Published in final edited form as:

Hear Res. 2007 August ; 230(1-2): 24–33.

Fixation and detachment of superior and anterior malleolar ligaments in human middle ear: Experiment and modeling

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Abstract

The aim of this study is to investigate the function of the superior malleolar ligament (SML) and the anterior malleolar ligament (AML) in human middle ear for sound transmission through simulations of fixation and detachment of these ligaments in human temporal bones and a finite element (FE) ear model. Two laser vibrometers were used to measure the vibrations of the tympanic membrane (TM) and stapes footplate. A 3-D FE ear model was used to predict the transfer function of the middle ear with ligament fixation and detachment. The results demonstrate that fixations and detachments of the SML and AML had different effects on TM and stapes footplate movements. Fixation of the SML resulted in a reduction of displacement of the TM (umbo) and the footplate at low frequencies ($f < 1000$ Hz), but also caused a shift of displacement peak to higher frequencies. Fixation of both SML and AML caused a reduction of 15 dB at umbo or stapes at low frequencies. Detachment of the SML had almost no effect on TM and footplate mobility, but AML detachment had a minor effect on TM and footplate movement. The FE model was able to predict the effects of SML and AML fixation and detachment.

Keywords

Middle ear ligament; Laser interferometry; Temporal bone; Finite element model; Middle ear mechanics

1. Introduction

The superior malleolar ligament (SML) connects the malleus head to the roof of the epitympanum and consists of a large number of densely arranged fibroblasts. The SML is not merely a suspensory ligament, but has true functional significance in malleolar mobility (Huttenbrink, 1989). Embryologically developed from Meckel's cartilage, the anterior malleolar ligament (AML) has both vertical and horizontal attachments to the neck of the malleus. The SML and AML are attached superiorly and anteriorly to the epitympanum and provide mechanical support to the malleus head. The SML and AML serve as moveable elements and act as suspensory structure for part of ossicular chain. Therefore, structural changes in the SML or AML may play an important role in affecting middle ear function.

Malleus fixation is a specific pathophysiologic entity and can arise as a result of several predisposing anatomic factors and several diseases affecting the epitympanum (Schuknecht, 1993; Mehta et al., 2002). Although true bony fixation of the malleus hinders ossicular chain

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mobility, thickening or hardening of the ligaments surrounding the malleus can restrict malleus mobility. In the case of chronic infection or a middle ear mass, the SML and AML can be damaged and disconnected from the malleus. During surgical release of malleus head fixation, the SML and AML are dissected. The absence of these two ligaments may affect middle ear sound transmission and result in conductive hearing loss.

Several studies in patients and human temporal bones have been conducted to investigate the effect of AML fixation on acoustic transmission. Using laser Doppler interferometry, Huber et al. (2003) measured the umbo and stapes footplate displacements in 19 patients with otosclerosis and five temporal bones in which AML fixation was simulated by applying glue to the surface of the malleus head. Nakajima et al. (2005a) simulated AML fixation and extensive malleus fixation in temporal bones and measured the effects of fixation on umbo and footplate movement and compared their findings with clinical results. Nandapalan et al. (2002) reported that histological changes in the AML and SML were associated with decreased malleus mobility and eventual fixation in otosclerosis. Their histological evaluation demonstrated that hyalinization of the SML appears to be parallel to AML hyalinization. However, the effect of SML fixation on middle ear transfer function remains undetermined and the role of combined SML and AML fixations has not been investigated.

Recently, our group completed a series of experiments in temporal bones that evaluated the effects of manipulations of the middle ear ligaments on TM and footplate movements using two laser vibrometers. Our data shed new light on the functions of these ligaments and muscle tendons in middle ear mechanics (Gan et al., 2004b, 2006). We also employed a finite element model of the human middle ear to simulate the experimental procedure and predict the effects of our surgical dissection on TM and footplate mobility. However, in those temporal bone experiments, neither the SML nor AML were cut as the first step in the sequence of dissections. Therefore, the data obtained from these experiments did not directly reflect the effect of the SML or AML on the TM and stapes movements. Experiments in which only the SML or AML were manipulated and other ligaments maintained intact could lead to a better understanding of the SML and AML on sound transmission from the TM to the stapes.

In this study, the SML and AML fixation or detachment were simulated in human cadaver ears or temporal bones. The effects of ligament fixation and detachment on the TM and stapes footplate mobility were measured simultaneously by using two laser Doppler vibrometers. A 3-D finite element (FE) model of the human ear developed by Gan et al. (2004b) was used to simulate SML or AML fixation and detachment and to predict the effect of ligament manipulation on middle ear transfer function.

2. Materials and methods

2.1. Human temporal bone preparation

Nine fresh-frozen cadaver temporal bones obtained through the Willet Body Program, University of Oklahoma Health Sciences Center were used in this study. The ages of individual donors ranged from 58 to 76 with a mean of 69 years (seven females and two males). To retard putrefaction and maintain soft tissue compliance, the bones were immersed in 1:10,000 Merthiolate in 0.9% saline solution at 5 °C until used (Gan et al., 2004c).

Before the surgical procedure was performed, debris from the external ear canal and the soft tissue in the mandibular fossa and carotid canal were removed. The integrity of the TM was examined through an operating microscope (OPMI-1, Zeiss, Thornwood, NY). Access to the stapes was obtained by a simple mastoidectomy and facial recess approach. The removal of the mastoid segment of the facial nerve in the facial recess facilitated laser access to the footplate of the stapes. Access to the head of the malleus was achieved through a posterior

atticotomy by opening the posterior-lateral attic wall of the middle ear. Extreme care was taken not to damage any ligamentous tissue or ossicular structure in the middle ear. The AML and SML were exposed with a good view for fixation and detachment of the ligaments as shown in Fig. 1.

Two reflective tapes of 0.5 mm², weighing 0.04 mg (3M Co., St. Paul, MN) were placed on the umbo and stapes footplate, respectively, as the laser targets. The bone was wrapped in gauze wetted with normal saline to avoid desiccation of the specimen during the experiment.

2.2. Laser interferometry measurement on temporal bones

The temporal bone experimental setup was similar to our previous studies and the full description is available elsewhere (Gan et al., 2004c). Briefly, the temporal bone was placed in a temporal bone holder and the temporal bone assembly was set on a vibration isolation table. One laser was aimed on the reflective tape at the stapes footplate and another laser was aimed on the reflective tape at the umbo. Pure tone, filtered sound signals of 90 dB from a function generator (Model 193, Wavetek, San Diego, CA) were delivered to the ear canal near the TM by an inserted earphone (Model ER-2, Etymotic Research, Grove Village, IL). A probe microphone (Model ER-7, Etymotic Research) used for monitoring the input sound pressure level (SPL) was secured paralleled to the sound delivery tube and was positioned approximately 2 mm from the umbo.

A hearing laser vibrometer (Model HLV-1000, Polytec PI, Tustin, CA) was used to measure the vibration of the TM (umbo). The helium–neon laser with an associated positioner-aiming prism was coupled to an operating microscope. The spectral magnitude and phase information from the laser vibrometer was obtained by a digitizing signal analyzer (Model DSA 601, Tektronix, Beaverton, OR) and recorded on a personal computer. Only data with a total harmonic distortion of less than 10% of pure tone signals according to the distortion index shown on the signal analyzer were accepted. The second laser Doppler vibrometer (Model OFV-501, Polytec PI, Tustin, CA) was used to measure movement of the stapes footplate simultaneously.

2.3. Experimental protocols

After surgical preparation of the temporal bone, the control measurement was performed with intact ligaments in the middle ear. The velocity or displacement measurements at the TM (umbo) and stapes footplate in response to 90 dB in the ear canal were obtained over a frequency range of 200–8 kHz with two laser vibrometers. Then the following two experiments were performed:

2.3.1. Experiment I – SML and AML fixation—Fixation of the SML was created by applying polyurethane glue (Henkel Consumer Adhesives Inc., Avon, OH) to the surface of the ligament between the malleus head and the epitympanum in four bones. AML fixation was performed in one bone by coating the ligament surface with glue. The umbo and footplate displacements were measured following both SML and AML fixations. Upon the completion of fixation experiment measurements, the coated glue was removed from the ligaments and the umbo and footplate velocities were measured again as a reference check for ligament detachment tests.

To investigate the effects of SML and AML fixation on movement of the TM at different locations, an additional reflective tape was placed at the center of the anterior-superior (AS) quadrant of the TM in one bone and the displacements at both this point and the umbo were measured.

2.3.2. Experiment II – SML and AML detachment—The four bones that were used in Experiment I for SML fixation were further used for the SML detachment experiment by cutting the SML with a surgery micro-scissor through the opened epitympanum under an operating microscope. Another four bones were used to simulate AML detachment using the same method as that for SML detachment, and then were used to conduct both SML and AML detachment by dissection of both ligaments.

2.4. Finite element modeling

A 3-D FE model of the human ear (Fig. 2) reported by Gan et al. (2004b) was used to simulate detachment and fixation of the SML or AML. The FE model was created based on 780 histological sections (20 μ m thickness) from a left human temporal bone. Material properties of the middle ear ligaments were listed in Table 2 of Gan et al.'s paper (Gan et al., 2004b). The Young's modulus for the SML and AML were 4.9 and 21 MPa, respectively, for normal ear or control in this study. To simulate fixation of these two ligaments, the Young's modulus of AML or SML was increased by a factor of 100. For simulation of detachment, the Young's modulus of SML or AML was set to 0.1 MPa which is extremely small compared with the control value. The acoustic-structural coupled FE analysis between the external ear canal and the TM with a 90 dB SPL sound pressure in the ear canal was conducted using ANSYS (ANSYS Inc, Canonsburg, PA). The model provided the velocity or displacement data of the TM at the umbo and the stapes footplate across the frequency range of 200–8 kHz in normal (control), Exp. I and Exp. II conditions.

3. Results

3.1. Experiment results

3.1.1. SML and AML fixation—The results from SML and AML fixation experiments in temporal bones are shown in Figs. 3–5. Fig. 3 shows the displacements of the TM (umbo) and stapes footplate measured in 3 groups of bones. The top panels show amplitude and the bottom panels represent phase. Fig. 3a shows the data obtained from SML fixation, Fig. 3b shows the data from AML fixation (one bone), and Fig. 3c shows the data from both ligaments fixed (five bones). The input sound pressure in the ear canal was maintained at 90 dB. Fig. 3a indicates that the SML fixation caused a reduction of umbo displacement magnitude of 3–7 dB and a reduction of footplate displacement of 2–5 dB at low frequencies (<1000 Hz). At high frequencies (1500–3000 Hz), SML fixation did not affect umbo displacement, but an increase of 4–7 dB was noted in footplate movement. The peak displacement of the TM and footplate shifted from 1000 to 1800 Hz as shown in Fig. 3a. Fig. 3b shows that AML fixation produced a reduction of 2–3 dB of the umbo displacement and 3–4 dB of the footplate at frequencies of 200–1000 Hz. However, the displacement peak did not shift in comparison with Fig. 3a. Fixation of both AML and SML caused a significant reduction of the TM and footplate movement (10–16 dB) at frequencies less than 1500 Hz as shown in Fig. 3c. No obvious change was observed at high frequencies ($f > 1500$ Hz).

Fig. 4 shows the magnitude change (in dB) of the umbo and footplate displacement in three fixations with respect to the control. It is clearly seen that SML fixation caused more reduction at umbo movement than that of the AML fixation at $f < 1000$ Hz (Fig. 5a). However, AML fixation had more effect at the footplate than SML fixation at $f < 1500$ Hz (Fig. 4b). At frequencies of 1500–3000 Hz, SML fixation caused an increase up to 7 dB at the footplate and this was not observed for AML fixation. When both ligaments were fixed, the reduction of footplate displacement reached 10–15 dB and the TM reduction reached 7–12 dB at $f < 1000$ Hz as shown in Fig. 4.

Fig. 5 shows the comparison of the displacement at the umbo and the displacement at the location on the anterior-superior quadrant (AS) of the TM under SML, AML and both SML and AML fixations. The control displacement curve for the AS location shows a notch at 1500 Hz (Fig. 5b) and there is no notch in the umbo control curve (Fig. 5a). However, when SML or AML or both ligaments were fixed, the notch in the AS curve disappeared. The appearance/disappearance of the notch suggests a change in the mode of TM motion with AML or SML fixation.

3.1.2. SML and AML detachment—Effects of SML and AML detachment on umbo and FP movements are shown in Fig. 6. Fig. 6 shows the displacements of the TM (umbo) and stapes footplate measured in three groups of bones. Fig. 6a shows the data obtained from SML detachment, Fig. 6b shows the data from AML detachment, and Fig. 6c shows the data from both ligaments being detached. The TM (umbo) and stapes footplate displacements in response to a 90 dB SPL input were measured before (control) and after SML and AML were dissected. The mean displacement magnitude curves of four bones (Fig. 6a) show that the SML detachment had little effect on motion of the umbo and footplate. AML detachment had a small effect on umbo movement at frequencies below 2000 Hz which resulted in an increase of umbo displacement as shown in Fig. 6b. No significant change in footplate movement was observed with AML detachment. When both SML and AML were dissected, displacements of the TM and footplate had a minor change at low frequencies ($f < 1000$ Hz) as shown in Fig. 6c.

3.2. FE modeling results

3.2.1. SML and AML fixation—The effects of SML and AML fixations on umbo and footplate displacements magnitude and phase in response to 90 dB sound pressures in the ear canal were predicted by the FE model and shown in Fig. 7. Fig. 7a shows the displacement changes of the TM (umbo) and footplate in the case of SML fixation in comparison with the control curves. A reduction (3–5 dB) of the TM and footplate mobility relative to control was observed at $f < 1500$ Hz. At high frequencies ($f > 1500$ Hz), fixation of the SML caused a small decrease of displacement at the TM and footplate. The mobility change induced by AML fixation was similar to that by SML fixation as shown in Fig. 7b. When both SML and AML were fixed, the reductions of the TM and footplate displacements were observed over frequency range of 200–8 kHz with a reduction value of 15 dB at low frequencies ($f < 2$ kHz).

3.2.2. SML and AML detachment—SML and AML detachments were simulated in the FE model. The model-derived displacement magnitudes and phases at the umbo and footplate induced by 90 dB sound pressure in the ear canal are shown in Fig. 8. Fig. 8a illustrates that SML detachment did not have a significant effect on the TM and footplate movements. In the case of AML detachment (Fig. 8b), there was a minor increase of displacement magnitude at low frequencies ($f < 900$ Hz) and no change at high frequencies. The displacement changes caused by detachment of both SML and AML (Fig. 8c) were similar to that of the AML dissection (Fig. 8b).

4. Discussion

4.1. Fixation of SML and AML

Huber et al. (2003) and Nakajima et al. (2005a) reported AML fixation measured in human temporal bones with a similar experimental setup of the present study. Fig. 9 shows the comparison of the data obtained from this study with that reported by Huber et al. and Nakajima et al. as the TM (Fig. 9a) and footplate (Fig. 9b) displacement magnitude changes relative to control or a middle ear with intact ligaments. Huber et al.'s data showed the umbo displacement was reduced by a 3–6 dB at frequencies below 2 kHz, while a 2.5 dB reduction was reported by Nakajima et al. at $f < 800$ Hz. Our results showed a 2–3 dB loss of umbo displacement at

$f < 1$ kHz which fell in the range of published data by Huber et al. and Nakajima et al. At high frequencies ($f > 1$ kHz), our data were close to Nakajima's data.

The change of displacement magnitude at the footplate induced by AML fixation obtained in this study was between the data reported by Huber et al. (2003) and Nakajima et al. (2005a) across the frequencies of 200–2 kHz as shown in Fig. 9b. A 5–12 dB loss up to 2.5 kHz was measured by Huber et al. and 3–6 dB at $f < 600$ Hz was reported by Nakajima et al. Our data showed a 4–5 dB reduction over frequencies of 200–1 kHz. As a summary, there is agreement between our results and published data on the effect of AML fixation. This indicates that our experimental setup, fixation method and laser measurement are consistent with the published work on ligament fixation. It is also noticed that the cement-bar fixation at the malleus head had a larger effect than bar-fixation at the AML as reported by Nakajima et al. A cement bar at the malleus head produced an average reduction of 15 dB in stapes and umbo velocity at low frequency. The location of Nakajima et al.'s malleus head fixation is similar to this study's SML fixation. However, the results obtained in this study show only a 5–7 dB change in umbo and stapes displacement at low frequency. This difference indicates that "cement bar" at the malleus head provided stronger fixation on mobility of the malleus than the fixation on the SML. The data difference between this study and Nakajima et al.'s cement-bar fixation may be related to the material used for fixation, the size of fixed area, and the distance between the malleus head and the epitympanum.

Primary malleus fixation includes a fixed malleus with associated limitation of the motion of the incus as well as the stapes (Moon and Hahn, 1981), leading to conductive hearing loss. A fixed malleus head produces a change in the impedance and in the acoustic energy transfer capacity of the tympanic membrane (Goodhill, 1966). Fixation of the malleus is a dynamic process and it may start with ligament hyalinization, such as SML or AML hyalinization. Structural changes in the AML or the SML play an important role in fixing the malleus partly or completely. However, speculation exists about the mechanical roles of AML and SML fixation in the change of middle ear transfer function. The results of this study obtained from measurements in temporal bones and calculated from FE model (Figs. 3 and 7) show that either SML or AML fixation caused a reduction of umbo and footplate mobility at low frequencies. SML fixation also resulted in an increase of the TM or footplate displacement at high frequencies (e.g., $f = 1.5$ –5 kHz) and this increase corresponding to displacement peak shift from 1000 to 1800 Hz (Fig. 3a). Compared with SML fixation, AML fixations had less effect on TM mobility, but relatively larger effect on footplate movement at $f < 1.5$ kHz (Fig. 4b). The different effects on the TM and footplate movements caused by SML and AML fixations indicate that these two ligaments have different mechanical functions on sound transmission through the middle ear. The dimension, shape and orientation differences of these two ligaments may be the main mechanism for their function variations.

Recently, Nandapalan et al. (2002) reported that SML hyalinization appears to be parallel to AML hyalinization. Therefore, the combined fixation of SML and AML is possibly a natural pathophysiological result. In this study, hyalinization or fixation of both AML and SML was simulated in temporal bones as well as in the FE model and the results show that the combined fixation had stronger effects on TM and footplate mobility than single ligament fixation (Figs. 3, 5 and 8). This seems reasonable because of multiple fixation locations. However, the combined fixation did not result in a simple summation of the results obtained from the individual fixations. When SML and AML were both fixed, the fixed area was enlarged, but more importantly, the orientation restrictions of the malleus head became wider and the freedom of movement at lateral, superior and anterior directions was reduced at the same time.

It has been reported that the vibration patterns vary at different locations of the TM in normal ears (Tonndorf and Khanna, 1972; Akache et al., 2007). This variation enables the opportunity

for evaluation of middle ear structures, but can also be a source of variance for the results. Our results in Fig. 5 also show that the TM vibration pattern changed at different locations when the SML or AML was fixed.

Moreover, several theoretical models were created and used to simulate the middle ear ligament function (Huber et al., 2003; Gan et al., 2006). In this study, the FE model of the human ear with accurate anatomic structure reported by Gan et al. (2004a) was manipulated to simulate the fixation and detachment of the SML and AML and conducted to acoustic-mechanical vibration analysis. Comparing the model-derived results (Fig. 7) with experimental data (Fig. 3) in three fixation cases, good agreement between the model and bone results were observed. This indicates that the FE model is able to predict the middle ear transfer functions under pathophysiological conditions.

4.2. Detachment of SML and AML

Detachment of the SML or AML may be seen after cholesteatoma surgery. To investigate the function of SML and AML for sound transmission, ligament cutting experiments are necessary and the data are useful in the study of the roles of ligaments in middle ear mechanics as well as in validation of the FE model. The result obtained from the SML and AML detachment experiment in temporal bones (Fig. 6) and predicted by the FE model (Fig. 8) provide similar conclusions: (1) detachment of the SML does not affect umbo and footplate movements across the frequency range of 200–8 kHz; (2) detachment of the AML has some effect on TM or footplate movement at $f < 2$ kHz. Detachment of the AML seemed to facilitate the TM (umbo) movement, but not footplate movement. The different effects on umbo and footplate movement illustrate that flexibility within the ossicular chain plays a role in sound transmission through the middle ear, e.g., Nakajima et al. (2005b).

In summary, the TM and footplate mobility change caused by SML or AML detachment was small, even when both were detached (Fig. 8c). The reason behind this phenomenon is due to the complex mechanical system of the middle ear. Besides the SML and AML, other ligaments and two intra-aural muscle tendons support the ossicular chain and affect its movement. In the live patients, only one or two ligaments detached might not significantly change ossicular chain mobility. For instance, in the surgical release of malleus fixation, surgeons may dissect the hyalinized SML and AML to correct the hearing loss induced by a fixed malleus head. Surgical release of non-fixed SML and AML may not be measurable clinically, but would result in subtle changes in hearing quality. Our FE model reflected the results measured in temporal bones as shown in Fig. 8c.

5. Conclusions

Fixation and detachment of the SML and AML have different effects on movement of the tympanic membrane and stapes footplate. Fixation of SML not only resulted in a reduction of the umbo and footplate displacement at low frequencies, but also caused a shift of the displacement peak to a higher frequency. Fixation of both SML and AML caused a 15 dB mobility loss of the stapes footplate at low frequencies and SML or AML fixations affected the TM vibration pattern. Detachment of the SML had almost no effect on TM and footplate mobility, but the AML detachment had minor influence on TM or footplate movement. Our FE model of human ear precisely predicted the effects of SML and AML fixations and disconnections on TM and footplate movements.

Acknowledgements

The authors gratefully recognize expert technical assistance of Don Nakmali, BSEE. This work was supported by NIH/NIDCD Grant R01DC006632.

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Fig. 1. View of a surgical window for exposure of SML and AML through an opened epitympanum in a human temporal bone. TTT stands for tensor tympani tendon.

Fig. 2. Anterior-medial view of a 3-D finite element model of human ear created from a temporal bone published by Gan et al. (2004b). The middle ear cavity was assumed transparent.

Fig. 3. Mean displacement amplitudes and phase of the TM (umbo) and footplate (FP) in response to 90 dB sound pressure in the ear canal under various ligament fixations. The top panels show displacement amplitude and the bottom panels show the phases. Solid lines represent the control measurements and the dash lines represent the experimental measurements. (a) SML fixation (four bones), (b) AML fixation (one bone), (c) both SML and AML fixation (five bones).

Fig. 4. Change of displacement magnitude in dB relative to control under three fixation cases: (a) TM and (b) footplate. The magnitude change results were calculated from displacement amplitude data in Fig. 3.

Fig. 5. Effect of the SML and AML fixation on the displacement change at the umbo (a) and the center of the anterior-superior (AS) quadrant of TM (b).

Fig. 6. Mean displacement amplitudes (top panel) and phases (bottom panel) of the tympanic membrane (TM) and footplate (FP) in response to 90 dB SPL input in the ear canal under following ligament disconnections: (a) SML disconnection (four bones), (b) AML disconnection (four bones), (c) both SML and AML disconnections (four bones).

Fig. 7. FE model predicted TM and footplate (FP) displacement magnitudes (top panel) and phases (bottom panel) in the following simulations: (a) SML fixation, (b) AML fixation, and (c) both SML and AML fixations.

Fig. 8. FE model predicted TM and stapes footplate (FP) displacement in the following simulations: (a) SML disconnection, (b) AML disconnection, and (c) both SML and AML disconnections.

Fig. 9. Comparison with other groups' published results on AML fixation experiments in human temporal bones. (a) Change of TM displacement in dB, (b) change of footplate (FP) displacement in dB.