COMPUTER AIDED THREE-DIMENSIONAL RECONSTRUCTION AND MODELING OF MIDDLE EAR BIOMECHANICS BY HIGH-RESOLUTION COMPUTED TOMOGRAPHY AND FINITE ELEMENT ANALYSIS

CHIA-FONE LEE^{1,2}, PEIR-RONG CHEN², WEN-JENG LEE³, JYH-HORNG CHEN^{1,4}, TIEN-CHEN LIU⁵

¹Institute of Biomedical Engineering, National Taiwan University, Taipei,

²Department of Otolaryngology, Buddhist Tzu Chi General Hospital, Hualien,

³Department of Medical Imaging, National Taiwan University Hospital, Taipei,

⁴Institute of Electrical Engineering, National Taiwan University, Taipei,

⁵Department of Otolaryngology, National Taiwan University Hospital, Taipei, Taiwan

ABSTRACT

In order to present a systematic and practical approach that uses high-resolution computed tomography (HRCT) to derive models of the middle ear for finite element analysis (FEA). This prospective study included 31 subjects with normal hearing and no previous otological disorders. Temporal bone images obtained from 15 right ears and 16 left ears were used for evaluation and reconstruction. High-resolution computed tomography of temporal bone was performed using simultaneous acquisition of 16 sections with a collimated slice thickness of 0.625 mm. All images were transferred to an Amira visualization system for 3D reconstruction. The created 3-D model was translated into two commercial modeling packages, Patran and ANSYS, for finite element analysis. The characteristic dimensions of the model were measured and compared with previous published histological section data. This result confirms that the geometric model created by the proposed method is accurate except the tympanic membrane is thicker than that of histological section method. No obvious difference in the geometrical dimension between right and left ossicles was found ($p > 0.05$). The 3D model created by finite element method and predicted umbo and stapes displacements are close to the bounds of the experimental curves of Nishihara's, Huber's, and Gan's data across the frequency range of 100-8000 Hz. The model includes a description of the geometry of the middle ear components, and dynamic equations of vibration. The proposed method is quick, practical, low cost and most importantly, non-invasive as compared with histological section methods.

Biomed Eng Appl Basis Comm, 2006(October); 18: 214-221.

Keywords: middle ear biomechanics; multi-body dynamic analysis; mathematical model

Received: April 18, 2006; Accepted: July 28, 2006

Correspondence: Tien-Chen Liu, Professor

Department of Otolaryngology, National Taiwan
University Hospital, Taipei, Taiwan

E-mail: liuent@ha.mc.ntu.edu.tw

1. INTRODUCTION

The human middle ear, including tympanic membrane and three auditory ossicles (malleus, incus, and stapes), is the mechanical system for sound

transmission from the outer to the inner ear. Sound entering the middle ear through the tympanic membrane initiates the transfer function. Vibration of the tympanic membrane leads to motion of the stapedial footplate, which generates a wave in the cochlea. An accurate three-dimensional geometric model of the human middle ear is a crucial first step for visualizing its spatial structure and for carrying out further morphological studies.

Finite element analysis is a computer simulation technique used in engineering and biomechanical analysis. The technique employs the Ritz method of numerical analysis and minimization of variational calculus to obtain approximate solution to vibration systems. Investigations on reconstruction of the middle ear geometry have been reported in several papers [1-5]. Funnel et al. first used histological sections of cat middle ear to reconstruct the geometry of the ossicles, the posterior incudal ligament, and the manubrium of malleus using a finite element (FE) model. Sun et al. constructed an FE model of the human middle ear on the basis of histological section images of a human temporal bone [3-4]. However, the specimen has to be decalcified and embedded before the actual risky process of sectioning and mounting of the slices on microscope glass plates.

The advent of high-resolution computed tomography (HRCT) made it possible to perform virtual instead of physical sectioning, and computer assistance facilitated the construction of reliable 3-D mathematical anatomical models. In this article, we try to demonstrate how HRCT can be used to create detailed dedicated geometrical models and how finite element analysis of this model can be used to study middle ear mechanics. We present a systematic and practical approach involving HRCT to generate middle ear models. FE and multi-body dynamic analysis of these models can be performed. The results were also compared to those using histological section methods and laser Doppler interferometer.

2. MATERIALS AND METHODS

2.1 High-resolution Computed Tomography of Temporal Bone

This prospective study included 31 subjects (13 female and 18 male, age 18-81 years old) with normal hearing and no previous otological disorders. Otoscopic examination and pure tone audiometry were performed for each subject before HRCT examination. The study was approved by the Institutional Ethics Committee and followed the revised version of Helsinki Declaration. Written informed consents were also obtained from each subject. Temporal bone

images obtained from the 15 right ears and 16 left ears were used for evaluation and reconstruction. The χ^2 test and Fisher exact test were used to detect significant differences in geometric values between the individuals and different ears. A significant difference between individuals ($P < 0.05$) indicated that geometric values from the right and left ears were not independent.

High-resolution computed tomography (HRCT) of temporal bone was obtained using a 16-slice CT system (Lightspeed16, GE Healthcare, Milwaukee, WI, USA). Scanning was performed using simultaneous acquisition of 16 sections with a collimated slice thickness of 0.625 mm. The helical pitch was 0.562, rotation time was 1 s, and tube voltage was 140 kV at 380 mA. Images were reconstructed using a standard algorithm at overlapping intervals (0.3 mm) to improve through-plane spatial resolution, 512x512 matrix and the reconstructed field of view (9.6 cm) was placed separately for each ear to maximize in-plane resolution. After capturing images, the landmarks of the temporal bone were identified by an otolaryngologist and a radiologist (Fig. 1). Then all of these images were transferred to an Amira visualization system (Mercury Computer Systems, Inc., Chelmsford, MA, USA) for 3D reconstruction.

Fig. 1. Reformed coronal HRCT image of a normal right temporal bone, including tympanic membrane (1), malleus (2), incus (3), and stapes (4).

In Amira, the reconstruction model of the middle ear can easily be manipulated for 3D visualization. Geometric dimensions could also be easily obtained by

Table I . Configurations of the middle ear model in comparison with those obtained from published data

Component dimensions	Mean (right ear)	Mean (left ear)	Range (right ear)	Range (left ear)	Histological data ³	Published data
Ear drum						
Diameter along the manubrium (mm)	9.14	9.06	8.80-9.68	8.85-9.19	8.76	8.0-10.0
Diameter perpendicular to the manubrium (mm)	9.08	9.07	8.80-9.20	8.94-9.17	8.93	7.5-9.0
Height of the cone (mm)	1.43	1.41	1.35-1.55	1.36-1.47	1.46	2.0
Surface area (mm ²)	65.06	64.57	61.41-67.86	63.30-65.52	66.30	55.8-86.0
Thickness (mm)	0.41	0.45	0.39-0.49	0.43-0.51	0.05-0.074	0.04-0.1
Malleus						
Length from the manubrium to the end of the lateral process (mm)	4.28	4.25	4.18-4.41	4.17-4.37	4.2	5.8
Length from the lateral process to the end of the head (mm)	5.04	4.99	4.41-5.2	4.40-5.90		
Total height (mm)	7.87	7.89	7.54-8.12	7.48-8.12	7.65	7.6-9.1
Incus						
Length along the long process (mm)	6.51	6.46	6.36-6.71	6.39-6.54	6.08	7.0
Length along the short process (mm)	4.15	4.16	3.97-4.33	3.99-4.32	4.49	5.0
Stapes						
Height (mm)	2.91	2.88	2.84-3.19	2.83-3.01	2.87	2.5-4.0
Length of the footplate (mm)	2.34	2.45	1.99-2.52	2.33-2.51	2.5	2.64-3.36
Width of the footplate (mm)	1.20	1.22	0.91-1.38	1.12-1.39	1.38	0.7-1.66
Thickness of the footplate (mm)	1.03	0.88	0.91-1.25	0.39-1.06		

measuring the model. The characteristic dimensions of the model were measured and were listed in Table I . To prepare for FEA of the middle ear, the created 3-D model was translated into Patran (MSC. Software, Perth, Australia) and ANSYS (ANSYS, Inc., Canonsburg, PA, USA), two commercial FE modeling packages. On the basis of the model, FE meshes of the middle ear were created using Patran. The tympanic membrane was meshed by 3 layers of eight-noded hexahedral solid elements were created for the eardrum. An ultrastructural study of the eardrum showed the regularity of the radial and circumferential fibers appearing in the pars tensa [3-4]. The tympanic membrane was modeled as a 3 layers of eight-noded hexahedral solid elements structure with homogenous and orthotropic material properties [3-4]. The locations of these ligaments and muscle were estimated from textbooks of anatomy [5]. There were 6630 eight-noded hexahedral SOLID 45 elements created for the ossicles and ligaments/tendons. Five ligaments of the middle ear were modeled eight-noded hexahedral SOLID 45 elements. Each ligament was 0.8 mm long and 0.5 mm x 0.5 mm. The two muscles of the middle ear were also modeled with eight three-dimensional eight-noded elements (SOLID45). The tensor tympani muscle was taken as 3 mm long and 0.5 mm x 0.5 mm in cross-section, while the stapedial muscle was taken to be 2 mm long and 0.43 mm x 0.46 mm in cross-section.

2.2 Finite Element Analysis of Middle Ear

To determine the vibration response of a structure over a range of frequencies requires the solution of the equation [6],

$$M \frac{d^2u}{dt^2} + C \frac{du}{dt} + Ku = f + fs$$

Where M, C and K are the mass, damping and stiffness matrices, respectively, u is the displacement vector, f is the nodal force vector, and fs is a fluid pressure load vector describing the fluid/structure interaction which occurs, in this case, at the tympanic membrane.

Physical properties of the tympanic membrane and middle ear ossicles were obtained from published data annotated in Table II [4-10]. The periphery of tympanic membrane was assumed to be connected to the bony wall of ear canal through an elastic ring, 0.2 mm wide and 0.2 mm thick, with a Young's modulus of 6.0×10^7 N/m². The Poisson's ratio was assumed to be 0.3 for all materials of the middle ear system. The element-damping matrix for the solid and shell elements was expressed by

$$[C] = \alpha[M] + \beta[K]$$

Where [M] and [K] were element mass and stiffness matrices of the solid and shell elements, respectively, and α and β were the damping parameters [6]. The malleus, eardrum, and the

Table II. Mechanical properties used for the middle ear finite element model^[4-10]

Structure	Data for the finite element model
Eardrum	
Density	1.2 g/cm ³
Young's modulus (pars flaccida)	1.0x10 ⁷ N/m ²
(pars tensa)	2.0x10 ⁷ N/m ² (longitudinal direction)
	3.5x10 ⁷ N/m ² (radial direction)
Thickness	0.1 mm (by cross-calibration)
Malleus	
Density	
Head	2.55x10 ³ Kg/m ³
Neck	4.53x10 ³ Kg/m ³
Handle	3.70x10 ³ Kg/m ³
Young's modulus	1.41x10 ¹⁰ Kg/m ²
Incus	
Density	
Body	2.36x10 ³ Kg/m ³
Short process	2.26x10 ³ Kg/m ³
Long process	5.08x10 ³ Kg/m ³
Young's modulus	1.41x10 ¹⁰ N/m ²
Stapes	
Density	2.20x10 ³ Kg/m ³
Young's modulus	1.41x10 ¹⁰ N/m ²

incudomalleolar and incudostapedial joints were connected by coupling of the corresponding FE nodes. The cochlear fluid was assumed to be a viscoelastic constraint. The in-plane stiffness action on the stapes footplate owing to the stapedial annular ligament was represented by 25 linear spring elements distributed evenly around the periphery of the footplate [3-4]. These springs are perpendicular to the side periphery of the footplate. Each spring was attached to the corresponding node of the side periphery at one end,

and fixed at the other, simulating the attachment to the margin of the vestibular fenestra. Cochlear fluid impedance was considered to be viscous damping in several FE models [5-7]. The action of the cochlear fluid on the stapes footplate was modeled as a set of 49 spring-dashpot elements distributed on the footplate. The detailed modeling for the boundary conditions was shown in Table III [2, 3-7, 9]. Finally, displacement of the stapes footplate and tip of malleus induced by the sound pressure at the eardrum 80-dB SPL (dB of sound

Table III . Boundary conditions used for the middle ear finite element model^[2, 3-7, 9]

Middle ear components	Young's modulus or spring constant	Damping
Superior malleal ligament	$4.9 \times 10^4 \text{ N/m}^2$	$\alpha = 0 \text{ s}^{-1}$ $\beta = 0.0001 \text{ s}$
Lateral malleal ligament	$6.7 \times 10^4 \text{ N/m}^2$	
Posterior incudal ligament	$6.5 \times 10^5 \text{ N/m}^2$	
Anterior malleal ligament	$2.1 \times 10^6 \text{ N/m}^2$	
Posterior stapedial muscle	$5.2 \times 10^5 \text{ N/m}^2$	
Tensor tympani muscle	$2.6 \times 10^6 \text{ N/m}^2$	
Cochlear fluid	60 N/m	0.06 N s/m
Stapedial annular ligament	9 N/m	0 N s/m

pressure level) were computed from the FE model over auditory frequency range of 100 to 8000 Hz. Cross-calibration was a process for determining additional model parameters by comparing the umbo and stapes footplate displacements between our working FE model and the experimental data obtained from human temporal bone. The objective of the process was to minimize the difference of our working FE model and the experimental data, by selecting appropriate, as yet, undetermined parameters of the working FE model. Umbo and stapes footplate displacement data obtained at the input sound pressure of 80 dB at the eardrum were used to derive undetermined parameters of the final FE model using this cross-calibration process. The mechanical properties of middle ear components, joints, and connections were assigned based on data published by others and our estimations from published experimental observation. Only one parameter (thickness of tympanic membrane) was determined using the FE model cross-calibration process. Thus, the final FE model with all parameters was complete for subsequent model evaluations or mechanical analyses. Finally, experimental results on human or human temporal bone were used to comparatively evaluate the finite element model [7, 12-14]. The experimental data from 64 normal human subjects published by Nishihara [13], 10 temporal bones reported by Huber [14] and stapes footplate displacements obtained from 17 human temporal bones by Gan [7] were selected for model evaluation. When each of the pure tone sounds of 80 dB SPL were

delivered to the eardrum, the displacements of the umbo and stapes footplate were measured using a laser Doppler interferometer.

3. RESULTS

Figure 2A shows a surface rendering of the middle ear model. The surface model not only approximates the real biostructure, but also facilitates translating the model information to a form suitable by other software for generation of finite element meshes. Volume generation of this middle ear model with facets is demonstrated in Fig. 2B. Table I shows the characteristic dimensions of the model and dimensions from previously published histological section data. The table confirms the accuracy of all the geometric model dimensions except for the accuracy of the tympanic membrane thickness, which is greater than that measured using the histological section method. No obvious differences in geometric dimension were found between the right and left ossicles ($p > 0.05$). Therefore, we got one set of data from the same people to perform model mesh creation, reconstruction and finite element analysis.

FE meshes of the middle ear were created from the model translated into Patran (Fig. 2C) using the manual meshing capabilities of Patran.

With a uniform harmonic pressure stimulus of 80 dB SPL applied to the lateral side of the eardrum in the finite element model, harmonic analysis was conducted

across the frequency range 100-8000 Hz using ANSYS. The predicted umbo and stapes footplate displacements were converted to the frequency response curve of peak-to-peak displacement and are

Fig. 2A. Initial surface rendering of the middle ear from HRCT.

Fig. 2B. Volume rendering and facies generation of the middle ear.

Fig. 2C. Finite element meshes of the middle ear created in Patran.

shown in Fig. 3 with Gan's [7], Nishihara's [13] and Huber's [14] data. The model-predicted umbo displacements are close to the bounds of experimental curves of Nishihara's [13] and Huber's [14] experimental data across the frequency range of 100-8000 Hz (Fig. 3A). Likewise, the finite element model predicted stapes footplate displacement close to the bounds of Gan's [7] experimental results (Fig. 3B). Our FE model curve is lower than the experimental curve, especially in the frequencies of 100-700 Hz. However, the trend is similar to the experimental curve. The difference between the FE model and experimental data may come from the significant variations of individual temporal bone.

Fig. 3A. Amplitude of umbo displacement vs. frequency of the acoustic stimuli at 80 dB SPL. The finite element model predicted umbo displacements was close to the bounds of the 64 experimental curves of Nishihara's, Huber's experimental data across a 100-8000 Hz range.

Fig. 3B. Amplitude of stapes footplate displacement vs. frequency of the acoustic stimuli at 80 dB SPL. The finite element model predicted stapes footplate displacements was close to the Gan's experimental results.

4. DISCUSSION

In this article we presented some examples illustrating the benefit of having precise geometrical information about the middle ear. Clearly, in designing distributed models (such as finite element models), the shapes and positions of the middle ear ossicles, tympanic membrane, ear canal, middle ear cavity, ligaments, muscles, and tendons are of major importance [1-2]. Knowledge of the geometry of the object under study is of great help for the kinetic and dynamic analysis of experimental results from motion studies. In middle-ear mechanics, this means that the anatomy of the tympanic membrane and middle-ear ossicles has to be precisely known.

The proposed geometric modeling method provides researchers with a feasible approach to capture middle ear geometry for constructing 3D models as well as physical study. This method allows accurate assessment of the middle ear anatomy except for the thickness of the tympanic membrane using HRCT section images of the human temporal bone because of the limited resolution. The voxel size of HRCT is about $0.187 \times 0.187 \times 0.3 \text{ mm}^3$. Therefore, a complete tympanic membrane could not be reconstructed easily. Magnetic resonance microscopy (MRM) is designed to observe the hydrogen nucleus, which is abundant in the body. Magnetic resonance microscopy (MRM) is closely related to MRI and it can be seen as an extension of the MRI technique to microscopic dimensions. Due to advances in MRI technology the spatial resolution of images has increased, allowing for the microscopic study of structures. As a result, hard bone does not image as well as soft tissue. Thus, MRM can be used complementarily to HRCT.

To confirm the validity of this model, the motion of tympanic membrane and ossicles obtained with this model is compared with that shown by the measurement data. Both displacements maintained almost constant values up to 8000 Hz and have the maximum values around 800-900 Hz. At frequencies over 900 Hz, this value decreases with an increase in the frequency. However, peaks around 800-900 Hz in this model are compatible with those in the measurement. Aritomo [15] reported that the individual difference in displacement of both the umbo and stapes footplate was larger at low frequencies and that some temporal bones showed a clear peak in amplitude at resonance frequency. Therefore, it is considered that the differences mentioned above are within the permissible range.

In conclusion, the proposed method is quick, low cost, practical and most importantly, non-invasive as compared with histological section methods or laser

scans. This work also highlights modeling the middle ear by detailed sub-domain parameters. A working finite element model, constructed using a realistic geometric model from computer-aided reconstructions of HRCT images, was cross-calibrated with middle ear displacement data to obtain a final finite element model of middle ear biomechanics. These comparative evaluations showed that the finite element model predictions, in general, matched empirical results obtained from laser Doppler interferometry in human subjects or of human temporal bones. Preliminary clinical applications of the finite element model predicted the effects of passive implant mass loading on ossicles and change in tympanic membrane stiffness on middle system function. These results suggest that the finite element model is potentially useful in the study of middle ear biomechanics and in the design and testing of implantable middle ear hearing devices. This middle ear finite element model may also be used to study perforations of the eardrum, otosclerosis, and both the passive and active functions of implantable hearing devices [4, 14]. If a complete FE model of the middle ear were constructed, spatial variations in displacement on the tympanic membrane and three-dimensional ossicular vibrations, could be clarified without direct measurements, which are difficult to perform. It would be possible to predict how the middle-ear function is affected by various kinds of middle-ear pathologies and to understand how individual differences in middle-ear structures affect that function prior to surgery. The model needs to be improved in several respects such as by determining more accurate boundary conditions of middle ear ligament and muscle geometry and mechanical properties, constraints of cochlear fluid, and the acoustic effects of the external ear canal and the middle ear cavity.

REFERENCES

1. W.R.J. Funnell, S.M. Khanna, W.F. Decramemer, On the degree of rigidity of the manubrium in a finite element model of the cat ear drum, *J Acoust Soc Am*, 1992; 91: 2082-2090.
2. H.J. Beer, M. Bornitz, H.J. Harstke, R. Schmidt, G. Hofmann, U. Vogel, Modeling of components of the human middle ear and simulation of their dynamic behavior, *Audiol Neuro-Otol*, 1999; 4: 156-162.
3. Q. Sun, K.H. Chang, K.J. Dormer, K.D.Jr. Robert, R.Z. Gan, An advanced computer-aided geometric modeling and fabrication method for human middle ear, *Med Engineering Physics*, 2002; 24: 595-606.
4. Q. Sun, R.Z. Gan, K.H. Chang, K.J. Dormer,

- Computer-integrated finite element modeling of human middle ear, *Biomechan Model Mechanobiol*, 2002; 1: 109-122.
5. D.J. Kelly, P.J. Prendergast, A.W. Blayney, The effect of prosthesis design on vibration of the reconstructed ossicular chain: a comparative finite element analysis of four prostheses, *Otol and Neurotol*, 2003; 24: 11-19
 6. N.M. Baran. Finite element analysis on microcomputers: McGraw-Hill; 1988
 7. R.Z. Gan, Q. Sun, K.D.Jr. Robert, K.H. Chang, K.J. Dormer, Three-dimensional modeling of middle ear biomechanics and its applications, *Otol and Neurotol* 2002; 23: 271-280
 8. H. Wada, T. Metoki, and T. Kobayashi, Analysis of dynamic behavior of human middle ear using a finite-element method, *J Acoust Soc Am*, 1992; 92: 3157-3168.
 9. I. Koike. The structure and Function of the Middle ear. Tokyo: University of Tokyo Press; 1960
 10. G. Hermann, H. Liebowitz. Mechanics of bone fracture, In: Liebowitz H, eds. *Fracture: An Advance Treatise*. New York: Academic Press, 1972; 7: 772-840.
 11. P. Ferris, P.J. Prendergast, Middle-ear dynamics before and after ossicular replacement, *J Biomech*, 2000; 33: 581-590.
 12. S. Nishihara, H. Aritomo, R.L. Goode, Effect of changes in mass on middle ear function, *Otolaryngology- Head Neck Surgery*, 1993; 109: 899-910.
 13. S. Nishihara, R.L. Goode. Measurement of tympanic membrane vibration in 99 human ears. In: Hüttenbrink KB, eds. *Middle ear mechanics in research and otosurgery*. Dresden University of Technology, Dresden, Germany; 1996: 91-93.
 14. A. Huber, G. Ball, M. Asai , R. Goode, The vibration pattern of the tympanic membrane after placement of a total ossicular replacement prosthesis. In: *Proceeding of the International Workshop on middle ear mechanics in research and otosurgery*. Dresden, Germany; 1997: 219-222.
 15. H. Arimoto, Ossicular vibration in human temporal bones, *J Otol Rhinol Laryngol Soc Japan*, 1989; 92: 1359-1370.