

Dynamic analysis of the biomechanic behavior of the middle ear and tympanic membrane through the application of the finite element method



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Abstract

The aim of this paper is the dynamic analysis of the biomechanical behavior of the middle ear and the tympanic membrane through the application of the finite element method (FEM). A digital model representing the middle ear (tympanic membrane and ossicular chain) was built through CAT images. The discretization of the model using the finite element method was done based on the ABAQUS program. The tympanic membrane was considered in two ways: with one layer and divided into three layers. The latter is closer to the real situation. Mechanical properties were taken from previous works. The tympanic membrane behavior was analyzed for an excitation corresponding to the interval between 100 Hz and 10 kHz. The Sound Pressure Level considered was 105 dB. The results obtained were the umbo displacement and the central point of the footplate of the stapes. The largest displacements at the umbo level are found close to 1kHz, whereas at the level of the footplate of the stapes are closer to 500Hz. We can conclude that the results reached with the three layered tympanic membrane have higher amplitude than the results found considering the tympanic membrane with one layer, being closer to the experimental results.

Key words: Biomechanics; Middle Ear; Tympanic Membrane; Computer Simulation.

Resumen

Análisis dinámico del comportamiento biomecánico del oído medio y de la membrana timpánica a través de la aplicación del método de los elementos finitos

Este trabajo tiene por objetivo el análisis dinámico del comportamiento bio-mecánico del oído medio y de la membrana timpánica a través de la aplicación del método de los elementos finitos. Se construyó un modelo digital representativo del oído medio (membrana timpánica y cadena osicular), a través de imágenes de Tomografía Axial Computarizada. La discretización del modelo, usando el método de los elementos finitos, se llevó a cabo teniendo como base el programa ABAQUS. La membrana timpánica se consideró de dos formas: con una capa y dividida en tres capas, ésta segunda se considera la más próxima de lo real. Las propiedades mecánicas se retiraron de trabajos anteriores. Se analizó el comportamiento de la membrana timpánica para una excitación correspondiente al intervalo entre 100 Hz y 10 kHz. Se considero el nivel de presión sonora de 105 dB SPL (Sound Pressure Level). Como resultados, se obtuvieron los desplazamientos del umbo y del punto central de la platina del estribo. Los desplazamientos más grandes a nivel del umbo se encuentran próximos de 1kHz mientras que a nivel de la platina del estribo se aproximan de 500Hz. Podemos concluir que los resultados obtenidos con la membrana timpánica de tres capas son de amplitud superior a los resultados considerando la membrana timpánica con una capa y más cercanos a los resultados experimentales.

Palabras clave: Biomecánica; Oído Médio; Membrana Timpánica; Simulación por Computador.

Análise dinâmica do comportamento biomecânico do ouvido médio e membrana timpânica através da aplicação do método dos elementos finitos

O presente trabalho tem como objectivo a análise dinâmica do comportamento biomecânico do ouvido médio e membrana timpânica através da aplicação do método dos elementos finitos. Construiu-se um modelo digital representativo do ouvido médio (membrana timpânica e cadeia ossicular), através de imagens de Tomografia Axial Computorizada. A discretização do modelo, usando o método dos elementos finitos, foi feita com base no programa ABAQUS. A membrana timpânica foi considerada de duas formas: com uma camada e dividida em três camadas, sendo esta segunda a mais próxima do real. As propriedades mecânicas foram retiradas de trabalhos anteriores. Analisou-se o comportamento da membrana timpânica para uma excitação correspondente ao intervalo entre 100 Hz e 10 kHz. Considerou-se o nível de pressão sonora de 105 dB SPL (Sound Pressure Level). Como resultados, obtiveram-se os deslocamentos do umbo e do ponto central da platina do estribo. Os maiores deslocamentos ao nível do umbo, se encontram próximos a 1kHz enquanto ao nível da platina do estribo se aproximam de 500Hz. Podemos concluir que os resultados obtidos com a membrana timpânica de três camadas são de amplitude superior aos resultados considerando a membrana timpânica com uma camada e mais perto de resultados experimentais.

Palavras-chave: Biomecânica, Orelha Média; Membrana Timpânica; Simulação por Computador.

INTRODUCTION

The auditory system is divided into peripheral and central systems. The peripheral auditory system consists of the external ear, the middle ear and the inner ear and the central auditory system consists of the auditory nerve and cortex.¹⁻³ The function of the auditory system is essentially to transform the pressure variations originated by the propagation of hearing waves received by the tympanic membrane into electric impulses at the inner ear. These impulses are channeled through the auditory nerve to the brain, changing it into hearing sensations.^{4,5}

The external ear (the pinna and the external auditory meatus or ear canal) that collects and recognizes the sound energy and directs it towards the middle ear (eardrum and bony chain). In the tympanic membrane, the pressure and decompression movements transforms the sound energy into mechanical energy being communicated to the ossicular chain (malleus, incus and stapes). The ossicles of the middle ear are articulated in such a way that the displacements of one of them interfere indirectly on the displacement of others. The movement of the malleus handle also determines a movement at the stapes towards the oval window of the cochlea, causing the propagation of a vibration movement through the fluids of the inner ear (vestibule, semi-circular canals and cochlea), changing the mechanical energy into hydraulic energy. Vibrations captured by the cochlear nerve are then transformed into impulses to the brain, resulting in sound sensations.

Hearing loss can be caused by several factors that can be either genetic (like, for example, a child born with hearing loss due to German measles of the mother) or non genetic ones (inflammatory disease, toxicity, noise, accidents or injuries). Deafness, characterized by the loss of sound

perception can be partial or total, temporary or permanent. Any hearing loss can limit the quality of life, therefore any action that may relieve this difficulty is of great interest and importance. Thus, a biomechanical analysis of the tympanic membrane and its structures was carried out, as well as the relations established with the ossicular chain (malleus, incus and stapes). With this idea in mind it will be easier to simulate some pathologies, comparing them to the normal ear, enabling a better prognosis. It can also help with the selection of more suitable prosthesis.

The Finite Element Method is currently the most widely used method in the mechanical calculation of complex systems, as it is the case of the human middle ear. The Finite Element Method can be understood as a modeling of a problem that involves continuous means through the analysis of discrete parts of these means (sub-domains), called finite elements (connecting among them in given points, called knots) for which it is possible to know a mathematical description of its behavior. This process of structured analysis of the parts of the whole is known as discretization (subdivision). The application of the Finite Element Method has to do with solving a complex issue through the sequential and structural solution of a set of easier problems with mathematical solution (exact or approximate one), that when gathered lead to a solution of the initial global problem. This method can be applied on the mechanical calculation bearing in mind the determination of displacements, deformations and tensions.⁶⁻¹⁰

Elements can have unidimensional, bidimensional or three-dimensional features. In the case of bidimensional applications, the most commonly used elements have a triangular or quadrangular shape, whereas in three-dimensional problems, elements are of tetrahedric or hexahedric shape. The relation between the system of forces applied

on an element and the displacements of the knots is done through a set of coefficients, rigidity coefficients adequately organized in a matrix, called rigidity matrix. In order to obtain the mechanical behavior of the whole domain, these matrix are gathered in an appropriate manner constituting the rigidity matrix of the domain being analyzed. This matrix will form the matrix of the coefficients of a system of equations where the unknown vector corresponds to the vector of knot displacements. When dealing with a problem where coefficients of rigidity depend on displacements, the problem takes a non linear character and it is solved with interactive processes.

A 3D digital model of the middle ear and the tympanic membrane was built through CAT images.¹¹ Discretization of the model was done using the finite element method based on the ABAQUS program.¹² Mechanical properties were taken from previous studies.^{13,14} Thus, the umbo displacements were obtained (central part of the tympanic membrane and that corresponding to the end of the malleus handle) and the central area of the footplate of the stapes for a frequency between 100Hz and 10kHz, and for a sound level pressure of 105 dB SPL.

The presented work shows a non-invasive methodology that enables to analyze the biomechanical behavior of the human middle ear from a CAT exam. This technique will enable the design of custom ordered prosthesis for specific patients, using telehealth techniques without the need for the prosthesis to meet the patient personally.

OBJECTIVES

General Objective

The general objective of this work is to analyze the dynamic behavior of the middle ear and the tympanic membrane through a biomechanical study, using the application of finite element method as a tool.

Specific objectives

- To study the sound transmission mechanism by the middle ear;
- To create a model of the middle ear and the tympanic membrane through CAT images;
- To carry out the model discretization based on the Finite Element Method, considering the tympanic mem-

brane in two ways: with one layer and with three layers;

- To simulate the vibro-acoustic behavior of the middle ear using a frequency range between 100Hz and 10kHz, for a sound pressure level of 105 dB SPL;
- To calculate displacements at the umbo level;
- To calculate displacements at the level of a central point of the footplate of the stapes;
- To compare the results with the results found by other authors.

MATERIALS AND METHODS

The digital geometrical model of the middle ear that includes the tympanic membrane and the ossicles (malleus, incus and stapes) was built based on the CAT imaging exam.¹¹ These images were obtained from a 65 year old woman with normal hearing (Figure 1- left). Since the outlines of images of the middle ear were difficult to recognize due to its structure and mainly to its reduced size, a methodology based on manual segmentation,¹⁵ using a Computer Aided Design (CAD) software was used (Figure 1 – right).

The outlines of the structures of a sectioned organ were treated as closed polygons. Each outline formed a limited amount of selected dots of the limits of each object. Once all the outlines were taken out from the cross sections, the reconstruction among them was done and finally the three-dimensional geometrical model was obtained.

The tympanic membrane and ossicles discretization was done using the ABAQUS program, generating the finite element mesh. Figure 2 (A,B,C,D) shows the geometry representation used in the middle ear model together with the mesh of finite elements. Later, ossicles were put together forming the ossicular chain close to the tympanic membrane (Figure 2 – right).

Tympanic membrane was discretized in two ways: with one layer and with three layers (the latter is closer to the real one). The tympanic membrane with one layer is made of 3.722 (three dimensional) hexahedric elements of C3D8 type, a total of 7.648 knots. On the other hand, for the tympanic membrane with three layers, 11.165 hexahedric elements of the C3D8 type were used, a total of 15.295 knots.

The tympanic membrane was also divided into two parts (Figure 3): a *pars flaccida* (located in the upper area and less fibrous) and the *pars tensa* (the membrane itself which is responsible for its vibration). In relation to the ossicles, the option was to use C3D4 type tetrahedric elements and not hexahedric ones as in the tympanic membrane, due to the

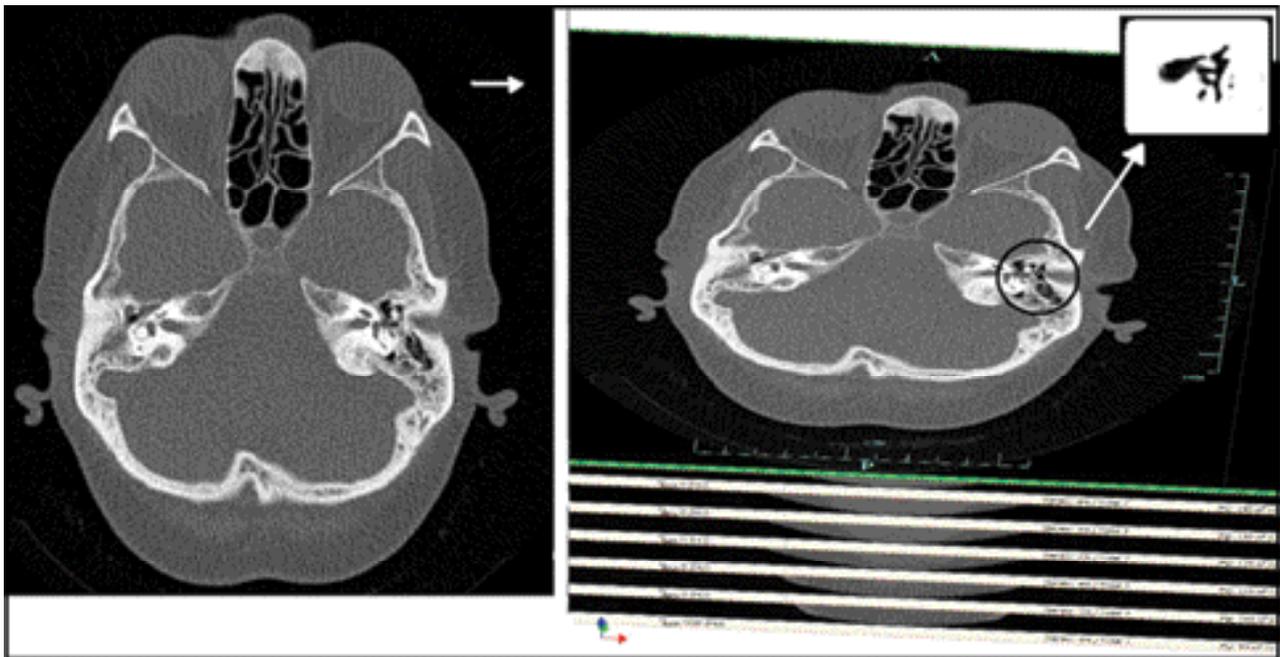


Figure 01 - 2D Axial image done with CAT scan of the middle ear.

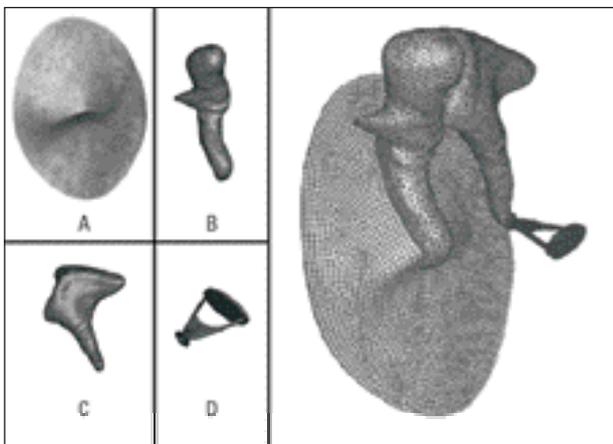


Figure 02 - Representation of finite element geometry and mesh; A) tympanic membrane; B) malleus; C) incus; D) stapes.

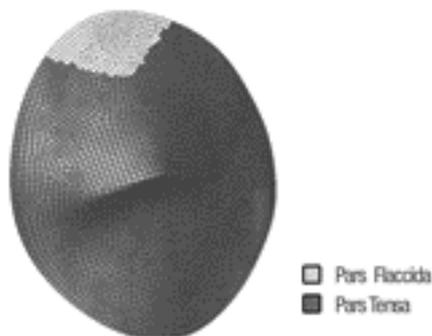


Figure 03 - Representation of the tympanic membrane: *pars tensa* and *pars flaccida*.

strongly irregular geometries. Malleus is made of 18.841 elements. Incus is made of 39.228 elements and the stapes is made of 9.218 elements. In this piece of work unidimensional elements were used for ligaments and tendons since the tension status (and/or deformation) is uni-axial (only one axis).

The respective material properties were applied for the several components of the model, such as the Young module, Poisson's coefficients, buffer densities and coefficients, based on previously published studies.^{13,14} Some of these properties are shown on Table 1 where E is the Young's module. The index Θ indicates the tangential direction and the r radial direction.

When considering tympanic membrane with only one layer, the *pars tensa* properties were considered as being orthotropic properties.¹⁶ In the *pars tensa* of the three layered tympanic membrane, layers 1 and 3 take in the same isotropic properties of the *pars flaccida* and layer 2 (central one) has orthotropic properties due to its fibers.

Ossicles were also divided into regions according to its properties. The malleus was divided into three parts: head, neck and handle; the incus was divided into: body and short and long apophysis; the stapes takes in the same properties all over its parts (head, neck, crura and footplate).

Connections between the ossicles malleus/incus and incus/stapes were done through mathematical formulations representing the contact,^{12,17} with a coefficient of friction equal to 0.9.¹⁸

The suitable borderland conditions were assigned to the level of the tympanic membrane, base of the stapes, ligaments and muscles. Ligaments and muscles suspend the ossicles. The tympanic membrane was attached all around its periphery simulating a tympanic sulcus. The footplate of the stapes was also attached simulating the annular ligament.

Based on the Yeoh's model, the ligaments were considered as having a hyperelastic non-linear behavior. Constants c_1 , c_2 e c_3 were obtained from another reference.¹⁹

The model is used as a basis for several simulations at the dynamic level, on a frequency range between 100 Hz and 10 kHz, for several acoustic pressure values, applied on the tympanic membrane. However, this study will show the displacements of the umbo and of a central point of the footplate of the stapes for a sound pressure level of 105 dB SPL.

The sound pressure level is corresponding to the pressure caused by vibration, measured at a given point. The decibel scale SPL defines sound levels comparing sound pressures, p , with a reference sound pressure, $p_0 = 20\mu\text{Pa}$, corresponding to the hearing threshold and it is given by:

$$\text{SPL} = 20 \log \frac{p}{p_0}$$

Thus, the result is an excitation of the tympanic membrane with a pressure of 3.56Pa equivalent to 105 dB SPL.

RESULTS AND DISCUSSION

A simulation was done placing a sound pressure of 105 dB SPL on the tympanic membrane. Results were compared, both in terms of the umbo displacement and that of the central part of the footplate of the stapes, for frequencies ranging between 100Hz and 10kHz.

Figures 4 and 5 show the displacements obtained at the level of the umbo and at a central point of the footplate of the stapes, for the tympanic membrane considered with one layer and for the tympanic membrane with three layers. These results were compared to Hironobu Kurokawa²⁰ studies. Kurokawa's study (also for 105 dB SPL) shows displacements of the umbo and the footplate of the stapes based on a measurement method on six human temporal bones from males with ages ranging between 61 and 74 years old, using Laser Doppler Vibrometer.

It can see in the results that displacements obtained with the tympanic membrane with three layers have

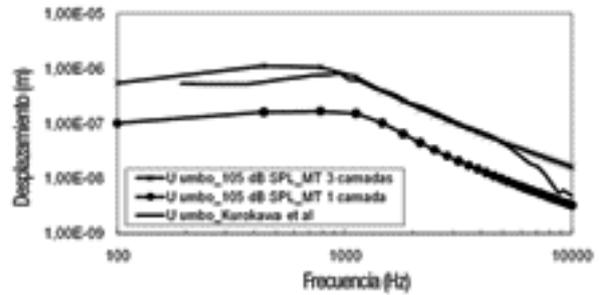


Figure 04 - Umbo displacements for a sound pressure level of 105 dB SPL.

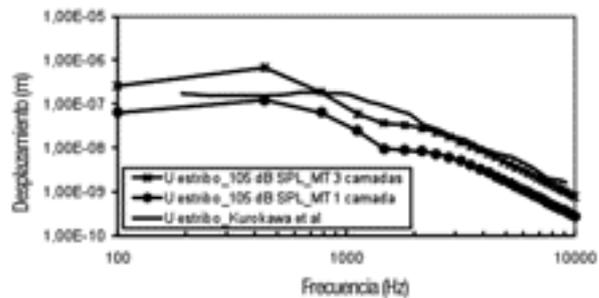


Figure 05 - Displacement of the central part of the footplate of the stapes for a level of sound pressure of 105dB SPL.

higher amplitude than the displacements obtained with the tympanic membrane of one layer, both for the umbo and for the footplate of the stapes. It is also noticed that the largest displacements at the level of the umbo took place for frequencies closer to 1.000 Hz. However, for the stapes, the largest displacements appear to be close to 500 Hz.

It can also observe that the results of the displacements of the umbo (Figure 4) with the tympanic membrane of three layers are closer to the result reached by the other author on all the frequency range. For displacements of a central point of the footplate of the stapes, Kurokawa's experimental results are much closer to the two models of this piece of work where the three layered model is closer both to high frequencies and to the medium and low ones.

CONCLUDING REMARKS

This study investigated the application of the finite element method in the biomechanical study of the middle ear and the tympanic membrane. For this, a computer model was used for the biomechanical simulation of the human middle ear. An excitation corresponding to the interval between 100 Hz and 10 kHz was induced on the tympanic

Table 1 - Properties of materials assigned to the 3D model of the middle ear.

Properties of the materials							
		Density (Kg/m ³)	Model		Poisson's Coefficient	Young Module (N/m ²)	
Tympanic Membrane						E	
<i>Pars Flaccida</i>		1,20E+03	Elastic	Isotropic	0,3	1,00E+07	
						E(θ)	E(r)
II	Capa 1	1,20E+03	Elastic	Isotropic	0,3	1,00E+07	1,00E+07
	Capa 2	1,20E+03		Orthotropic		2,00E+07	3,20E+07
	Capa 3	1,20E+03		Isotropic		1,00E+07	1,00E+07
<i>Pars Tensa - 1 capa</i>		1,20E+03		Orthotropic		2,00E+07	3,20E+07
Ossicles						E	
Malleus	Head	2,55E+03	Elastic	Orthotropic	0,3	1,41E+10	
	Neck	4,53E+03					
	Handle	3,70E+03					
Incus	Body	2,36E+03					
	Short	2,26E+03					
	Long	5,08E+03					
Stapes		2,20E+03					
Ligaments and Muscles					c1	c2	c3
Malleus higher L.		1,00E+03	Hiper-elastic	Yeoh	6,31E+03	-1,00E+04	2,20E+06
Malleus lateral L.		1,00E+03			6,31E+03	-1,00E+04	2,20E+06
Malleus anterior L.		1,00E+03			7,34E+04	-3,74E+02	5,86E+05
Incus posterior L.		1,00E+03			5,46E+04	-4,17E+04	1,25E+06
Incus higher L.		1,00E+03			6,31E+03	-1,00E+04	2,20E+06
Stapes annula L.		1,00E+03			6,31E+03	-1,00E+04	2,20E+06
Eardrum tensor muscle		1,00E+03			2,78E+04	-1,63E+04	6,35E+05
Stapedius muscle		1,00E+03			5,46E+04	-4,17E+04	1,25E+06

membrane and the sound pressure level of 105dB SPL. The results obtained, both at the level of the umbo and at the base of the stapes were compared to the experimental results of another author known in the literature.

Some differences were noticed on the results for models with one layer and for those considering three layers. The model based on the three layers caused more movement of the whole system, both at the umbo and at the base of the stapes, with the main difference for the lowest frequencies. This allows us to conclude that the tympanic membrane with the three layers model is more flexible. The results obtained with the three layered model are closer to the results found by the other author, enabling to assign more reliability in the results obtained with the three layer model.

The presented work can lead to further studies, such as the inclusion of external and inner ear, tympanic cavity, simulation of pathologies such as tympanic perforations, myringosclerosis, tympanosclerosis, otosclerosis, otitis, Eustachian tube functioning, as well as the application of the middle ear partial or total prosthesis, contributing with future studies related to hearing rehabilitation.

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