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Numerical analysis of the effects of canal wall-up and canal wall-down mastoidectomy on the sound transmission characteristics of human ears

PEIHAN LIU[1], JIN WAN[2], WEN LIU[3, 4]*, YU ZHAO[1], SHANSHAN YAN[4, 5], WEN JIANG[3,4], HOUGUANG LIU[1]*

[1] School of Mechatronic Engineering, China University of Mining and Technology, Xuzhou, China.
[2] Xuzhou Third People's Hospital, Xuzhou, China.
[3] Artificial Ear Laboratory of Jiangsu Province, Xuzhou, China.
[4] Department of Otolaryngology, Affiliated Hospital of Xuzhou Medical University, Xuzhou, China.
[5] Graduate School of Xuzhou Medical University, Xuzhou, China.

Purpose: The aim of this work was to study the effect of canal wall-up (CWU) and canal wall-down (CWD) and mastoid obliteration in conjunction with CWD (CWD-MO) mastoidectomy on the sound transmission characteristics of the human ear. *Methods*: Three mastoidectomy surgical methods, CWU, CWD and CWD-MO, were simulated on the freshly dissected cadaver heads. Then, the finite element (FE) models corresponding to these surgical methods were established by micro-computed tomography (Micro-CT) and reverse engineering technology, and the accuracy of the models was verified. Finally, the FE Models were used to analyze the effects of different surgical methods on the sound transmission characteristics of the human ear. *Results*: For CWU, since the integrity of the outer wall of the ear canal is ensured, the sound pressure (SP) gain of the ear canal and the stapes footplate displacement (FPD) gain after this operation are close to normal values. For CWD, due to severe damage to the outer wall of the ear canal, a negative gain of the ear canal SP occurs in the high-frequency range, and the resonance frequency is significantly reduced. For CWD-MO, the frequency range of SP negative gain in the ear canal is reduced due to the addition of fillers in the ear canal to reduce the degree of damage, and the resonance frequency is increased compared to CWD. *Conclusions*: The impact of three types of mastoidectomy, including CWU, CWD, and CWD-MO, on the sound transmission characteristics of the human ear after surgery is relatively small.

Key words: *canal wall-up, canal wall-down, sound pressure gain, stapes footplate displacement gain, finite element*

1. Introduction

Chronic suppurative otitis media and middle ear cholesteatoma are common chronic inflammatory diseases of the middle ear and mastoid. Most patients with such diseases are accompanied by different degrees of conductive hearing loss, which significantly affects the patient's quality of life. Mastoidectomy is the preferred treatment for this type of middle ear disease and accounts for the majority of the otologist's operative time [8], in severe cases involving the posterior wall of the ear canal, with low risk of disease recurrence after surgery [18], [32]. The most commonly used surgical methods include canal wall-up (CWU) and canal wall-down (CWD) mastoidectomy. The purpose of CWU is to completely remove the lesion while preserving the integrity of the posterior wall of the external ear canal and the outer and lateral walls of the upper tympanum as much as possible. In the case of

* Corresponding authors: Wen Liu, Department of Otolaryngology, Affiliated Hospital of Xuzhou Medical University, Huai Hai West Road No. 99, Xuzhou, 221002, P. R. China. Phone: +8613615102636, e-mail: liuwen1972@163.com; Houguang Liu, School of Mechatronic Engineering, China University of Mining and Technology, Da Xue Road No.1, Xuzhou, 221116, P. R. China. Phone: +8618761435299, e-mail: liuhg@cumt.edu.cn
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CWD, a cavity is formed in the ear. Therefore, regular cleaning of the ear canal is necessary to prevent infection. Additionally, in cases of CWD, hearing is affected to some extent due to structural changes in the ear [23]. To address the issues associated with CWD, many surgeons opt for different materials, such as bone powder, fascia and other autologous tissues, to fill the surgical cavity. This approach is known as mastoid obliteration in conjunction with CWD (CWD-MO) [2], [26], [36].

Regarding the effect of CWU and CWD on postoperative hearing, there are conflicting conclusions in the published literature [1], [9], [10], [16], [19], [31]. A large number of studies have reported that CWU can obtain better hearing outcomes after surgery than CWD [1], [10], [31]. However, this surgical approach hinders the complete visualization of the intraoperative cholesteatoma resection process and increases the risk of disease recurrence [18], [24]. In view of the inherent problems of CWU, some researchers believe that CWD is better than CWU [9]. Some researchers also believe that there is no difference between the two [16], [19]. With the development of CWD-MO, the problems of CWD are solved. Salem et al. [28] believe that CWD-MO has a lower disease recurrence rate compared to CWD, and because CWD-MO does not require long-term control of ear disease after operation, it is better than CWU. In clinical practice, the choice of surgical method depends on the extent of lesions and the degree of mastoid bone development [17]. Because the mastoid bone undergoes developmental changes as an individual grows. In children and adolescents, the mastoid bone is not fully developed and it continues to grow. Therefore, CWU mastoidectomy is usually prioritized in pediatric cases to avoid interfering with the developmental process of the ear. In adults, the mastoid bone is usually fully developed, allowing the surgeon to choose a CWD or CWU mastoidectomy based on the patient's specific needs and extent of disease. Therefore, it is difficult to draw reliable conclusions based solely on clinical data. In addition, Karamert et al. [17] only measures the average hearing threshold and air-bone conduction difference after surgery, and does not specifically compare the hearing characteristics of different frequencies, such as ear canal sound pressure (SP) gain and stapes footplate displacement (FPD) gain. Therefore, it is necessary to use different methods to accurately evaluate the impact of different surgical procedures on the sound transmission characteristics of the human ear.

The finite element (FE) analysis method has been widely used in biomechanical analysis [25], [34]. The FE model of the human ear can truly simulate the sound transmission process of the human ear [5], [7]. Therefore, some scholars use the FE model of the human ear to study ear diseases, and their research conclusions have certain reference value for clinical research [4], [38]. Zhou et al. [39] studied the effect of CWD and CWD with conchaplasty on sound transmission in the ear canal, and the results showed that there was no significant difference in the SP distribution of the ear canal between the two surgical methods. Previous studies of middle ear mechanics have generally not included the mastoid cavity, so the impact of the mastoid cavity on sound transmission is unclear. For this question, Lee et al. [20] established a middle ear FE model containing the mastoid cavity. Research shows that the FE model of the human ear including the mastoid cavity can provide more information for the study of middle ear mechanics. Based on this model, Lee et al. [21] studied the SP distribution of the ear canal after CWD. The study found that the SP resonance frequency in the ear canal decreased after the operation and the peak resonance amplitude did not change significantly. Although researchers have conducted relevant research in this field, there are no reports on the effects of CWD and CWU mastoidectomy on the sound transmission characteristics of the human ear.

This paper is based on the FE model of the human ear earlier constructed by our team [22]. Considering that the research problem is mainly aimed at the middle ear, in order to simplify the model calculation, the cochlea is simulated with dashpots and concentrated mass. The air in the middle ear cavity presents little impedance and has little effect on the dynamics of the middle ear compared to other structures in the middle ear [40], so the middle ear cavity is ignored. The simplified FE model was used to simulate the sound transmission characteristics of the human ear after CWU, CWD and CWD-MO. Study by Zhou et al. [39] indicates that after CWD and CWD with conchaplasty (similar to CWD-MO), the FPD phase lags change slightly compared to that of normal ears. Meanwhile, since CWU ensures the integrity of the ear canal, its induced FPD phase lag is also small compared with that of normal ears. It can be seen that the postoperative impact on the phase angle is small. Considering that our study mainly focused on the biomechanical properties of the human ear, the study of postoperative phase angle was ignored. Finally, on the premise of not considering the middle ear lesions, by comparing the ear canal SP gain change, and the displacement frequency response curve of the stapes footplate (FP) and the umbo to evaluate the influence of these three different surgical methods on the sound transmission characteristics of the human ear.

2. Materials and methods

2.1. Normal human ear FE model

Considering that this paper mainly studies the influence of postoperative changes in the shape of the ear canal on the sound transmission characteristics of the human ear, we used our previously reported human ear FE model [22]. Based on the model, ignoring the middle ear cavity, cochlea impedance was simulated using five rows of dashpots and concentrated mass. All of them were arranged as two dashpots connected in series with concentrated mass located at the connection point of the two dashpots, as presented in Fig. 1. Each concentrated mass weighed 5.1 mg and the damping coefficient was 0.02 Ns/m for every dashpot [12].

2.2. Experimental materials required for mastoidectomy model construction

Fresh adult male frozen cadaver heads were selected to simulate CWU, CWD and CWD-MO mastoidectomy. The electric drill power system used was the BIEN-AIR OSSEODOC from Switzerland. The microscope used was the ZEISS OPMI Vario/S88 from Germany. The CT equipment used was the Siemens Somatom Force CT, using supine spiral scanning with the nasion-inion line as the baseline, scanning from the upper edge of the range to the prominence of the petrous pyramid and reaching the tip of the mastoid, with a layer thickness of 0.625 mm and a layer spacing of 0.3 mm, and the imaging was saved through PACS software. The medical imaging three-dimensional reconstruction software used was MIMICS (Materialise, Belgium), and the obtained data was imported into the reverse molding software Geomagic Studio (Geomagic, USA) to save the solid model and import it into Hypermesh (Altair, USA) for FE mesh division.

2.3. Establishment of radical mastoidectomy model

2.3.1. Establishment of CWU mastoidectomy model

After thawing the cadaver head, the external ear canal was cleaned under the ear endoscope to check the smoothness of the external ear canal and the integrity of the eardrum. Simulated CWU mastoidectomy on the left ear included: incision behind ear, periosteum peeling and palva flap. Mastoid was then opened with electric drill and bone meal was left. The mastoid process and sinus tympanum were contoured. The sinus tympanic entrance and upper tympanic chamber were opened, the short process of incus, incus body, incudostapedial joint and malleus head were exposed. The posterior wall of the external ear canal was preserved and thinned, the vertical segment of the facial nerve and the chorda tympani nerve were contoured, the facial nerve recess was opened, the posterior arch was removed, and the complete incus, incudostapedial joint and round window niche were exposed. The operation cavity was flushed, the periosteum and skin were sutured. Otoendoscopy again showed that the external ear canal and eardrum were intact. Micro-

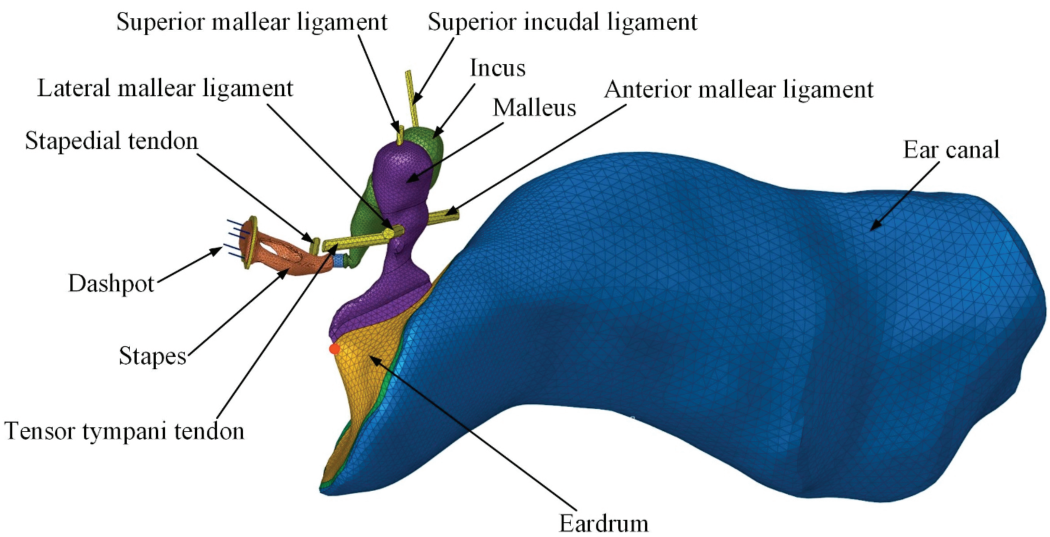


Fig. 1. Finite element model of normal human ear (the red dot indicates the ear canal sound pressure extraction location)

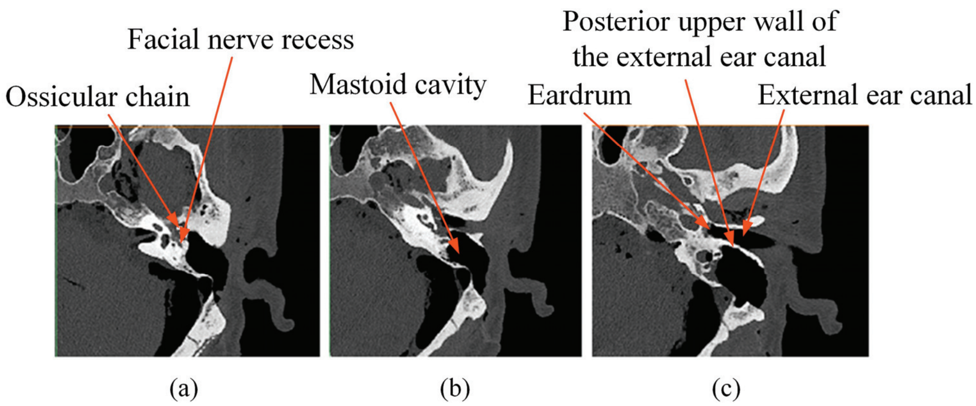


Fig. 2. CWU Micro-CT axial scan: (a) upper tympanic level, (b) mesotympanic level, (c) lower tympanic level

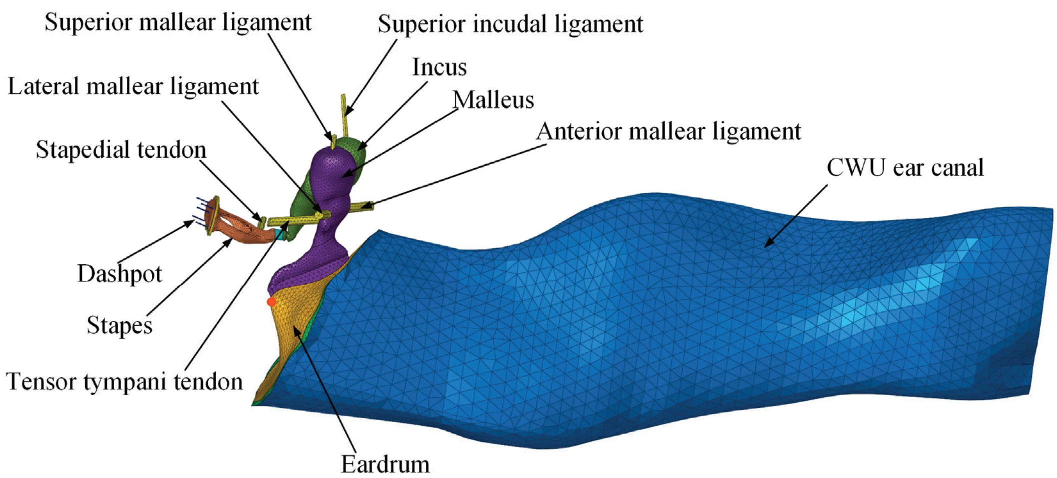


Fig. 3. CWU's finite element model of the human ear (the red dot indicates the ear canal sound pressure extraction location)

computed tomography (Micro-CT) of the temporal bone was performed immediately after surgery.

The CT images obtained at three different levels of the upper, middle and lower tympanic chambers are shown in Fig. 2. It can be seen that the mastoid cavity is basically contoured, the posterior upper wall of the external ear canal is preserved, the facial nerve recess is open, the ossicular chain structure exists, the eardrum is intact and the original shape of the external ear canal is preserved. The image was introduced into the computer and the external ear canal of the CWU was meshed by acoustic tetrahedral elements AC3D4, with a total of 140,822 elements, and finally, the CWU FE model was obtained, as shown in Fig. 3. The surgical cavity volume after CWU mastoidectomy was 1720 mm^3.

2.3.2. Establishment of CWD mastoidectomy model

CWD mastoidectomy was performed on the basis of the above CWU mastoidectomy. The flap behind ear and the palva flap were opened, and the temporalis fascia was taken. The skin of the posterior upper wall of the external ear canal in a rectangle 2 mm outside the drum ring was cut, and a rectangular external ear canal flap with a pedicle on the drum was made. The posterior wall and top wall of the external ear canal were gradually lowered, the anterior arch column was ground away, and the malleus was exposed more thoroughly. The bone wall of the external ear canal below the opened facial nerve was ground recess to enlarge and smooth the external ear canal. The temporalis fascia was built into the edge of the eardrum and covered the upper tympanic cavity, and the posterior superior wall skin flap of the external ear canal was placed into the operation cavity to cover the temporalis fascia. A little cartilage of the concha cavity and the cartilage of the bottom wall of the cartilage of the external ear canal were removed, two-flap auricle otoplasty was performed, the operation cavity was filled with the palva flap behind the ear and the incision was sutured. The operation cavity was observed under the ear endoscope, a little temporal muscle was taken to fill the

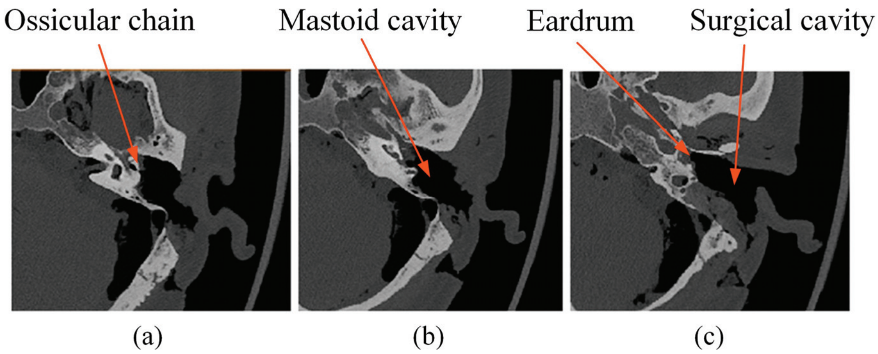


Fig. 4. CWD Micro-CT axial scan: (a) upper tympanic level, (b) mesotympanic level, (c) lower tympanic level

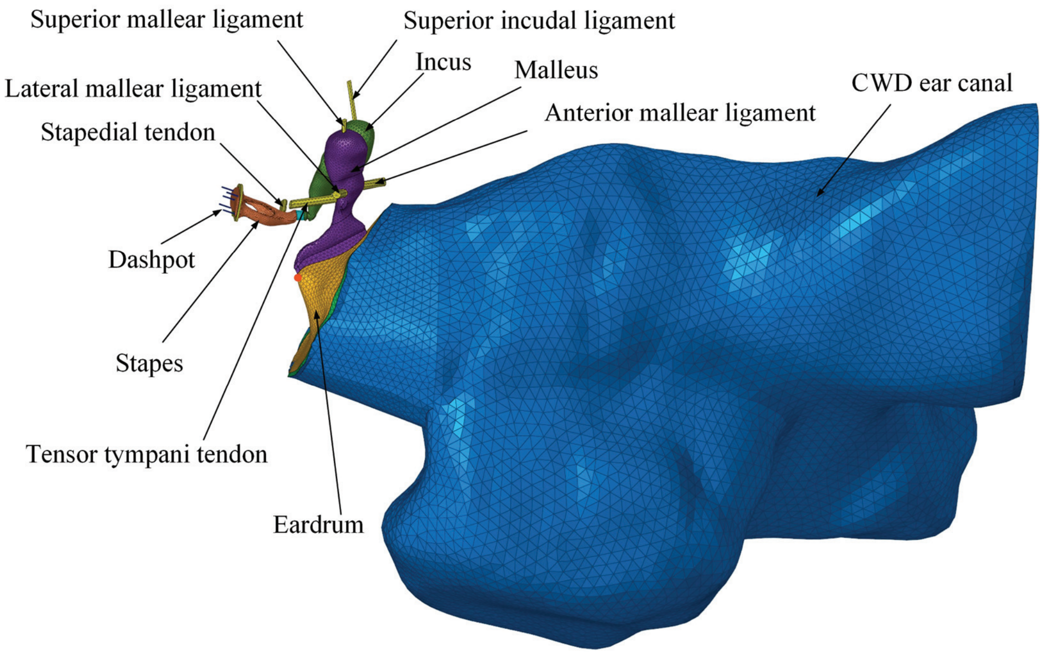


Fig. 5. CWD's finite element model of the human ear (the red dot indicates the ear canal sound pressure extraction location)

irregular part of the operation cavity, fix it with biological glue, and try to make the operation cavity smooth and close to the normal postoperative changes. Micro-CT of the temporal bone was performed immediately after surgery.

The CT images obtained at three different levels of the upper, middle and lower tympanic chambers are shown in Fig. 4. It can be seen that the mastoid cavity is basically contoured, the posterior superior wall of the external ear canal is resected, and the external ear canal, upper tympanic cavity, antrum tympanum and mastoid process are fused into one large surgical cavity. The ossicular chain structure is present and the eardrum is intact. The image was introduced into the computer, and the external ear canal of the CWD was meshed by acoustic tetrahedral elements AC3D4, with a total of 620,310 elements, and finally the CWD FE model was obtained, as shown in Fig. 5. The surgical cavity volume after CWD mastoidectomy was 6601 mm^3.

2.3.3. Establishment of CWD-MO mastoidectomy model

On the basis of the CWD, the paved temporalis fascia was removed, and the reserved bone powder was taken to fill the mastoid and tympanic antrum to narrow the operation cavity, and then covered with fascia and fixed with biological glue to simulate postoperative changes. Smooth operation cavity was observed under ear endoscope. Micro-CT of the temporal bone was performed immediately after surgery.

The CT images obtained at three different levels of the upper, middle and lower tympanic chambers are shown in Fig. 6. It can be seen that the mastoid and tympanic antrum are filled with bone powder, and the

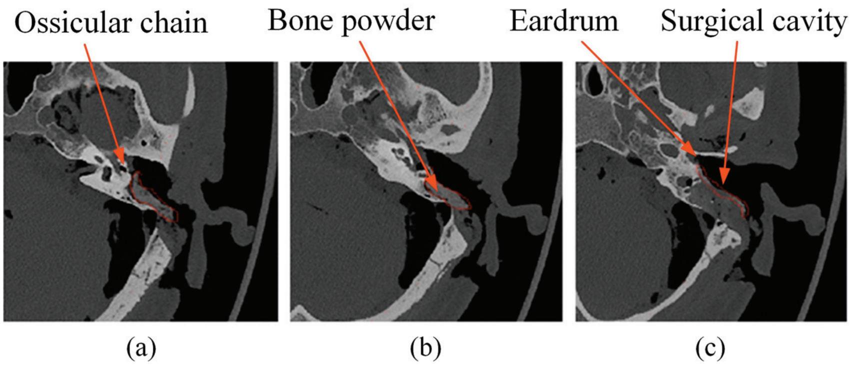


Fig. 6. CWD-MO Micro-CT axial scan: (a) upper tympanic level, (b) mesotympanic level, (c) lower tympanic level

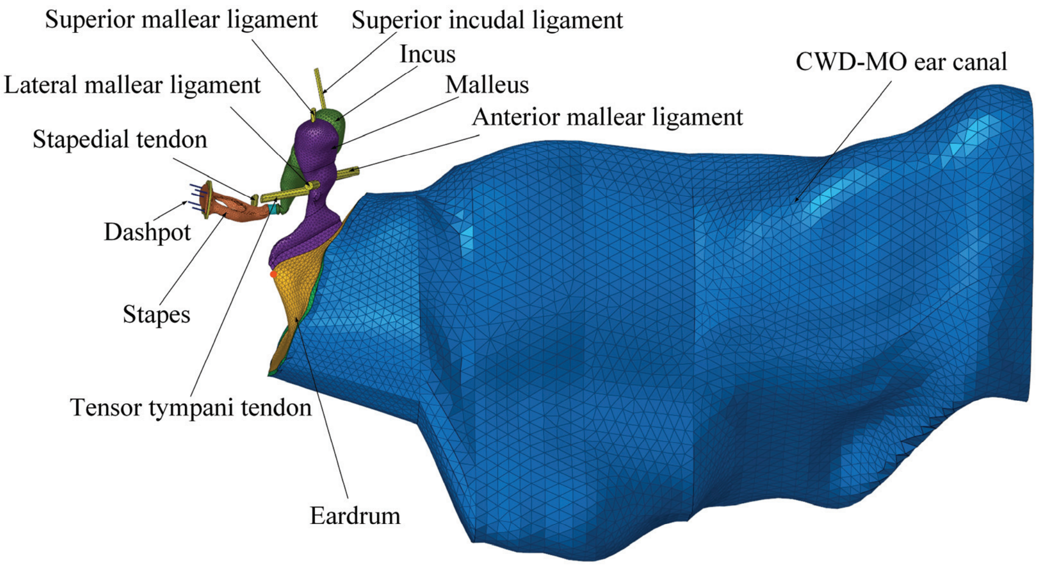


Fig. 7. CWD-MO's finite element model of the human ear (the red dot indicates the ear canal sound pressure extraction location)

external ear canal, upper tympanic cavity, tympanic antrum and mastoid are fused into a slightly reduced surgical cavity. The structure of the ossicular chain is present and the eardrum is intact. The image was introduced into the computer, and the external ear canal of the CWD-MO was meshed by acoustic tetrahedral elements AC3D4, with a total of 457,568 elements, and finally the CWD-MO FE model was obtained, as shown in Fig. 7. The surgical cavity volume after CWD-MO mastoidectomy was 4769 mm^3.

2.4. Simulation process

The sound transmission process of the normal ear and the ear canal after three types of surgery was simulated in ABAQUS (Dassault Systèmes, Johnston, RI, USA). A 90 dB SPL (0.632 Pa, root mean square value) SP was loaded at the entrance of the ear canal, and steady-state dynamics analysis was performed in the frequency range of 200–8000 Hz. The SP located at the red dot (Fig. 7) on the umbo was obtained, as well as the FPD. The maximum amplitude and frequency of the FPD were measured simultaneously, as well as the amplitude and average amplitude at 500, 1000, 2000 and 4000Hz. The SP gain and the FPD gain were calculated based on the Eqs. (1) and (2), respectively.

$$p_{eq} = 20 \times \log_{10}\left(\frac{p}{p_0}\right), \tag{1}$$

$$d_{eq} = 20 \times \log_{10}\left(\frac{d}{d_0}\right), \tag{2}$$

where, p is the SP value at the red dot (Fig. 7), p_0 is the SP applied at the entrance of the ear canal, d is the displacement of the umbo or the FP after three types of surgery, d_0 is the displacement of the umbo or the FP in normal ear.

The FPD gain was obtained using Eq. (2), and the FPD gain at 500, 1000, 2000 and 4000 Hz were calculated for the three surgical procedures. The FPD gain at 500, 1000, 2000 and 4000 Hz was averaged to obtain the average FPD gain for the three surgical cavities. The higher the average FPD gain value, the better the sound air conduction effect.

3. Results

3.1. Validation of the FE model

In order to ensure the reliability of the model, it was validated by comparing four sets of data. First, the SP gain of the ear canal was verified, as shown in Fig. 8. The ear canal SP gain results obtained from the analysis of the FE model of the normal human ear were used as a reference curve to compare and verify with the published test data and FE data, to ensure the reliability of the comparative analysis of the ear canal SP gain after the three surgical procedures. The results show that below 3000 Hz, the model is in good agreement with the experimental and simulation results of Gan et al. [13], Shaw et al. [29] and Yao et al. [35]. The resonance frequency is reached around 4000 Hz, and the SP gain reaches its peak at this time, which is consistent with the results of Shaw et al. [29] and Yao et al. [35]. Compared to results obtained by Gan et al. [13], the resonance frequency is slightly higher, which may be a result of the difference between the ear canal geometry used in their model and this model. At the frequency of 4000 Hz, the SP gain reaches its peak and increases to about 16 dB, which is higher than the peak value of about 10 dB obtained by Gan et al. [13], Shaw et al. [29] and Yao et al. [35], while the research results of Garcia-Gonzalez et al. [15], a SP gain of 0–20 dB can be obtained. At frequencies above 4000 Hz, the trend of the curves is consistent with the results of Shaw et al. [29] and Yao et al. [35]. In summary, the FE model is accurate enough for the subsequent analysis of ear canal SP gain.

Next, the displacements of FP and umbo were compared and verified with experimental data. In Figures 9 and 10, the mean values of the FPD and the umbo displacement measured by Gan and Wang [14] in the temporal bone experiment are shown. In this experiment, the vibrations of the umbo and the stapes FP are measured simultaneously using two laser vibrometers on the umbo and the FP. In comparison, the same SP was used to act on the outer eardrum of this FE model, and a steady-state dynamic analysis was performed in

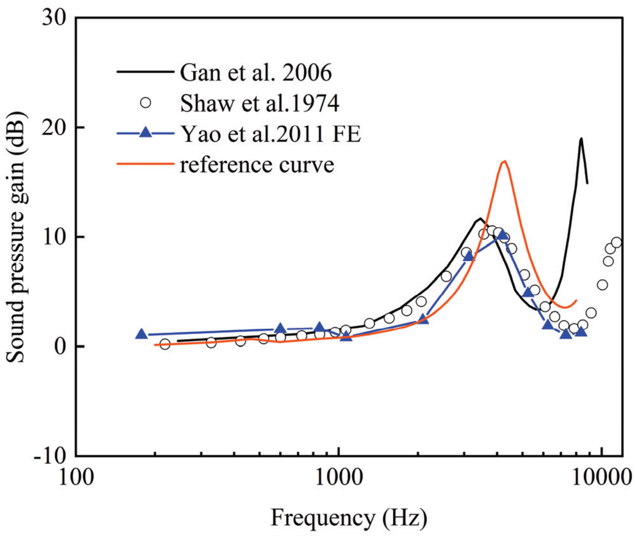


Fig. 8. Equivalent SP Gain Comparison Verification

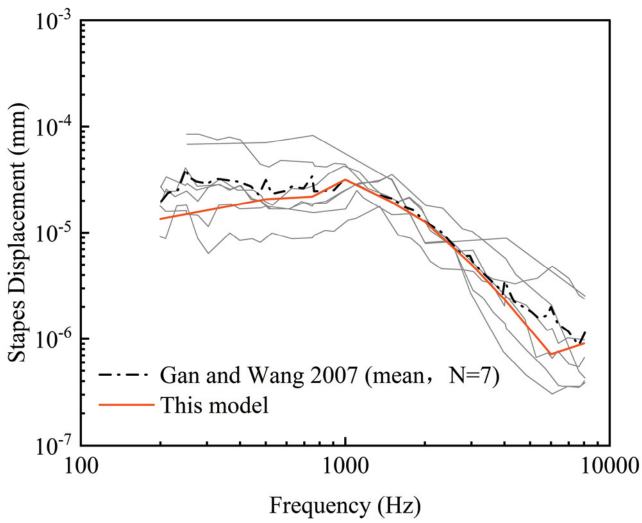


Fig. 9. FPD comparison verification

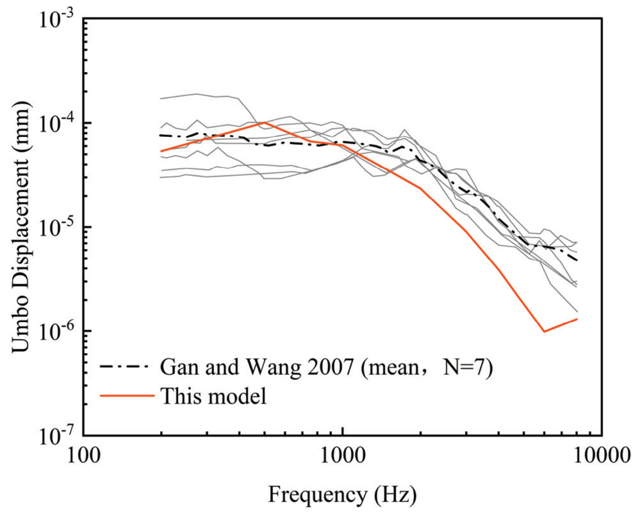


Fig. 10. Umbo displacement comparison verification

the frequency range of 200–8000 Hz. The results of model predictions are plotted in Figs. 9 and 10. The results show that the displacements of the FP and umbo derived from the model are in good agreement with the experimental curves. These comparative validations demonstrate that the model can be used to analyze the sound transmission properties of the human ear.

3.2. Ear canal SP gain after three surgical procedures

The SP gain at the red dot (Figs. 3, 5 and 7) of the ear canal after radical mastoidectomy for CWU, CWD and CWD-MO was analyzed, as shown in Fig. 11. The results show that for the SP gain of CWU, the peak value of the first resonance frequency is slightly lower than the reference curve and the peak value of the ear canal SP gain is also slightly lower. However, it can still obtain a SP gain of about 13 dB, and the overall trend of the curve is consistent with the reference curve, and there is no postoperative ear canal SP negative gain. For CWD and CWD-MO, the volume of the ear canal is reduced after filling with bone powder, but it is still higher than the volume of the ear canal after CWU and the volume of the ear canal in normal ears. Based on Fig. 11, it can be seen that for the ear canal SP gain after CWD, in the frequency range of 2700–6000 Hz and 7000–8000 Hz, that is, in most of the high-frequency range, the ear canal SP is in a negative gain state. For the postoperative ear canal SP gain of CWD-MO, the SP in the range of 3800–6000 Hz is in a negative gain state, and compared to the SP gain after CWD, there is a more obvious improvement. The resonance frequency of the ear canal after these two procedures is reduced compared to the normal ear model, and the volume of the ear canal cavity is larger, resulting in a lower resonance frequency.

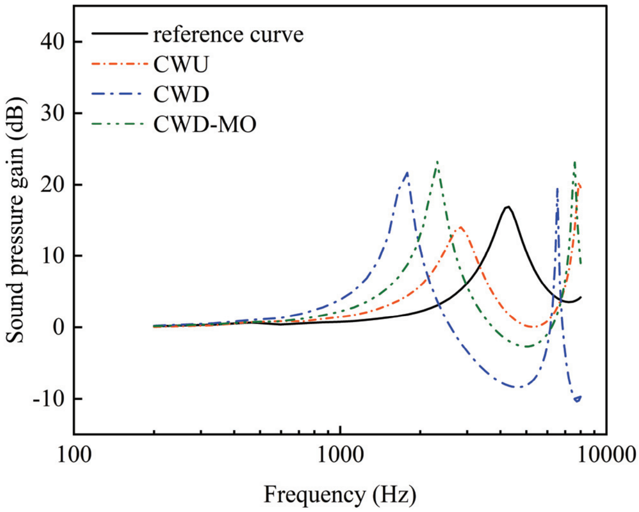
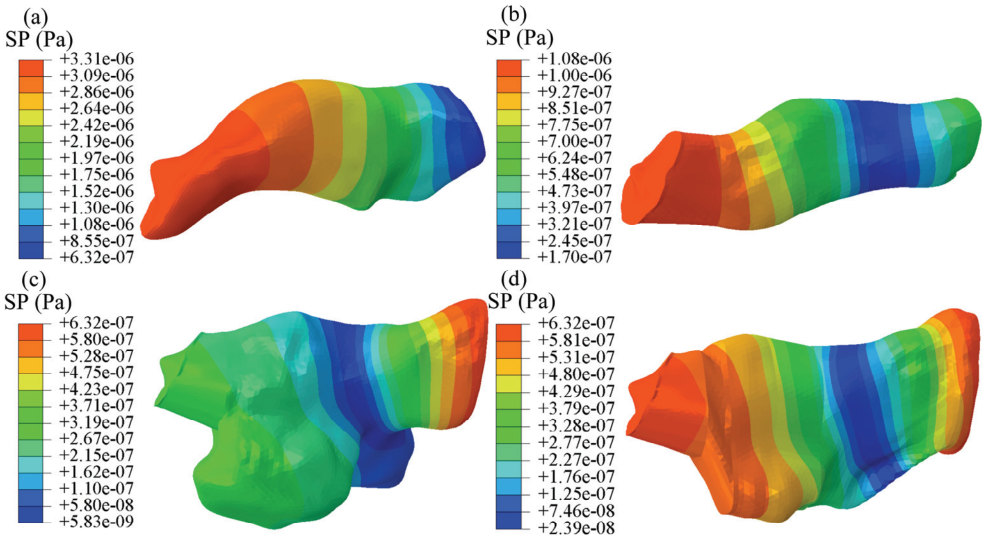


Fig. 11. Ear canal SP gain after different surgical procedures

The SP distribution maps of four ear canals at 3902 Hz are shown in Fig. 12. Using Eq. (1), it can be calculated that, at this frequency, the SP gains at points near the umbo after mastoidectomy for CWU, CWD and CWD-MO are 3.72 dB, – 0.7 dB and – 7.42 dB, respectively. These values respectively correspond to the curve values in Fig. 11 at the frequency of 3902 Hz. At this frequency, the ear canal SP gain after CWU



Frequency=3902 Hz

(a) Normal ear canal (b) Ear canal after CWU surgery
(c) Ear canal after CWD surgery (d) Ear canal after CWD-MO surgery

Fig. 12. Distribution of SP in different shapes of ear canal at 3902 Hz

mastoidectomy is obviously better than offer the other two surgeries. For the normal ear canal shown in Fig. 12a, it can be seen that the SP gradually increases from the entrance of the ear canal to the eardrum, and finally, the SP reaches the eardrum to vibrate the eardrum, which, in turn, drives the ossicles to vibrate. The vibration of the auditory ossicles drives the lymph fluid in the cochlea to vibrate, thereby generating bioelectrical signals. Finally, the brain receives the signals and converts them into the sounds we can hear. This is the propagation process of pressure waves. However, the distribution of SP in the ear canal after the three surgical procedures showed an increase first and then a decrease, and the distribution of SP was irregular. At this frequency, compared to the normal ear canal, the SP of the ear canal after the three surgical procedures decreased to varying degrees near the umbo. This affects the transmission of SP in the ear canal, causing our hearing effects to decrease. Among them, the CWD has the greatest postoperative reduction, and it was observed that the larger the volume of the ear canal cavity, the greater the decrease in SP. At 3902 Hz, the SP amplitude of the CWU is greater than that of the CWD-MO, and the CWD-MO is greater than that of the CWD. This is consistent with the results of the SP gain graph shown in Fig. 11.

3.3. The amplitude and gain of the stapes FP after three operations

The frequency response curve of the FPD is shown in Fig. 13. The reference curve in Fig. 13 represents the FPD obtained from the FE model analysis of a normal human ear. Based on this curve, the FPD gain is obtained using Eq. (2), as shown in Fig. 14. In Figures 13 and 14, it can be seen that the differences in FPD amplitude in the middle and low frequency bands below 1000 Hz between the CWU, CWD, and CWD-MO techniques and normal human ears are relatively small. In the 1000–3000 Hz frequency band, the frequency band where the maximum amplitude of the surgical cavity with different volumes is changed compared to that of the normal human ear: the frequency of the maximum amplitude of the CWU is about 3000 Hz, the maximum amplitude is 2.31×10^{-5} mm, and the maximum FPD gain is 8.72 dB; the frequency of the maximum amplitude of CWD is about 1800 Hz, the maximum amplitude is 1.42×10^{-4} mm, and the maximum FPD gain is 19.76 dB; the frequency of the maximum amplitude after CWD-MO is between the two, between 2000 Hz and 3000 Hz, the maximum

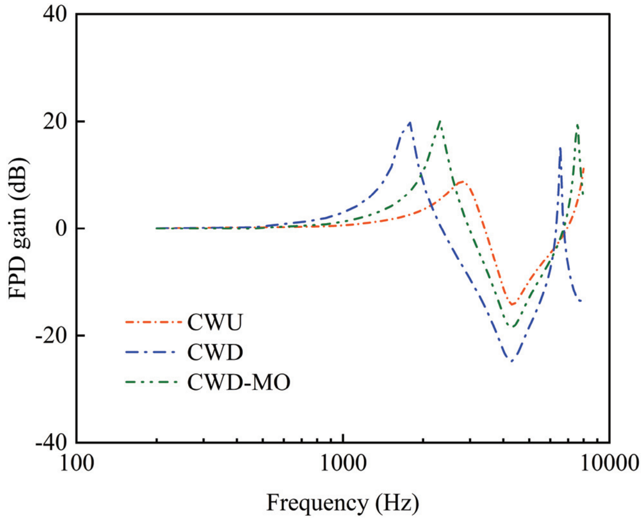


Fig. 14. FPD gain after different procedures

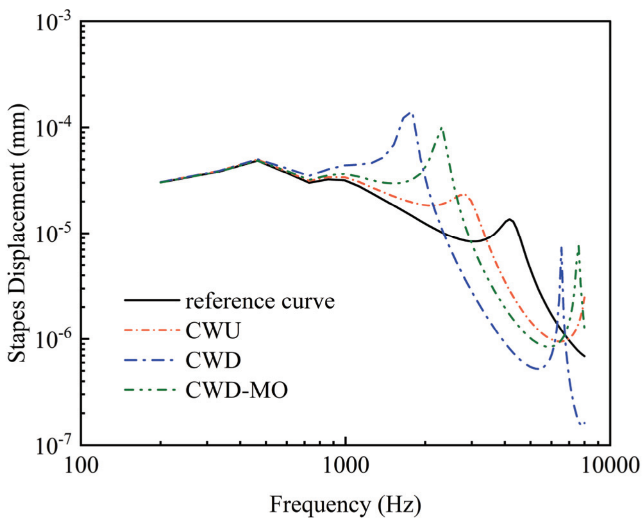


Fig. 13. FPD after different operations

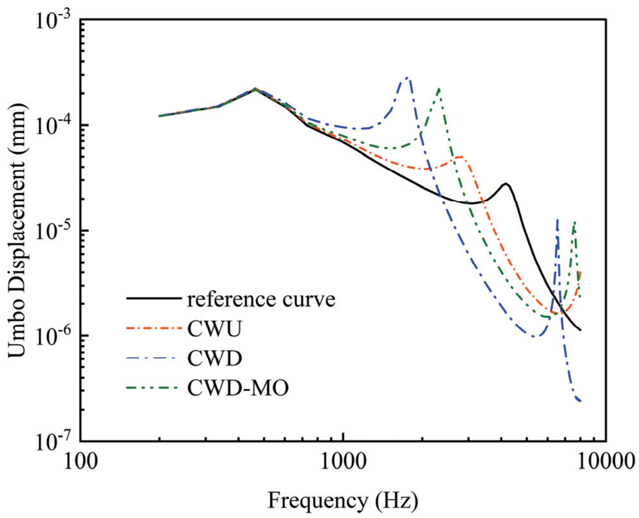


Fig. 15. Umbo displacement after different operations

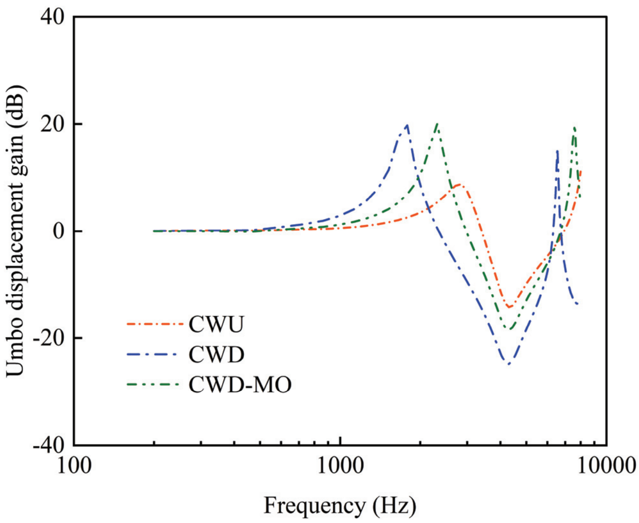


Fig. 16. Umbo displacement gain after different operations

amplitude is 1.02×10^{-4} mm, and the maximum FPD gain is 20.03 dB. Umbo displacement curves and displacement gain curves also show the same trend, as shown in Figs. 15 and 16.

Based on the results obtained in Fig. 11a, the average value of the FPD amplitude at 500, 1000, 2000 and 4000 Hz was calculated. The average amplitude of the CWU was 2.63×10^{-5} mm, and the average FPD gain was 4.38 dB; the average amplitude of the CWD was 3.62×10^{-5} mm, and the average FPD was 8.28 dB; the average amplitude of CWD-MO was between the two, with an average amplitude of 3.33×10^{-5} mm and an average FPD gain of 7.42 dB.

4. Discussion

Surgical excision of lesions and reconstruction of hearing is the main treatment for chronic suppurative otitis media and middle ear cholesteatoma. The CWU mastoidectomy can preserve the integrity of the external ear canal wall as much as possible, avoiding various inconveniences caused by the enlarged surgical cavity, but it requires high technical requirements and is limited by the field of view, with a high rate of lesion recurrence. CWD mastoidectomy combines the mastoid, antrum and middle ear into one surgical cavity, which can thoroughly clean the lesion. However, the postoperative dry ear period is long, and the epithelium of the surgical cavity lacks self-cleaning function, requiring regular follow-up to clean the scab and prevent ear canal infection [1], [11], and, due to the enlargement of the ear canal, there might be some impact on postoperative hearing [23]. Currently, most studies suggest that adult cholesteatoma patients who undergo CWU mastoidectomy have a higher risk of recurrence compared to CWD mastoidectomy [11], [27], [30]. The use of autologous bone meal, cartilage, fascia, muscle, skin or allogeneic tissue (such as hydroxyapatite, etc.) to fill and reduce the surgical cavity in CWD mastoidectomy is also a common clinical method [2]. However, there are different conclusions on the postoperative hearing recovery effects of these three surgical methods. In order to study the sound transmission characteristics of the middle ear, many scholars use the computer FE model method to conduct dynamic simulations, and the research involves the physiology and pathology of the eardrum, the ossicular chain, and the inner ear, and has a certain fit with clinical research [3], [7], [37].

In this study, fresh cadavers were used to establish the corresponding FE models of CWU, CWD and CWD-MO. Based on the FE analysis method, the SP gain at a point near the umbo compared with the normal human ear after three different mastoidectomy surgeries was studied, as well as the postoperative FP and umbo displacement amplitudes. This makes it possible to explore the differences in air conduction and SP conduction in the middle ear after different surgical procedures from a biomechanical perspective. The results of this study show that CWU, CWD, and CWD-MO mastoidectomy have great differences in postoperative ear canal SP gain. For the latter two surgeries, as the surgical cavity volume of the ear canal expands after surgery, the cavity appearing in the ear canal may affect the physical properties of the ear canal or middle ear, resulting in SP loss, which is consistent with the findings of Van et al. [33]. Moreover, the larger the volume of the surgical cavity, the more the resonant frequency is reduced, and the more frequency bands are in the negative gain of the ear canal SP, which is detrimental to the patient's postoperative hearing recovery. For CWU mastoidectomy, because the integrity and regularity of the shape of the ear canal are better ensured, the SP gain of the ear canal is much better than the latter two surgical methods, and, compared to the normal human ear, the peak gain of the ear canal SP is only reduced by about 3 dB.

For the displacement curves of FP and umbo, there is little difference in the influence of the three surgical methods on postoperative low-frequency band conduction, and the displacement amplitude of FP in the frequency band below 1000 Hz is more consistent. However, in the middle and high frequency bands, the resonance frequency bands of different volumes of surgical cavities change. The maximum amplitude of CWU is around 3000 Hz, the maximum amplitude of CWD-

-MO is between 2000–3000 Hz, and the maximum amplitude of CWD is around 1800 Hz. The external ear canal not only transmits sound and resonates sound waves, but also increases the displacement of FP and umbo by in the range of 3000–4000 Hz [12], which is consistent with the maximum displacement amplitude of CWU at around 3000 Hz in this paper. With the resection of the posterior superior wall of the external ear canal and conchaplasty to enlarge the external auditory canal opening, the external auditory canal and the mastoid cavity merge into one large cavity. According to the principle of Helmholtz resonance cavity [6], the volume change of the external auditory canal leads to the change of the resonance frequency. As the ear canal widens and the resonance frequency decreases, umbo's vibration has a better response between 1000–2000 Hz, and the FP also responds accordingly through the transmission of the ossicular chain. And for CWD-MO, the volume of the operative cavity of the external ear canal lies between the two, and its resonance frequency also lies between the two, giving rise to the results described above, with the frequency at which the maximum amplitude is located lying between 2000 and 3000 Hz. This is also consistent with the results of the ear canal SP gain analysis. To facilitate a better understanding of the relationship between FPD amplitude and displacement gain, this study converted the vibration amplitude of the stapes footplate at each frequency into equivalent displacement gain based on the formula, and calculated the average amplitude values at 500, 1000, 2000 and 4000 Hz. The results showed slight differences in the average equivalent displacement gain at the FP after the three surgical procedures. The average equivalent displacement gain for CWU was 4.38 dB, for CWD was 8.28 dB, and for CWD-MO was 7.42 dB. The differences between them were extremely slight, which was consistent with the meta-analysis results of Salem et al. [28]. This may be due to the fact that the surgery did not significantly affect the ability of the machine to transmit sound vibrations, i.e., the stapes can still effectively transmit sound vibrations to the inner ear. The analysis indicated that CWD-MO technology achieved a lower incidence rate compared to CWD, and was better than CWU in improving long-term control of ear diseases. However, due to the limitations of lesion range and surgical conditions, it is difficult to conduct randomized grouping in clinical studies, and the conclusions drawn may be biased. In contrast, this model assumed the same middle ear conditions and only studied the results of air conduction after different surgical procedures, which is relatively reliable.

Although FE models help to better understand the biomechanics of the human ear, they do not match the actual structures of the human middle ear completely. The structure of the middle ear is very subtle, and the Micro-CT is limited by the precision, direction and position of the test, which may cause varying degrees of distortion in the established model. The material properties of middle ear components are extremely complex, especially the nonlinear mechanical properties of the soft tissues of the middle ear, such as muscles, ligaments, and mucosal folds, which are difficult to accurately represent on computers, so it is difficult to accurately simulate the resistance, inertia and stiffness that determine the resistance of the media conductance of the middle ear. In addition, the model established in this study is based on a single cadaver head, while the actual middle ear diseases vary greatly. Postoperative air conduction is affected by various factors such as the range and nature of the lesion, the reconstruction method of the tympanic membrane ossicular chain, the function of the pharyngeal eustachian tube, the postoperative inflammatory state and the individual situation of the patient. Therefore, the model cannot reflect the real diseased middle ear and has limited clinical guidance significance, but undoubtedly provides a direction for the study of middle ear mechanics.

5. Conclusions

To assist doctors in choosing a suitable surgical method for patients with chronic suppurative otitis media and cholesteatoma, this study investigated the effects of CWU, CWD, and CWD-MO mastoidectomy on hearing. To assist in the analysis, three surgical methods were simulated on fresh cadaver heads, and three corresponding human ear models were established based on Micro-CT and validated for the middle ear model. The results showed that all three surgical methods had different degrees of impact on ear canal SP gain after surgery, and CWD and CWD-MO resulted in SP loss, which would reduce hearing. The frequency at which the maximum amplitude of the postoperative FPD is located also changes with the morphology of the postoperative ear canal cavity for all three procedures, and the larger the volume of the cavity, the lower this frequency is, and the wider the band in which the negative FPD gain occurs. In addition, there was little difference in the mean postoperative FPD gain between the three procedures. The study was subject to various limitations, and the analysis results of the model may not fully reflect the actual hearing recovery of postoperative patients in clinical practice. Therefore, doctors still need to make judgments to choose a reasonable surgical method. At the same time, since this article mainly analyzes the displacement of the FP center point, the non-uniformity of the FPD is not considered. We will overcome this limitation in future research. Although the analysis results of this study have limited guiding significance for clinical research, they can still provide some reference for clinical research.

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