bell's palsy when assessed by a 4-frequency pure tone average (PTA).[6] However, a number of questions still remain. For example, it is not clear if this surgical procedure is a better approach for hearing preservation compared to other surgical techniques, such as incudostapedial separation or incus repositioning, due to the scarcity of the available clinical data regarding the impact of joint disarticulations on hearing. Furthermore, the frequency dependency of the impact with each technique remains elusive. Finally, the factors determining the feasibility of the ossicular chain preservation technique with ossicular chain disarticulation on an as-needed basis are unclear.

To address these questions, we reviewed our facial nerve decompression surgeries in severe Bell's palsy, zoster sine herpete and Ramsay Hunt syndrome over an 11-year period, providing the largest case series for transmastoid facial nerve decompression to date. Furthermore, we analyzed temporal bone computed tomography (CT) images to illustrate the feasibility of this technique in terms of anatomical features.

2 | MATERIALS AND METHODS

2.1 | Participants and setting

The study protocol was approved by the Institutional Review Board of Nagoya City University, with a waiver of informed consent for a retrospective medical records review (approval number 60-18-0001). Participants were recruited through a tertiary referral center, the otolaryngology clinic at Nagoya City University Hospital, Japan, between January 2007 and June 2018 for transmastoid facial nerve decompression surgery with a diagnosis of severe facial palsy from Bell's palsy, zoster sine herpete, or Ramsay Hunt syndrome.[13–15] Surgeries were performed on patients who demonstrated House-Brackmann grade VI and a ≤10% electroneuronography score by either AI or SM with assistance from otolaryngology fellows. Patients gave informed consent to participate in the study and were given the opportunity to opt out at any time.

The inclusion criteria for this study were: patients who were ≥ 18 years of age at surgery, patients with a preoperative 4-frequency (0.5, 1, 2, and 4 kHz) air conduction pure-tone average (PTA) threshold of ≤40 dB, and patients who could be followed up for 12 months or until the level of the postoperative deterioration in 4-frequency air conduction PTA became 10 dB or less. Inclusion and exclusion criteria are summarized in Supplementary Table 1.

2.2 | Patient evaluation

Hearing was measured with pure-tone audiometry (AA-78; Rion Co. Ltd., Tokyo, Japan). Absent responses to air-conducted and bone-conducted sound were coded as 120 dB and 80 dB, respectively.

The biometric characteristics of the ossicular chain of the surgical patients were evaluated on preoperative temporal bone CT images obtained by using the Somatom Definition Flash scanner (Siemens Healthcare, Forchheim, Germany) with acquisition at 0.4-mm thickness in a suborbitomeatal plane at 120 kV, 250–300 mA. The axial and coronal planes were reconstructed at 0.5-mm thickness. Both images were stored digitally at Nagoya City University Hospital, Japan.

Digitally-stored CT images were displayed using the Centricity Universal Viewer (GE Healthcare, Chicago, IL). Precise measurements were made based on consensus between experienced facial nerve specialists (AI and MT) using electronic calipers provided by the EV Insite system (PSP Corporation, Tokyo, Japan), based on methods described in previous reports.[16,17] Twelve aspects of each temporal bone CT were recorded by direct measurement, six on axial sections and six on coronal sections.

2.3 | Surgical technique

The detailed surgical procedure has been reported previously.[6] In summary, we performed ossicular disarticulation on an as-needed

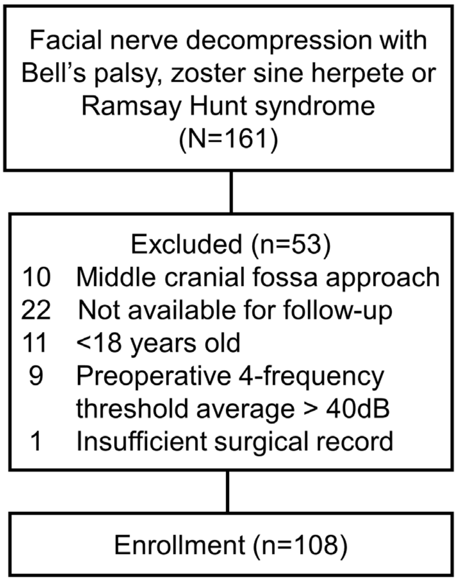

FIGURE 1 Flow diagram of enrollment of participants

basis to preserve as much of the ossicular chain as possible (supplementary method 1). We attempted to preserve the ossicular chain by achieving the necessary access just medial to the incus and malleus head by mobilizing the malleus and incus anterolaterally instead of disarticulating them. If this approach did not work, we disarticulated only the incudostapedial joint (incudostapedial separation technique). Temporal incus removal was only performed when both of these approaches did not work (incus repositioning technique). The disarticulated chains were reconstructed with fibrin glue.

2.4 | Statistical methods

Unless otherwise noted, all data are presented as the mean ± standard error. Differences among the three groups were compared using one-way analysis of variance (ANOVA), followed by pairwise comparisons with Dunn's test (SigmaPlot; WaveMetrics, Inc., Lake Oswego, OR). Differences between categorical variables were evaluated by Fisher's exact test (SigmaPlot).

3 | RESULTS

3.1 | Completion of facial nerve decompression without ossicular chain disruption

During the study period, a total of 161 patients underwent facial nerve decompression surgery; 53 patients were excluded from the study due to failure to meet the inclusion criteria (Figure 1, Supplementary Table 1). In the analysis described below, the participants included 108 patients with an intact ossicular chain (55 men and 53 women; mean age 44.4 ± 1.3 years, range 18–75 years) with either Bell's palsy, zoster sine herpete or Ramsay Hunt syndrome.

Among the 108 enrolled patients, 89 patients (82.4%) underwent facial nerve decompression without any ossicular chain disarticulation (ossicular chain preservation technique). However, the incudostapedial separation technique was required in 5 patients (4.6%) and the incus repositioning technique in 14 patients (13.0%).

Facial nerve segments between the geniculate ganglion and the mastoid segment were fully exposed and decompressed in all the enrolled cases. However, accessibility to the labyrinthine segment varied depending on the anatomical features in each temporal bone.[18] The labyrinthine segment was approachable in 59.6% of cases (53 patients; 11 to the proximal segment and 42 to the distal segment) using the ossicular chain preservation technique. With the incudostapedial separation technique, approach to labyrinthine segment was possible in 60.0% of cases (3 patients, all to the proximal segment) and in 71.4% (10 patients; 2 to the proximal segment and 8 to the distal segment) with the incus repositioning technique. The accessibility rates to the labyrinthine segment in these three groups were not significantly different among the three techniques (Fisher's exact test, $p = .843$).

3.2 | Better hearing preservation in facial nerve decompression with the ossicular chain preservation technique

To determine if hearing outcomes differed between these three surgical techniques, we first compared mean 4-frequency air-conduction PTA thresholds (0.5, 1, 2, 4 kHz) (Figure 2). With the ossicular chain preservation technique, a total of 81 patients (91%) presented with a hearing threshold change of 10 dB or less postoperatively and the remaining 8 patients (9%) presented with a deterioration of 11–20 dB (Figure 2, left). For the other two techniques, the ratios were three patients (60%) with ≤10 dB and two patients (40%) with 11–20 dB in the incudostapedial separation technique and seven patients (50%) with ≤10 dB and six patients (43%) with 11–20 dB in the incus repositioning technique. One patient with the incus repositioning technique presented with a hearing deterioration of 31–40 dB postoperatively. The ratios of patients presenting with a 10-dB or less change were significantly different among the three techniques (Fisher's exact test, $p < .001$), and a pairwise comparison demonstrated that the ratio between the ossicular chain preservation technique and incus repositioning technique was significantly different (Fisher's exact test, $p = .008$).

Mean 4-frequency air-conduction PTA threshold changes in each technique were also evaluated. The changes were a deterioration of 1.4 ± 0.7 dB ($n = 89$) in the ossicular chain preservation technique, 6.0 ± 2.1 dB ($n = 5$) in the incudostapedial separation technique and 12.7 ± 2.3 dB ($n = 14$) in the incus repositioning technique. Based on these metrics, the mean PTA threshold in the ossicular chain preservation technique was significantly better than that of the incus

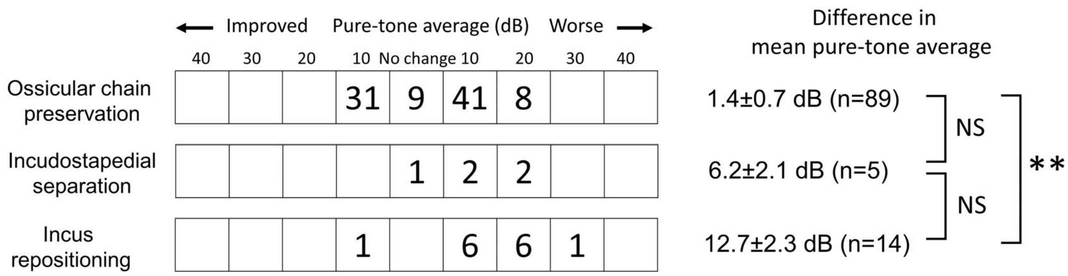

FIGURE 2 Hearing outcomes for each surgical technique. The number of patients with each magnitude (in dB) of difference between their preoperative and postoperative 4-frequency mean air-conduction pure-tone average threshold values (0.5, 1, 2, 4 kHz) are presented (left chart) with the mean values (right). For example, boxes headed "10" include the number of patients whose PTA threshold values were in the range 1–10 dB (improved or worsened) postoperatively, boxes headed "20" indicate the range 11–20 dB and so on. NS, not significant; ***p* < .01.

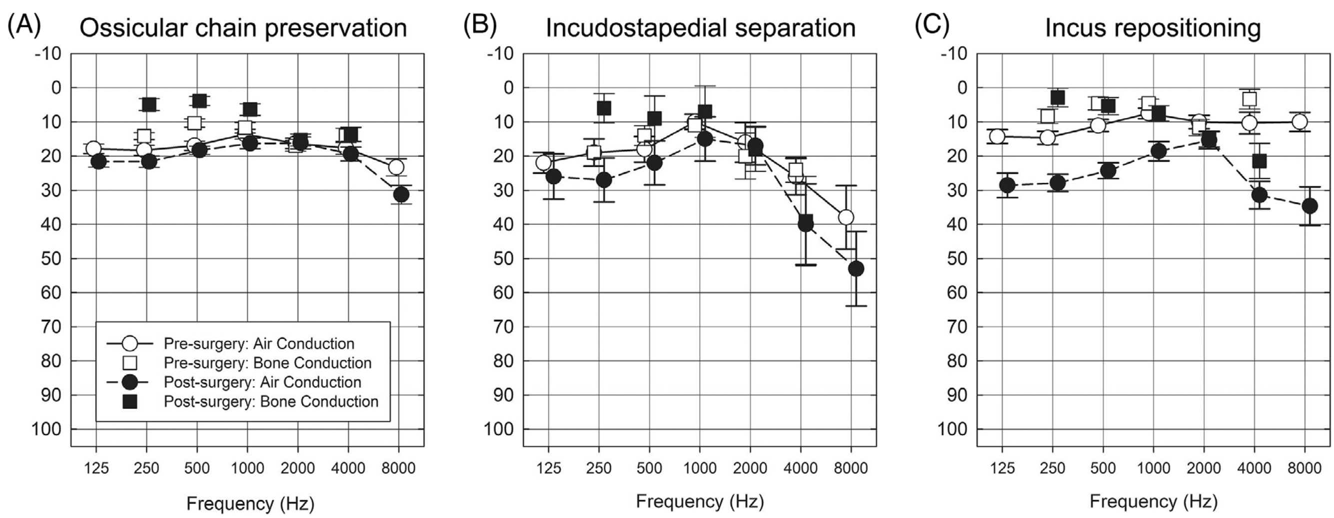

FIGURE 3 Mean frequency-specific hearing levels pre and postoperatively for air and bone conduction for the three types of surgery. Each audiogram indicates the frequency-specific preoperative and postoperative audiometric data with ossicular chain preservation (A), incudostapedial separation (B) and incus repositioning (C). Circles and squares represent air and bone conduction, and open and filled symbols represent pre and postoperative hearing levels, respectively.

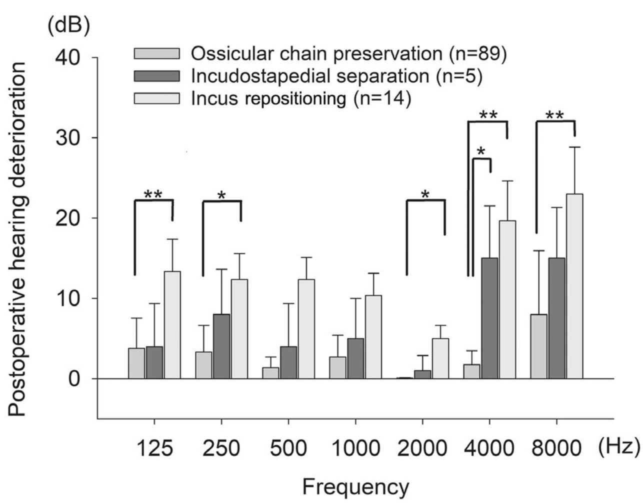

FIGURE 4 Mean postoperative frequency-specific hearing deterioration (in dB) with each surgical technique. Each bar represents the mean of the changes between pre and postoperative hearing levels in air conduction level at each frequency. **p* < .05; ***p* < .01.

repositioning technique (one-way ANOVA followed by Dunn's Method, $p = .005$; Figure 2, right).

Next, we compared the changes in frequency-specific hearing thresholds. Figure 3 shows preoperative (open symbols) and postoperative (filled symbols) conduction levels for air (circles) and bone (squares) for each of the techniques (Figure 3A–C; changes in air-conduction level at each frequency are summarized in Figure 4). At all frequencies, hearing deterioration was the lowest with the ossicular chain preservation technique, followed by the incudostapedial separation and incus disarticulation techniques. The ossicular chain preservation technique resulted in significantly better hearing outcomes compared with the incus repositioning technique at 125, 250, 2000, 4000, and 8000 Hz and compared with the incudostapedial separation technique at 4000 Hz (one-way ANOVA, followed by Holm-Sidak method; Figure 4). These results suggest that ossicular chain preservation is particularly beneficial to reduce hearing deterioration in both high and low frequency ranges.

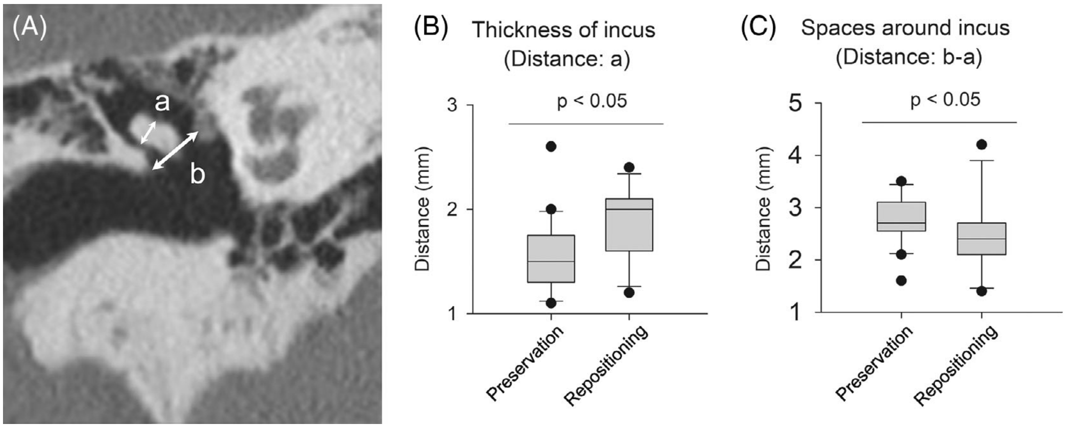

FIGURE 5 Biometric measures on CT images for patients who underwent surgery in which the ossicular chain was preserved with the ossicular chain preservation technique or repositioned with the incus repositioning technique. Biometric measurement on the axial CT image at the level of the incus body. Distances were compared between the groups in which the ossicular chain was preserved (ossicular chain preservation technique) and those in which they were not (incus repositioning technique) using the as-needed basis disarticulation strategy. (A) Representative axial CT image used for biometric measures; incus body thickness (distance a) and distance between the most medial point of the bony spur and the most medial point of the facial nerve (distance b). (B) Box-and-whisker plots of incus thickness (a); (C) Incus thickness (a) subtracted from the distance between the spur and the facial nerve (b).

3.3 | Incus body thickness is associated with the feasibility of the ossicular chain preservation technique

We performed incudostapedial and incudomalleolar joint disarticulation on an as-needed basis when disarticulation was required for accessibility medial to the incus and mallear head. To identify the anatomical features of those cases for which we were able to use the ossicular chain preservation technique and those cases which required ossicular disarticulation (Supplementary Figure 1A–E), we compared biometric parameters of the temporal bone on temporal bone CT images (Supplementary Figure 2A). We retrospectively investigated preoperative CT images acquired using the same scanner with the same protocol, namely 0.5-mm thick axial and coronal images of the affected side. Thirty-two preoperative temporal bone CT images in 32 patients (21 patients who underwent the ossicular chain preservation technique, 2 patients who underwent the incudostapedial separation technique, and 9 patients who underwent the incus repositioning technique) met the criteria. Eleven distances and 1 angle thought to potentially affect accessibility to the pregeniculate area were measured on both axial and coronal images, and compared between those cases without disarticulation (ossicular chain preservation technique group) and those with (incudostapedial separation and incus repositioning group; Figure 5, Supplementary Figure 2B-K). Among these biometrics at the level of the incus body (Supplementary Figure 2A), incus body thickness on coronal CT images was significantly higher in patients requiring disarticulation compared with those who did not (1.85 ± 0.10 mm vs. 1.56 ± 0.08 mm, respectively, $p = .038$; Figure 5A,B). In addition, the width of the space obtained by anteromedial incus retraction to allow for visualizing the part medial to the incus (taken as the difference between the residual distance and the incus thickness from the distance between the scutum and the facial nerve on coronal CT images at the same coronal levels) was significantly shorter in patients requiring disarticulation compared with those who did not (2.44 ± 0.22 mm vs. 2.76 ± 0.10 mm, $p = .027$; Figure 5A,C). These results indicate that the anatomical features of the incus and adjacent areas strongly determine the feasibility of the ossicular chain preservation technique.

4 | DISCUSSION

In clinical settings, the impact of disarticulations on the efficiency of sound transmission is largely unknown due to the scarcity of literature reporting on manipulations of the intact ossicular chain. There is one previous study reporting hearing outcomes using the incus repositioning technique which suggested that real life manipulations of the intact ossicular chain is not as efficient as suggested by the theoretical values obtained in experimental settings.[19–22] In their study, May & Klein reported that 14% of patients presented with a 15-dB or more air-bone conduction gap following intratemporal facial nerve surgery with temporal incus removal and repositioning.[12] In the present study, 1 out of 14 patients (7%) with the incus repositioning technique demonstrated an air-bone conduction gap exceeding 20 dB, agreeing with the previous result. These inconsistent hearing outcomes may be ascribed to the imposed mechanical balance of the repositioned incus. To achieve efficient transmission, ossicular grafts and prostheses must couple well at their ends to bone or soft tissue.[23] In routine type III tympanoplasty, stable coupling of the incus is usually achieved due to the use of artificial bone or a remodeled incus with high-mechanical stability. However, in incus repositioning technique, there can be torsional stress which reduces stability on the articular surfaces of both the incudomallear and incudostapedial joints which are reglued with fibrin glue. This difficulty in achieving good ossicular coupling may underlie this hearing outcome.

This mechanical unsteadiness may underlie the frequency-dependent hearing outcomes of incus repositioning cases by hampering a good ossicular coupling. In the present study, patients who required incus removal and regluing demonstrated a significant decrease in sound transmission in both high (2000 Hz and above) and low (250 Hz and lower) frequency ranges. This outcome is similar to that of a cadaveric study investigating incudostapedial joint separation and regluing using liquid adhesive which showed sound transmission dampening at low and high frequencies.[20] In contrast, incus repositioning of both the incudomallear and incudostapedial joints using cyanoacrylate, a firm and strong adhesive,[24] demonstrated a dampened transmission only at frequencies below 1000 Hz. Similarly, increasing the rigidity of the incudostapedial joint using cyanoacrylate resulted in a decrease in sound transmission at below 1000 Hz.[19] Furthermore, sound transmission was regained when hydroxyapatite bone cement was used to repair the separated incudostapedial joint.[22] These frequency dependencies indicate that it is the quality of the ossicular coupling that is important for hearing outcomes, rather than the number of reconstructed joints.

Hearing deterioration after incudostapedial separation and regluing was milder than that after incus removal. In the present study, the patients who underwent the incudostapedial separation technique demonstrated a 6.2 dB threshold elevation in the 4-frequency PTA threshold average, which was similar to the 7.0 dB threshold elevation in a previous study of the incudostapedial separation technique.[25] In contrast to techniques that involve disarticulations of the ossicular joints, the ossicular chain preservation technique, which ensures that both the incudomalleolar and incudostapedial joints remain intact, led to a hearing threshold elevation of less than 5 dB at any frequency except for at 8 kHz. These outcomes support the notion that the structures removed in the ossicular chain preservation technique such as the posterior incudal ligament and surrounding membranous folds are non-vital structures for hearing, as reported previously.[26] The decrease at 8 kHz may be ascribed to the sensory neural hearing loss due to a surgical complication, as previously reported.[12] This is presumably due to sound vibration from the burr reaching the ossicular chain during drilling of the incus buttress.

We attempted to identify the anatomical features which help or hinder the ossicular chain preservation technique by evaluating high-resolution preoperative CT images. The size of the ossicles varies substantially between individuals.[27] Recent advances giving higher resolution on CT scanners enables us to utilize these images to evaluate ossicular metrics. In spite of the substantial number of studies of this kind,[28,29] no standardized metric for measurement of the anatomical features of the human ossicles on CT images has been proposed to date. In addition, to the best of our knowledge, the only available data regarding incus thickness was provided by Heron in 1923 who reported a minimum thicknesses of 1.6 mm and a maximum of 2.6 mm, with an average of 2.0 mm,[30] which is in accordance with the variability in incus thickness observed in the present study. In the ossicular chain technique, the horizontal and pyramidal segments are visualized between the facial nerve and the medial surface of the incus body; we speculate that a thicker incus or smaller space for mobilizing the incus directly hampers the visualization because the amount of tilt of the incudo-malleal complex is similarly limited by the anterior mallear ligament and stapes which both fix the incus body and long process (Supplementary Figure 1D,E).

The limitations of this study include the retrospective, non-randomized design. Based on our surgical protocol, incudostapedial separation and/or incus removal were performed only when the anatomical features did not allow for further surgical manipulation due to poor visibility. This strategy can introduce bias in patient allocation in terms of anatomical features. If poor visibility correlates to poor aeration of the middle ear and round window, poorer hearing outcomes with the incus repositioning technique can be ascribed at least partially to the anatomical features. Middle ear conductance is dependent on ossicular coupling, acoustic coupling, and stapes-cochlear input impedance within the middle ear, and poor aeration of the middle ear and round window induces a reduction in conductance due to greatly reduced ossicular coupling in type I, II, and III tympanoplasty.[31] However, hearing outcomes for each of our surgical techniques were similar to those in previous reports of studies without patient allocation,[12,25] so the effect could be minimal, if present at all.

5 | CONCLUSIONS

The present study demonstrated the advantage of the ossicular chain preservation technique in hearing preservation over incus removal and reconstruction techniques during transmastoid facial nerve decompression surgery. Furthermore, imaging analysis revealed the anatomical features of the incus and the adjacent areas that determine the feasibility of the ossicular chain preservation technique. Our observations confirm the impact of ossicular joint reconstruction on hearing, and the benefit of the ossicular chain preservation technique on hearing outcomes.

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CONFLICT OF INTEREST

There are no conflicts to report.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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