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OBSERVATION OF VIBRATION RESPONSE OF TYMPANIC MEMBRANE USING FINITE ELEMENT METHOD

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ABSTRACT

The middle ear plays an essential role in sound perception: it conducts air-borne sound energy from the external environment into liquid waves inside the inner ear via ossicular vibrations. However, the middle ear is often the site of infections, congenital disorders and other pathologies, which can lead to conductive hearing loss. Tympanometry is an acoustic method to evaluate middle ear function by measuring TM's mobility and responses. However, current clinical results are inadequate due to our insufficient knowledge of the complex mechanics of the auditory system. This is a need to understand the TM vibration responses to the sound pressure level at certain frequencies. Such responses will find useful information such as displacement to develop a screening tool for middle ear diagnosis. Computational models have been introduced to analyze this phenomenon, where the tympanic membrane (TM) is key component in the auditory system. In this study, a finite element (FE) model has been proposed for TM. The geometry was reconstructed using magnetic resonance imaging (MRI) data. The material model was developed from previously published data. The model was employed to analyze the vibration of the TM under the sound load of pure tone. The vibration was observed for the sound load of 90dB SPL at three specific frequencies (226Hz, 678Hz and 1000Hz).

Keywords: *Five Keywords are Required Separated By Commas (Capitalize Each Work Italic)*

1. INTRODUCTION

The complex tasks of hearing are accomplished by the Auditory System in three different conceptional steps. First, the sound signal (acoustic excitation) must be transmitted to the receptors. Second, the acoustic excitation getting the receptors in form of pressure changes must be transduced into electrical signals, and third, these electrical signals must be correctly processed so that they can efficiently indicate qualities of the sound source (pitch, loudness, timbre and location). Every of these conceptional steps has its own anatomical correspondence: The conductive system (outer and middle ear), conducting the sound signal from the air to the inner ear; the *sensorineural system* (cochlea and eighth cranial nerve), involving physiological response to the excitation, activation of the associated nerve cells and the encoding of the sensory response into a neural signal, and the *central auditory nervous system* (auditory cortex, medial geniculate nucleus and the cochlear nucleus), dealing with the neurally encoded information (Figure 1).

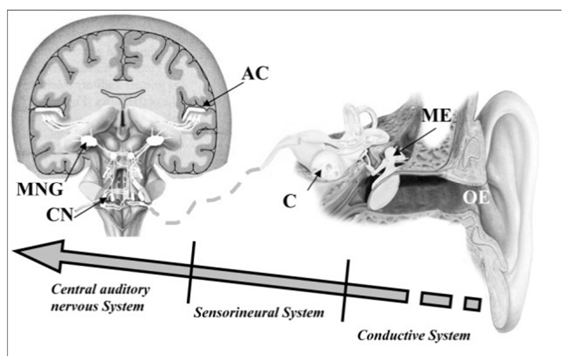

*Figure 1: Diagram of the Auditory System: Conductive System with the outer ear (**OE**) and the middle ear (**ME**), Sensorineural System with the cochlea (**C**) and the eight cranial nerve (**CN**) and Central auditory nervous System with the auditory cortex (**AC**) the medial geniculate nucleus (**MGN**))and the cochlear nucleus (**CN**). [1]*

The middle ear assumes a noteworthy part in listening to and is the site of numerous infections,

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inborn abnormalities, injuries and different diseases, for example, cholesteatoma, that add to hearing loss. Situated between the outside ear and the inner ear, the middle ear comprises of an air-filled space housed inside of the temporal bone which incorporates a chain of three little bones, or ossicles, associating the TM to the oval window. To date, non-obtrusive diagnostic devices and the nature of middle ear prostheses are frequently deficient. A superior comprehension of middle ear mechanics will add to progressions in finding and treatment of hearing loss.

Computational models are very useful to analysis middle ear mechanics; in that, they allow numerical experimentation to better understand the relationships between form and function. In order to achieve a more complete and quantitative understanding of middle-ear mechanics, various numerical models have been developed to interpret experimental data. In the first era of quantitative middle-ear modeling, lumped-parameter models were used extensively. However, those models contain parameters that are not directly related to middle-ear anatomy and structure, and cannot effectively simulate the complex three dimensional motions of the middle-ear system, which consists of asymmetrical, irregular and interconnected components. To overcome this deficiency, Funnell first introduced finite-element models into middle-ear research in 1975[2]. They are constructed based on real anatomical shapes, material properties, boundary conditions and loading conditions. Since then, more and more groups have used finite-element models to analyze middle-ear responses in humans and in other animals. In spite of the number of middle-ear studies published to date, many gaps remain in our knowledge, especially with respect to eardrum vibration patterns.

2. FINITE ELEMENT ANALYSIS

The finite element method (FEM) is the overwhelming discretization method in auxiliary mechanics. The main concept in the physical translation of the FEM is the subdivision of the mathematical model into disjoint (non-covering) parts of basic geometry called finite elements or elements for short. The reaction of every component is expressed as far as a limited number of degrees of flexibility described as the value of an obscure function, or functions, at an arrangement of nodal points. The reaction of the numerical model is then thought to be approximated by that of the discrete model got by interfacing or gathering the accumulation of all components. The disengagement gathering idea happens normally when looking at numerous artificial and natural systems. There have some commercial FEM software packages, such as Abaqus, Adina, Ansys etc. Fig. 7 shows the work flow of the Abaqus CAE to analysis a model using FE analysis method.

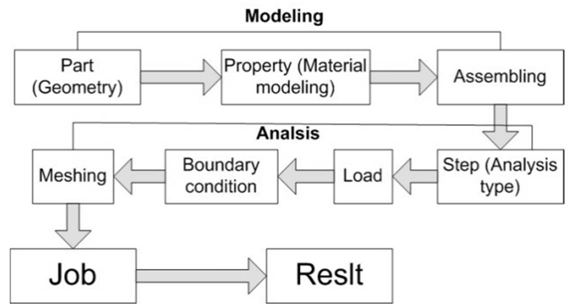

Figure 2: Work flow of Abaqus CAE for FEA

2.1 Geometrical Model of TM

Many *vivo* and *vitro* solution have been proposed for the geometrical model of human *TM* to be used in *FE* analysis. The geometry of the *TM* can be deduced from some specific sources, such as 1. Simplified Parametric 2. Serial Histological Sections. 3. *Nuclear magnetic resonance (NMR)* spectroscopy. 4. *Micro-computed tomography (µCT)* scans 5. Spiral CT 6. *High-resolution computed tomography (HRCT)*. 7. *Magnetic resonance imaging (MRI)*. Previously the authors have reconstructed their geometry based on these specific sources (Table 1).

Table 1 Summary of Human TM Geometrical Models

Source of Geometry	Thickness (µm)	Element type	Year
Parametric	100	Shell	2008[3]
Histological sections	50-100	Solid	2004[4]
NMR spectroscopy	100-800	Shell	2003[5]
µCT scan	75, 200	Shell	2004[6]
Spiral CT	50	Shell	2009[7]
HRTC	100	Solid	2010[8]

TM thickness is considered in many works as a key parameter in the FE modeling. Al though a uniformly distributed thickness value ranging 30 to 150 mm usually adopted.[7, 9-12]

The geometry of the *TM* has been deduced from an anatomic model. The anatomic model is reconstructed based on the *MRI* data of a human cadaver ear.

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http://audilab.bmed.mcgill.ca/_daren/3Dear. It was in virtual reality modeling language (VRML) file format as a 3D polygon mesh surface. Solid work software was used to make the model usable in Abaqus CAE. Its dimensions (Figure 3) are in the mean range of human values (elliptic major and minor axis is around 9 and 8 mm, separately, cone depth is around 1.46 mm). A default uniform thickness of 0.075 mm was accepted for both PT and PF (Table 2)

Table 2 *Present Geometrical Model for Human TM*

Source of Geometry	Thickness (µm)	Element type	Software
MRI	75	Membrane	Solid work and Abaqus CAE 6.14

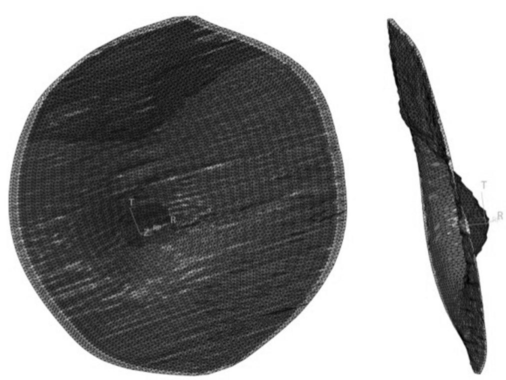

Figure 3: Tympanic membrane geometrical model in Abaqus CAE

2.2 Material Properties of TM

There have so many material modeling previously used. All the material models are varied depending on linear elastic behavior. The first question is that whether the linear elastic property of *TM* is isotropic or anisotropic and uniform.

There have three combination of material models mostly used based on *linear elastic (LE)* behavior (Table 3). *TM* divided into two major regions based on material properties. An *OR* model is assumed for the *PT* in most of the model while an *IS* model is used for the *PF*. Most of the *OR* models considered two young's module parameters, redial elasticity (E_r) and circumferential elasticity (E_c) except in farrazzini 2003,[1] where elasticity in thickness direction also obtained.

In this *FE* model, *TM* and tympanic annular ligament are modeled as membrane element. Here the material model is considered with *OR-IS* (*PT* is assumed as *OR* model and *PF* is assumed as *IS* model) and an *IS* model is considered for tympanic annular ligament (Table 4).

Table 3 *Summary of Human TM Material Models*

Material models	Variables	Pars Tensa (MPa)	Pars Flaccida (MPa)	Year
IS-IS	E	33.4	11	2014,[13]
		33.4	11.1	2013,[14]
		32	32	2009,[7]
		20	20	2008,[3]
OR-IS	E_r, E_c & E_z	35, 20 & ---	10	2010,[8]
		35, 20 & ---	10	2004,[4]
		4,1 & 0.9	0.9	2003,[1]
		32, 20 & ---	10	2002,[15]
OR-OR	E_r & E_c	85.7 & 48	45.6 & 20	2001,[16]

A default 1.2×10^3 kg.m^{-3} density value was assumed in all implemented models except in [1] reference model where a 1.0×10^3 kg.m^{-3} density value was specified.

A default 0.3 Poisson's ratio value was assumed, except in [1] reference models, where 0.4, 0.1 and 0.1 values in the radial, circumferential and thickness directions are specified for the PT and a 0.3 value for the PF).

Table 4 *Present Material Models for Human TM*

Region	Model	Type of property	Variable	Value
Pars Tensa	OR, LE	Young modules (MPa)	E_r E_c	35 20
		Shear Module (MPa)	G_{12}	10.781
		Poisson's ratio	ν	0.3
		Density (kg/m^2)	ρ	1.2×10^3
Pars Flaccida	IS, LE	Young modules (MPa)	E	10
Tympanic Annular	IS, LE	Young modules (MPa)	E	0.6
		Poisson's ratio	ν	0.3

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		Density (kg/m^2)	ρ	2.5×10^3

2.3 Analysis of The TM

A free 3-node triangular mesh of M3D3 elements (Abaqus) was employed in whole model (Figure 3). The model was meshed with 30448 elements and 15381 nodes. The *FE* model of *TM* was analyzed for dynamic displacement response. Explicit dynamic analysis procedure is used to observe the time domain response of the TM. TM was stimulated with 90dB SPL sound load of pure tone for 0.1 sec. The displacement of a node corresponding to umbo area was observed at 226 Hz, 678 Hz and 1000 Hz frequencies of the stimulation. These are the important frequencies used by tympanometry. 226 Hz pure tone is mostly used for adult and others two are usually used for child. The reflected sound signals are observed in tympanometry to measure the acoustic admittance of TM.

3. RESULTS AND DISCUSSION

Auditory signal is transferred through the middle ear and middle ear amplifies it to the sensorineural part. The auditory signal is also distorted in the middle ear. Here the auditory signal is observed at TM as displacement response in time function (Figure 4).

The Fast Fourier transform (FFT) shows that the auditory signal at TM contains mainly 226 Hz signal for 226 Hz stimulation and some lower frequency signals take places with a small effect on the main signal (Figure 4). The amplitude of displacement is not equal for each cycle. At 678 Hz and 1000 Hz stimulations, the auditory signal looks more distorted than 226 Hz stimulation. More inequity of the umbo displacement amplitude is occurred with the higher frequency stimulation (Figure 5 & 6). In the FFT it is clear that the main frequency content is same as stimulation frequencies (Figure 5 & 6). There have also a strong amplitude response at 0 Hz. The auditory signal is affected by some lower frequency signals. The frequencies are 0-500 Hz. Umbo vibration pattern is more stable under the sound load 226 Hz frequency.

****Figure 4****

****Figure 5****

****Figure 6****

4. CONCLUSION

Here we describe middle ear mechanics and finite element method to analysis the middle ear. The TM vibration response is analyzed under sound load of pure tone using FE method. The TM vibration response is important to understand the middle ear mechanics. The FE analysis results shows that how TM act under the sound load. The TM behavior is important to develop a diagnosis device based on TM response for hearing loss detection.

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REFRENCES:

[1] M. Ferrazzini, "Virtual middle ear: a dynamic mathematical model based on [the] finite element method," 2003.

[2] W. R. J. Funnell and C. A. Laszlo, "Modeling of the cat eardrum as a thin shell using the finite-element method," *The Journal of the Acoustical Society of America,* vol. 63, pp. 1461-1467, 1978.

[3] C. D. Le and Q. L. Huynh, "Mathematical models of human middle ear in chronic otitis media," in *Information Technology and Applications in Biomedicine, 2008. ITAB 2008. International Conference on*, 2008, pp. 426-429.

[4] R. Z. Gan, B. Feng, and Q. Sun, "Three-dimensional finite element modeling of human ear for sound transmission," *Annals of Biomedical Engineering,* vol. 32, pp. 847-859, 2004.

[5] D. Kelly, P. J. Prendergast, and A. Blayney, "The effect of prosthesis design on vibration of the reconstructed ossicular chain: a comparative finite element analysis of four prostheses," *Otology & neurotology,* vol. 24, pp. 11-19, 2003.

[6] C. S. Mikhael, W. R. J. Funnell, and M. Bance, "Middle-ear finite-element modelling with realistic geometry and a priori material-property estimates," in *28th Ann Conf Can Med Biol Eng Soc*, 2004, pp. 126-129.

[7] Y. Liu, S. Li, and X. Sun, "Numerical analysis of ossicular chain lesion of human

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

ear," *Acta Mechanica Sinica,* vol. 25, pp. 241-247, 2009.

[8] C.-F. Lee, P.-R. Chen, W.-J. Lee, Y.-F. Chou, J.-H. Chen, and T.-C. Liu, "Computer aided modeling of human mastoid cavity biomechanics using finite element analysis," *EURASIP Journal on Advances in Signal Processing,* vol. 2010, p. 6, 2010.

[9] N. P. Daphalapurkar, C. Dai, R. Z. Gan, and H. Lu, "Characterization of the linearly viscoelastic behavior of human tympanic membrane by nanoindentation," *Journal of the mechanical behavior of biomedical materials,* vol. 2, pp. 82-92, 2009.

[10] W. Decraemer and W. Funnell, "Anatomical and mechanical properties of the tympanic membrane," *Chronic otitis media: Pathogenesis-oriented therapeutic management,* pp. 51-84, 2008.

[11] M. Gaihede, D. Liao, and H. Gregersen, "In vivo areal modulus of elasticity estimation of the human tympanic membrane system: modelling of middle ear mechanical function in normal young and aged ears," *Physics in medicine and biology,* vol. 52, p. 803, 2007.

[12] W. Robert, J. Funnell, and C. Laszlo, "A critical review of experimental observations on ear-drum structure and function," *ORL,* vol. 44, pp. 181-205, 1982.

[13] M. R. Islam, K. Gan, and C. Umat, "UMBO displacement transfer function analysis using finite element modeling," in *Biomedical Engineering and Sciences (IECBES), 2014 IEEE Conference on*, 2014, pp. 516-519.

[14] T.-S. Ahn, M.-J. Baek, and D. Lee, "Experimental measurement of tympanic membrane response for finite element model validation of a human middle ear," *SpringerPlus,* vol. 2, pp. 1-12, 2013.

[15] Q. Sun, R. Gan, K.-H. Chang, and K. Dormer, "Computer-integrated finite element modeling of human middle ear," *Biomechanics and Modeling in Mechanobiology,* vol. 1, pp. 109-122, 2002.

[16] E. Abel and R. Lord, "A finite-element model for evaluation of middle ear mechanics," DTIC Document2001.

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

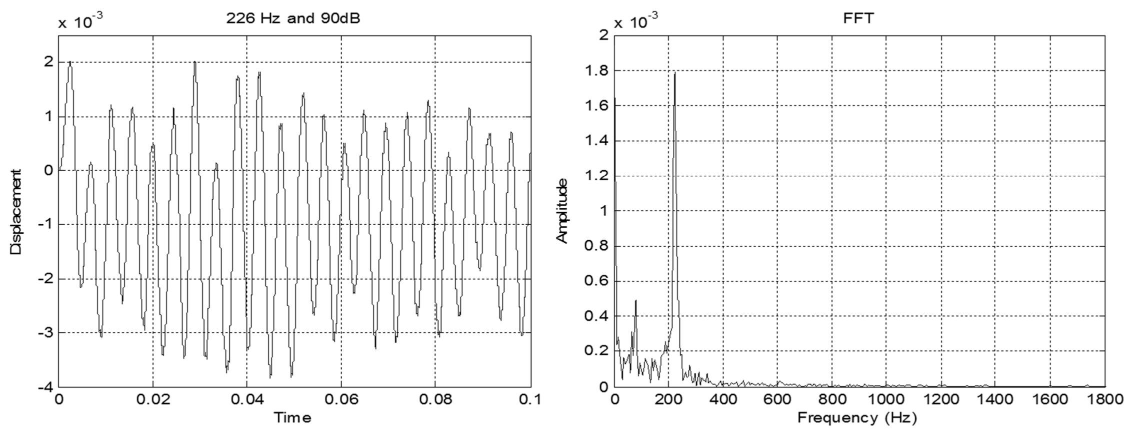

Figure 4: TM vibration response at umbo for the sound load of 226 Hz with 90dB SPL

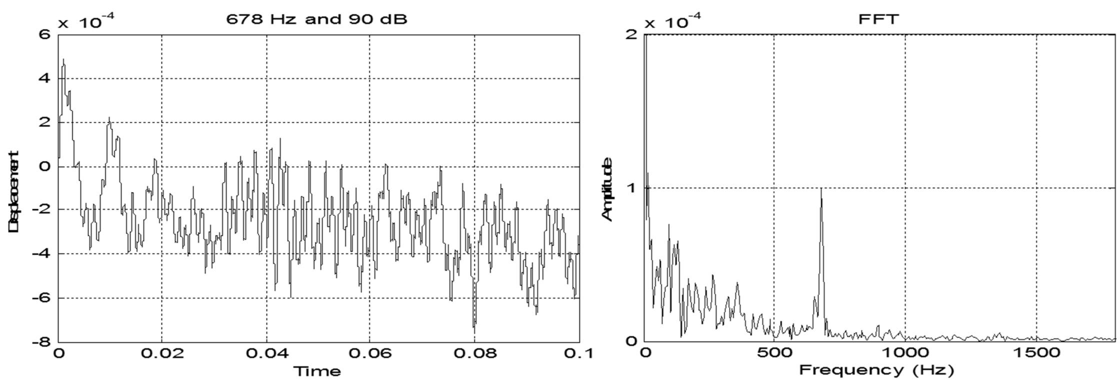

Figure 5: TM vibration response at umbo for the sound load of 678 Hz with 90dB SPL

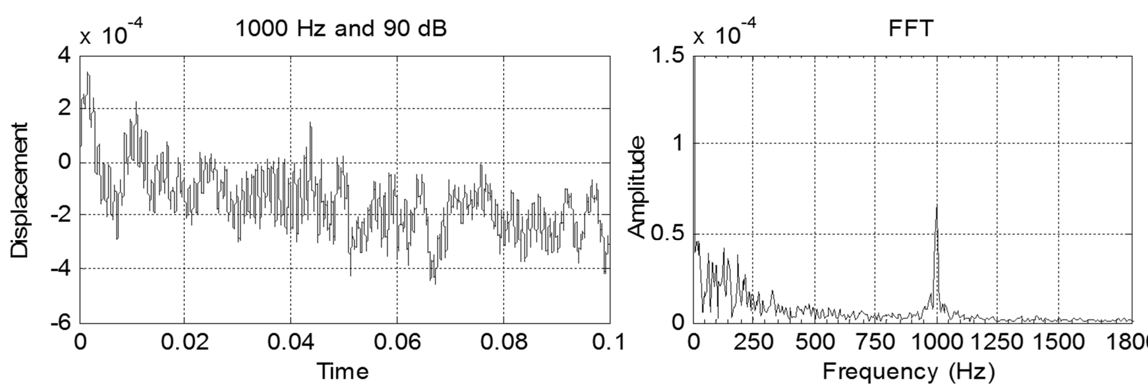

Figure: TM vibration response at umbo for the sound load of 1000Hz with 90dB SPL