BIOMECHANICAL STUDY OF MIDDLE EAR

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Summary. *The human ear is a complex biomechanical system and is divided by three parts: outer, middle and inner ear. The middle ear is formed by three ossicles (malleus, incus and stapes) that amplify the sound sending the sound waves to the inner ear.*
However, the ossicles can suffer from several damages, for example, the Otosclerosis, being a need the application of mechanical prosthesis, by chirurgic intervention, keeping the right travel of sound wave.
In this work, a finite element modelling of the middle ear was made. For this propose, we show an approximate 3D solid model of the ossicles and eardrum for a normal ear.
The discretization of these components was made with tetrahedral solid elements, using ABAQUS program. The connection between ossicles was made using contact formulation. The obtained results on the eardrum, considering different acoustic pressure values, are compared with the results of the model without ligaments.

1 INTRODUCTION

Several persons suffer of hearing loss which reflects a serious health public problem.

There are a few different types of hearing loss: conductive, sensoryneural and mixed (conductive and sensory combined).

The conductive hearing loss happens when there is a problem with a part of the outer or middle ear, which is often mechanical in nature and often, can be corrected by medicine and/or surgery. There are various causes for conductive hearing loss, including otitis media, perforated eardrum, ear wax, and Otosclerosis. At Otosclerosis, the hearing loss results from fixation of the stapes, so that sounds cannot be transported to the inner ear. The correction can be made by improving the application of mechanical prosthesis to replace the stapes, by surgery, to guarantee wave sound travel. The sensory hearing loss happens when the cochlea is not working correctly because the tiny hair cells are damaged or destroyed, or there is a problem with the connection from the cochlea to the brain, the auditory nerve.

It is pertinent to analyse the sound wave travel in the middle ear and its modulation nearly of real.

In order to study the implementation of prosthesis, it is very important to achieve a correct modelling of the vibro-acoustic behaviour of middle ear.

In this work, a finite element modelling of the middle ear was made. For this propose, the study started with an approximate 3D solid model of the ossicles and eardrum for a normal ear. The discretization of these components was made using tetrahedral solid elements. The numerical simulation was achieved with the ABAQUS program, with the mechanical properties available in the literature[1,2]. The connection between ossicles was made using contact formulation. We considered two ligaments of incus (superior and posterior) and three of malleus (superior, lateral and anterior). The results are compared with other models previously presented in which the ligaments are absence[3].

2 ANATOMO-PHISIOLOGIE OF THE EAR

The ear is the organ of hearing. Hearing is a series of events in which the ear converts sound waves into electrical signals and causes nerve impulses to be sent to the brain where they are interpreted as sound.

The ear has three main parts: the outer, middle, and inner ear. The outer ear is divided by the auricle and external auditory canal. The middle ear is an air-containing space, which is normally sealed laterally by the eardrum, and has three small bones, (the malleus, the incus, and the stapes) which are involved in sound conduction. Sound is collected by the auricle and directed through the outer ear canal. Air molecules under pressure cause the tympanic to vibrate. Low frequency sound waves produce slow vibrations and high frequency sounds produce rapid vibrations. These move the ossicles and cause vibration of the *oval window*.

The vibration is transferred to the snail-shaped cochlea in the inner ear; the cochlea is lined with sensitive hairs which trigger the generation of nerve signals that are sent to the brain.

3 BUILDING THE WORKING FINITE ELEMENT MODELLING

3.1 Geometric and finite element mesh modelling

Based in the work of Anson e Donaldson[4], the geometry of small bones of the middle ear (malleus, incus and stapes) and the eardrum were achieved. The solid modelling software used was SolidWorks program. After this, the finite element mesh of the middle ear ossicles was carried out, including the ligaments (figure 1).

The elements of the ossicles and eardrum are tetrahedral, with four nodes, like C3D4. Linear bars, like T3D2, model the ligaments and the stapedius annular ligament. The model has 124672 elements and 30418 nodes in the total.

3.2 Material Properties

Based in the work of Sun et al [2], it is reasonable to assume linear material properties for the middle ear system. The Poisson's ration was assumed equal to 0.3 for all materials.

Three ossicles were modelled with linear elastic isotropic behaviour, with a Young's modulus equal to 14.1 GPa.

Materials of the eardrum were assumed to have a Young's modulus of 10 GPa in the pars flaccida and of 20 GPa in the pars tensa. To the ligaments a Young's modulus of 2 GPa was used.
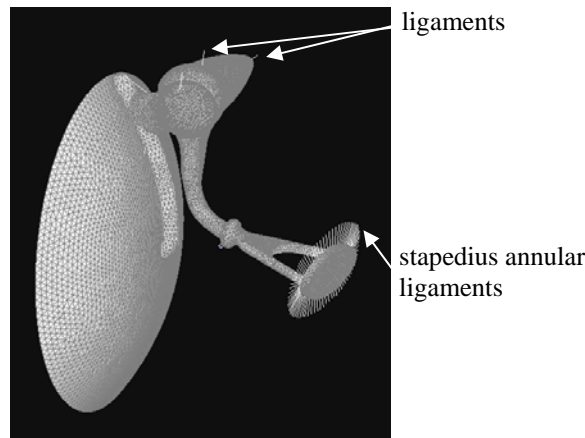

Figure 1: Finite Element Model of the middle ear ossicles, eardrum and ligaments.

3.3 Boundary conditions and contact

Boundaries of the finite element model include tympanic annulus, stapedius annular ligament and suspensory ligaments (anterior, superior and lateral of malleus and posterior and superior of incus). Connections between the malleus/incus and incus/stapes were modelled by contact elements, with friction rate equal zero.

3.4. Applied Load

The simulation was carried out with an applied uniform sound pressure corresponding to a 90 dB SPL (Sound Pressure Level). The sound pressure level[5] can be defined by:

$$SPL = 20 \log(p/p_0) \qquad (1)$$

Where $p_0 = 20$ μPa is the reference sound pressure, which is the audibility threshold.
Thus, 0.632 Pa of pressure is applied to the eardrum.

4 RESULTS

The displacement field in the normal direction to the eardrum is presented in the figure 2. There are differences both displacement distribution and maximum values. The greater distribution in the model without ligaments[3] occurs in the pars flaccida of eardrum, while in the model with ligaments occurs in the incus. The maximum value in the first model is 1.54E-05 and in the second is 5.08E-04. As for the efforts of stapes cruras, both models present compression efforts but it is greater in the model with ligaments.
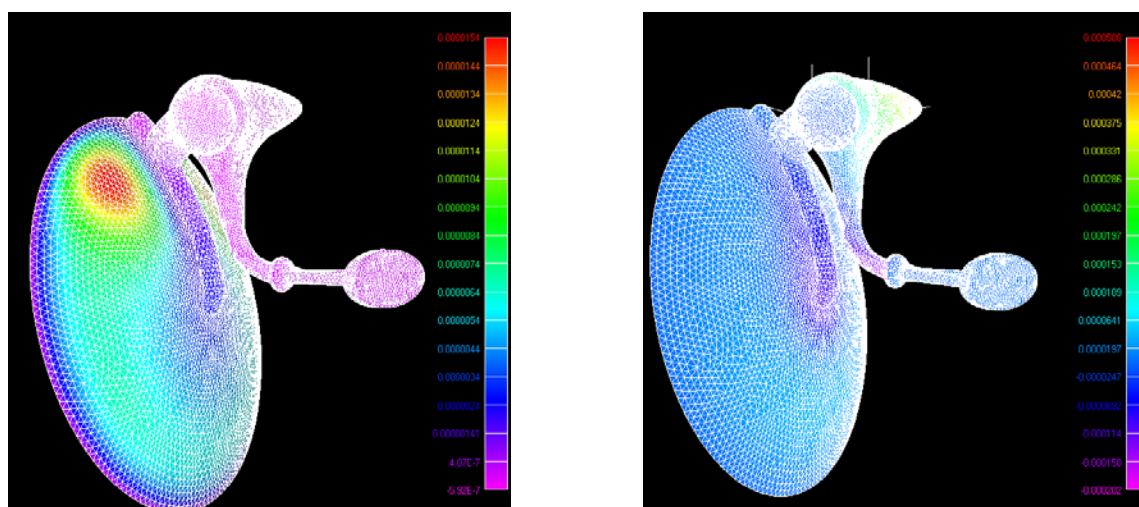
Figure 2 Displacements for two models: without (left) and with (right) ligaments.

5 CONCLUSIONS

In this paper the results of mechanical behaviour of the middle ear between two distinct models are compared. One, without ligaments (of the malleus and incus) and another with five ligaments to the outside of ossicular chain. In the both, the union between malleus / incus and incus / stapes are made by contact formulation. For the pressure applied in the eardrum the results of the two models are compared, and we can see significant differences in the displacements and stapes cruras efforts, presenting greater efforts in the model with ligaments.

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