



Review Article

Computer-aided modeling of sound transmission of the human middle ear and its otological applications using finite element analysis

Yu-Lin Song^{a,b}, Chia-Fone Lee^{c,d,*}

^aDepartment of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

^bHigh Technology Research Center, Yen Tjing Ling Industrial Research Institute, Taipei, Taiwan

^cDepartment of Otolaryngology, Buddhist Tzu Chi General Hospital, Hualien, Taiwan

^dDepartment of Medicine, Tzu Chi University, Hualien, Taiwan

ARTICLE INFO

Article history:

Received 11 July 2012

Received in revised form

19 July 2012

Accepted 24 July 2012

Keywords:

Computer aid design

Finite element method

Hearing devices

Human middle ear

Sound transmission function

ABSTRACT

A three-dimensional geometric model of the human middle ear can be constructed in a computer-aided design environment with acute geometry and microanatomy. A working finite element (FE) model of the human middle ear can be created by using the published material properties of middle ear components to study sound transfer function. In this article, we review the latest technology and advances in the field of the finite model. Biomechanics and modeling of the human middle ear are also used in the study of middle ear pathology and the development of hearing devices. Although current FE models are useful for better understanding of human middle ear biomechanics, at present none of the FE models have been accepted as tools for diagnosis and surgical planning. The main challenge is how to improve the accuracy of the FE model in terms of predicting middle ear transfer function. Owing to the inhomogeneous microstructure of the tissues in the middle ear, the mechanical properties of these tissues may vary depending on several methodological factors of measurement.

Copyright © 2012, Buddhist Compassion Relief Tzu Chi Foundation. Published by Elsevier Taiwan LLC. All rights reserved.

1. Introduction

The human ear can be divided into three sections, the outer ear, the middle ear, and the inner ear. The outer ear consists of the external portion of the ear (pinna) and the external auditory canal. It serves to conduct sound to the tympanic membrane (TM), which separates the middle ear from the ear canal. The TM is composed of three different layers of tissue. The membrane is connected to the bony portion of the ear by means of the annular ligament. The middle ear is an air-filled space containing three auditory ossicles, the malleus, incus, and stapes. The three ossicles form the ossicular chain, which links the TM to the oval window of the cochlea. The manubrium, which is part of the malleus, is connected to the TM, and the footplate of the stapes is connected to the oval window. The inner ear consists of the vestibule, the semicircular canal, and the cochlea. The vestibule and the semicircular canal are responsible for maintaining body equilibrium and balance. The cochlea is

a snail-shaped bony canal with three fluid filled chambers winding from the base to the apex. The cochlea acts as an acoustic intensity and frequency analyzer, and it transforms acoustic mechanical vibration into electric signals.

The function of human hearing has been investigated through the use of models [1]. In general, there are two groups of models. The first group consists of electroacoustic circuit models based on the close link between acoustics and electrical engineering [2,3]. The second group is composed of structural mechanical models, mainly finite element (FE) models [4–10]. An advantage of the latter is that mechanical function is related to mechanical parameters and therefore a complicated analogy can be avoided.

2. FE method

Finite element analysis (FEA) 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 solutions to vibration systems. Investigations of reconstruction of middle ear geometry have been reported in several papers [6,8–12]. Funnell et al first used the FE model of the cat eardrum as thin shell elements decoupled from the ossicular chain [11]. Using

* Corresponding author. Department of Otolaryngology, Buddhist Tzu Chi General Hospital, 707, Section 3, Chung-Yang Road, Hualien, Taiwan. Tel.: +886 3 8561825; fax: +886 3 8560977.

E-mail address: e430013@yahoo.com.tw (C.-F. Lee).

FEA, the geometry, ultrastructure characteristics, and material properties of a complex biological system can easily be modeled. If a complete FE model of the middle ear were constructed, spatial variations in displacement on the TM, ossicular vibration, and spatial pressure distribution in the middle ear cavity and external ear canal could be clarified without direct measurements, which are difficult to perform. In addition, it would be possible to predict how middle ear function is affected by various kinds of middle ear pathologies and to understand how individual differences in the middle ear structure affect that function [13,14]. The mechanical behavior of the structure can be studied using the finite element method. The elements into which the structure could be divided have various shapes. Once the structure of interest is divided, the mechanical behavior of each element is analyzed. The elements are connected at specific nodes on their boundaries; the interelement effects are taken into account at these nodes only. The response to the applied loads is expressed in terms of displacements of the elements' nodes, which result in a matrix equation relating the behavior of the element to the applied loads. The components of this matrix are functions of the shape and properties of the elements. Finally all the element matrix equations are combined into one overall system matrix equation.

3. Parameters for the FE model of the human middle ear and validation

3.1. Parameters of the FE model

To construct an FE model of the middle ear, it is important to determine the parameters of the middle ear that are to be incorporated into the model. These include geometric parameters, mechanical properties and boundary conditions [14]. Gan's research team used histological sections of a fresh human temporal bone [8,9]. We demonstrated how high-resolution computed tomography could be used to create detailed dedicated geometrical models and how finite element analysis of this model can be used to study middle ear mechanics [10]. In general, there are no significant differences in the anatomic parameters between these approaches. In our study of temporal bone images using high-resolution computed tomography in 31 subjects with normal hearing, the configurations of the middle ear, including the TM ossicles and tympanic cavity, showed no significant differences between individuals, in right and left ears. However, the volume of the mastoid cavity did show significant differences [15]. When constructing an FE model of the middle ear, the mechanical characteristics and functions of the middle ear are incorporated by assigning different material properties to the different parts of the middle ear system. Most of the mechanical properties used in FE models are based on the biological features of the middle ear components, and validated through the cross-calibration process [8–10,13,15,16]. In addition, Poisson's ratio has been assumed to be 0.3 for all materials in the middle ear system based on the fact that all published Poisson's ratios of middle ear components are close to this value. Damping is the energy dissipation properties and affects the transient response of the vibrating system. Rayleigh damping has been used [8–13]. The system damping matrix C is defined as the system mass M and stiffness K matrices with $C = \alpha M + \beta K$. Boundary conditions are important for determining the mechanical behavior of the human middle ear [14]. Boundaries of the FE middle ear model include the ligaments in the middle ear cavity, cochlear fluid, intra-auricular muscle/ligaments/tendons and tympanic annulus. Some material properties of the biological tissues in the middle ear used in the FE model are still under investigation. Precise measurements of the material properties on boundary conditions can contribute to the behavior of the middle ear FE model.

3.2. Validation of FE modeling

Validation is an important procedure to verify the validity of a developed FE model to ensure that the model simulates the physiological function of the middle ear accurately [14]. In addition, the FE model validation process can also be used to determine the unknown parameters and material properties used in the FE model. Hence, a validated FE model is able to simulate the physiological functions of the intended structures and provide accurate information on the middle ear system. In most studies, the middle ear FE model was validated by a cross-calibration process based on stapes footplate and umbo displacements measured from human temporal bones using laser Doppler vibrometry [8–10]. The Moiré technique is used for measuring the tympanic membrane shape and deformation [17]. Comparisons between the FE model and time-averaged holography have also been used [18].

4. Otological applications

Recently several FE models have been used to predict the effects of different ontological procedures on their postoperative effectiveness in terms of middle ear transfer functions [14]. William et al constructed FE models with different stapes prostheses, and compared their natural frequencies, which changed according to the shape of the prosthesis and the ossicular chain constraint imposed along the prosthesis [19]. Zahnert et al constructed an FE model of a special Bell prosthesis placed between the tympanic membrane and the stapes [20]. The simulations clearly showed the influence of geometrical and material modification of the prosthesis on its vibroacoustic transfer behavior.

Our group determined the acoustic transfer characteristics of the tragus cartilage for an optimal cartilage myringoplasty [21]. To do this, we developed a cartilage plate-tympanic-coupled model using FE analysis. Different thicknesses of cartilage plate should be used to repair tympanic membrane perforations of different sizes. Kelly et al investigated the difference in the amplitude of the ossicles between normal ears and reconstructed ears with commercially available partial and total ossicular replacement prostheses using FE models [22]. The amplitude of vibration of the stapes footplate was closer to that of the normal ear when a total ossicular replacement prosthesis was implanted. Partial ossicular replacement prostheses had lower umbo vibrations and higher stapedia footplate vibrations.

Implantable hearing aids, initially developed for sensorineural hearing loss, have recently become more important with the extension of indications toward mixed hearing loss. By directly converting sound to amplified mechanical energy, implantable hearing aids have the advantages of leaving the ear canal open, and generating less feedback and providing better sound quality than other types of hearing aid. FE analysis could be used to characterize the influences of the most important mounting parameters on the performance of the transducers in respect to the mass loading effect on stapes vibration and the efficiency of the driving force of the transducer on the ossicular chain. Our group recently developed a novel opto-electromagnetic actuator attached to the tympanic membrane [23]. The optimal electromagnetic force can be calculated from our middle ear FE model. Bornitz et al used a middle ear simulation model to investigate two principle types of actuators in respect to attachment points at the ossicular chain and the direction of excitation [24]. The stapes head proved to be an ideal attachment point for actuators of both types as this position is very insensitive to changes in the direction of excitation. The implantable actuators showed a higher ratio of equivalent sound pressure to radiated sound pressure compared with that of an open hearing aid transducer. Wang et al used the FE model to analyze the coupling effects

between the ossicular chain and the transducer of an implantable middle ear hearing device [25]. For a floating mass transducer with a less tight crimping connection or low supporting rigidity, a large drop of stapes displacement occurs at a specific frequency, with a peak reduction of about 25.8 dB. A tight connection or high supporting rigidity shifts the drop of the stapes displacement to a higher frequency. For a contactless electromagnetic transducer, an electromagnetic transducer of 25 mg placed near the incus-stapes joint produced a maximum decrease of the stapes footplate displacement of around 16.5 dB. The drop of the stapes footplate displacement caused by the mass loading effect can be recovered by transducer stimulation over a frequency range of 1500 to 4000 Hz. They concluded that FE analysis can enhance the coupling stiffness between the clip and the ossicular chain, which is helpful for maximizing the efficiency of transducer stimulation.

Pathological changes in the tympanic membrane are among the most common sequelae of middle ear disease or surgery. These include changes in the shape of the TM, thickness, stiffness and perforation. Gan et al noted that the thickness and stiffness of the TM could be simulated using an FE model [9]. As the TM thickness increased from 0.05 to 0.2 mm, the stapes footplate displacement was reduced, particularly at low frequencies. Increasing stiffness can reduce stapes footplate displacement at low frequencies and increase displacement at high frequencies. They also simulated middle ear effusion by using an FE model [26]. When the fluid level filled up to about 50% of the middle ear cavity, there was a significant reduction of the umbo displacement by 8 to 10 dB.

5. Conclusions and future directions

The FE model is potentially useful in the study of middle ear biomechanics and in the design and testing of implantable middle ear hearing devices [15]. It would be possible to predict how 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. Fey et al incorporated the measurement of the geometry of the ear canal, the 3D asymmetrical geometry of the eardrum and details of the eardrum fiber structure [27]. A variety of mechanical tests that measure the properties of soft tissue have been reported, such as uniaxial tensile, strip biaxial tension and shear tests. In addition to experimental measurements, numerous material models have been developed to simulate the behavior of tissue in analytical ways [28]. Weiss et al used a hyperelastic material model with an exponential strain energy function to fit experimental curves of the human medial collateral ligament through FE analysis [29]. There are several nonlinear hyperelastic material models available for analyzing mechanical properties of biological soft tissue, such as the Ogden, Mooney-Rivlin, and Yeoh models [28].

Although current FE models are useful for a better understanding of human middle ear biomechanics, at present none have been accepted as tools for diagnosis and surgical planning [14]. The main challenge is how to improve the accuracy of the FE model in terms of predicting middle ear transfer function. Owing to the inhomogeneous microstructure of the tissues in the middle ear, the mechanical properties of these tissues may vary depending on several methodological factors in measurement. The high variability in design choices and modeling parameters, arising also in the wide range of result values, elucidates the necessity for further and standardized experiments on structural characterization and model parameter identification, validation, and optimization; a sensitivity analysis could be also a useful tool to identify the parameters with the highest influence on model results [30]. Further development of a time-domain FE model of the middle ear may provide a useful tool for simulating and evaluating the natural vibration of TM and stapes

footplate displacement, particularly when considering nonlinearity of the middle ear and the cochlea [14].

References

- [1] Bornitz M, Zahnert T, Hardtke HJ, Hüttenbrink KB. Identification of parameters for the middle ear. *Audiol Neurootol* 1999;4:163–9.
- [2] Hudde H, Weistenhöfer C. A three-dimensional circuit model of the middle ear. *Acustica* 1997;83:535–49.
- [3] Goode RL, Killion M, Nakamura K, Nishihara S. New knowledge about the function of the human middle ear: development of an improved analog model. *Am J Otol* 1994;15:145–54.
- [4] Wada H, Metoki T, Kobayashi T. Analysis of dynamic behavior of human middle ear using finite-element method. *J Acoust Soc Am* 1992;92:3157–68.
- [5] Eiber A, Kauf A. Berechnete Verschiebung der Mittelohrknöchelchen unter statischer Belastung. *HNO* 1994;42:754–9.
- [6] Beer HJ, Bornitz M, Harstke HJ, Schmidt R, Hofmann G, Vogel U. Modeling of components of the human middle ear and simulation of their dynamic behavior. *Audiol Neurootol* 1999;4:156–62.
- [7] Williams KR, Blayney AW, Rice HJ. Middle ear mechanics as examined by the finite element method. In: Hüttenbrink KB, editor. *Middle ear mechanics in research and otosurgery. Proceedings of the International Workshop on Middle Ear Mechanics*, Dresden, 19–22 Sept 1996. Dresden: University of Technology; 1997, p. 40–7.
- [8] Sun Q, Chang KH, Dormer KJ, Robert Jr KD, Gan RZ. An advanced computer-aided geometric modeling and fabrication method for human middle ear. *Med Eng Phys* 2002;24:595–606.
- [9] Gan RZ, Feng B, Sun Q. Three-dimensional finite element modeling of human ear for sound transmission. *Ann Biomed Eng* 2004;32:847–59.
- [10] Lee CF, Chen PR, Lee WJ, Chen JH, Liu TC. Three-dimensional reconstruction and modeling of middle ear biomechanics by high-resolution computed tomography and finite element analysis. *Laryngoscope* 2006;116:711–6.
- [11] Funnell WR, Laszlo CA. Modeling of the cat eardrum as a thin shell using the finite-element methods. *J Acoust Soc Am* 1978;63:1461–7.
- [12] Funnell WR, Decraemer WF, Khanna SM. On the damped frequency response of a finite element model of the cat eardrum. *J Acoust Soc Am* 1987;81:1851–9.
- [13] Koike T, Wada H, Kobayashi T. Modeling of the human middle ear using the finite element method. *J Acoust Soc Am* 2002;111:1306–17.
- [14] Zhao F, Koike T, Wang J, Sieng H, Meredith R. Finite element analysis of the middle ear transfer functions and related pathologies. *Med Eng Phys* 2009;31:907–16.
- [15] Lee CF, Chen PR, Lee WJ, Chen JH, Chou YF, Liu TC. Computer aided modeling of human mastoid cavity biomechanics using finite element analysis. Special issue: image processing and analysis in biomechanics. *EURASIP J Adv Sig Pr* 2010:1–9.
- [16] Koike T, Wada H, Kobayashi T. Effect of depth of conical-shaped tympanic membrane on middle ear sound transmission. *JSME Int J* 2001;44:1097–102.
- [17] Funnell WR, Decraemer WF. On the incorporation of moiré shape measurements in finite-element models of the cat eardrum. *J Acoust Soc Am* 1996;100:925–32.
- [18] Tonndorf J, Khanna SM. Tympanic-membrane vibrations in human cadaver ears studies by time-averaged holography. *J Acoust Soc Am* 1972;52:1221–33.
- [19] Williams KR, Blayney AW, Lesser TH. A 3-D finite element analysis of the natural frequencies of vibration of a stapes prosthesis replacement reconstruction of the middle ear. *Clin Otolaryngol* 1995;20:36–44.
- [20] Zahnert T, Schmidt R, Hüttenbrink KB, Hardtke HJ. FE simulation of the vibrations of the Dresden middle ear prosthesis. In: Hüttenbrink KB, editor. *Middle ear mechanics in research and otosurgery*. Dresden: UniMedia GmbH; 1997, p. 200–6.
- [21] Lee CF, Hsu LP, Chen PR, Chou YF, Chen JH, Liu TC. Biomechanical modeling and design optimization of cartilage myringoplasty using finite element analysis. *Audiol Neurootol* 2006;11:380–8.
- [22] Kelly DJ, Prendergast PJ, Blayney AW. The effect of prosthesis design on vibration of the reconstructed ossicular chain: a comparative finite element analysis of four prostheses. *Oto Neurotol* 2003;24:11–9.
- [23] Lee CF, Shih CH, Yu JF, Chen JH, Chou YF, Liu TC. A novel opto-electromagnetic actuator coupled to the tympanic membrane. *J Biomech* 2008;41:3515–8.
- [24] Bornitz M, Hardtke HJ, Zahnert T. Evaluation of implantable actuators by means of a middle ear simulation model. *Hear Res* 2010;263:145–51.
- [25] Wang X, Hu Y, Wang Z, Shi H. Finite element analysis of the coupling between ossicular chain and mass loading for evaluation of implantable hearing device. *Hear Res* 2011;280:48–57.
- [26] Gan RZ, Wang X. Multifield coupled finite element analysis for sound transmission in otitis media with effusion. *J Acoust Soc Am* 2007;122:3527–38.
- [27] Fay J, Puria S, Decraemer WF, Steel C. Three approaches for estimating the elastic modulus of the tympanic membrane. *J Biomech* 2005;38:1807–15.
- [28] Cheng T, Gan RZ. Experimental measurement and modeling analysis on mechanical properties of tensor tympani tendon. *Med Eng Phys* 2008;30:358–66.
- [29] Weiss JA, Gardiner JC, Bonifasi-Lista C. Ligament material behavior is nonlinear, viscoelastic and rate-dependent under shear loading. *J Biomech* 2002;35:943–50.
- [30] Volandri G, Di Puccio F, Forte P, Carmignani C. Biomechanics of the tympanic membrane. *J Biomech* 2011;44:1219–36.