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The Influence of the Eardrum Perforations on the Dynamic Behaviour of the Human Middle Ear

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Summary

The ear can be divided anatomically, into three parts: external, middle, and inner ear. The eardrum separates the external from the middle ear. The perforation of the eardrum can result in conductive moderate hearing loss.

In this work, we intend to study the influence of eardrum perforation considering a finite element model of the middle ear, based in imagiology. The model includes all different ligaments and muscles with hyperelastic behaviour [1] using the Yeoh model [2]. The mechanical properties available in the literature are considered [3], [4]. The connection between ossicles is done, using contact formulation, which can be interpreted as a simulation of capsular ligaments.

With this purpose, a dynamic study using the ABAQUS program [5] is presented.

The eigenvalues are carried out. Considering sound pressure level of 100 dB SPL the obtained results for different sizes of eardrum perforations are compared with the results of normal eardrum.

keywords: Biomechanical, Finite element method, Middle ear, Eardrum perforations.

Introduction

Hearing refers the ability to hear sounds. The eardrum (Figure 1) is an ovoid and translucent membrane which is positioned obliquely at the external auditory canal. It is formed by three layers: the external epithelial, the middle fibrous (that gives the mobility to the eardrum) and the inner mucosal [6]. It's, also, divided in *pars tensa* (lower 4/5) composed by these three layers and *pars flaccida* (upper 1/5) having only the epithelial and mucosal layers. The eardrum is very thin (about 0.1 mm) receiving and transferring vibrations through the ossicles of middle ear (malleus, incus and stapes) to the inner ear. The malleus is attached to the eardrum and the portion that corresponds to the end of handle of malleus is known as umbo.

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Sometimes occurs the perforation of the eardrum (Figure 1) resulting from infection, trauma, explosion, loud noises, changes in air pressure or blocked Eustachian tubes. Perforations may heal in a few weeks, or up to a few months, with or without medication, but some of them require surgery intervention (tympanoplasty). In these cases hearing is usually recovered, but chronic infection, over a long period, may lead to permanent hearing loss.

A finite element model of the eardrum and the ossicles, based in imagiology, was made. The discretization of this 3D solid model was made using the ABAQUS program [5]. The mechanical properties are available in the literature [3], [4]. The connection between ossicles was made using contact formulation. The hyperelastic behaviour of the ligaments and muscles are considered and the properties are taken in account [1].

Looking for understanding the perforation eardrum behaviour, a dynamic study, considering eigenvalues and umbo and stapes footplate displacements were done.

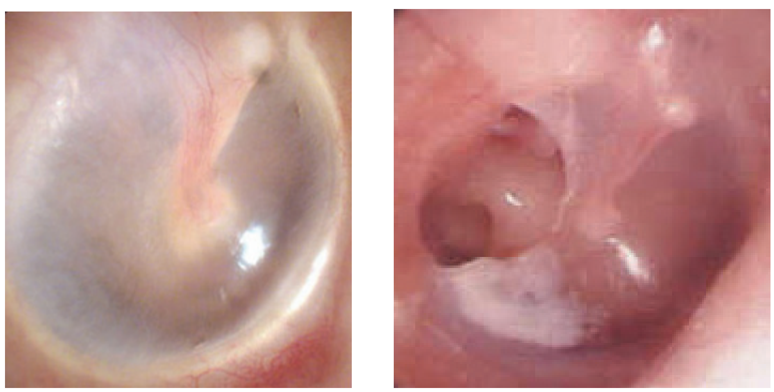


Figure 1: A normal and perforated eardrum, respectively.

Materials and Methods

Based in imagiology, the geometry of the eardrum and the middle ear ossicles were done. Then, the finite element mesh was carried out, including the ligaments and muscles. The elements of the eardrum are hexahedral with eight nodes, and the ossicles are discretized by tetrahedral elements with four nodes. Linear elements model the ligaments and muscles. The cochlear fluid is modelled with fluid elements, supposing unchanged volume conditions. The complete model has 72150 elements and 22879 nodes (for the model without perforations).

The material properties for the middle ear system are considered [4]. The Poisson's ration was assumed equal to 0.3 for all materials. Three ossicles were modelled with elastic behaviour, isotropic 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*. For the dynamic analysis purpose, we used the following values for density [4]: Eardrum (1.2E+03), Malleus (head: 2.55E+03; neck: 4.53E+03; handle: 3.70E+03), Incus (body: 2.36E+03; short process: 2.26E+03; long process: 5.08E+03) and 2.20E+03 for the stapes.

Based on Yeoh model [2], hyperelastic behaviour of the ligaments and muscles is also taken into account [1]. The strain-energy function ψ for this material model is given by:

$$\psi = c_1 (I_1 - 3) + c_2 (I_1 - 3)^2 + c_3 (I_1 - 3)^3 \quad (1)$$

where c_1, c_2, c_3 are material constants (presented in the Table 1 for each component), and I_1 is the first right Cauchy-Green tensor invariant.

Connections between the ossicles, malleus/incus and incus/stapes were modelled by contact formulation available in ABAQUS [5] with friction rate equal 0.9 [7].

Boundaries of the finite element model include tympanic annulus, stapedius annular ligament and suspensory ligaments (superior and anterior of malleus and posterior and superior of incus).

Table 1: Material constants [1] for ligaments and muscles (Yeoh model).

Ligaments and muscles constants		c_1	c_2	c_3
Malleus	- superior	4.0E+3	2.2E+3	-1.0E+3
	- anterior	4.0E+3	7.6E+4	-1.2E+4
	- lateral	4.0E+3	2.7E+3	-1.0E+3
Incus	- superior	4.0E+3	2.2E+3	-1.0E+3
	- posterior	0.0	4.0E+4	-1.4E+4
Stapes	- annular	9.0E+2	4.5E+4	-3.0E+4
Tensor tympanic muscle		1.4E+4	8.5E+4	-1.0E+4
Stapedius muscle		1.4E+4	8.5E+4	-1.0E+4

Simulations of three eardrum perforations were made (Figure 2). The first one with 0.6 mm of diameter corresponds to a needle insertion. This micro perforation may heal in a few hours. The second one with 2 mm can be obtained by trauma or post otitis media and can heal spontaneously or with help of medicine in a few weeks. The last one, the bigger, can result from chronic otitis only healing by surgery (tympanoplasty) looking for eardrum reconstruction.

Results and Conclusions

The first 20 eigenvalues (Table 2) were obtained for the normal eardrum and for the three perforations. The results allow us to conclude that there aren't significant differences between them. Only for some of the highest eigenvalues we can found little differences for the bigger perforation.

Considering the umbo and stapes footplate displacements a dynamic study is

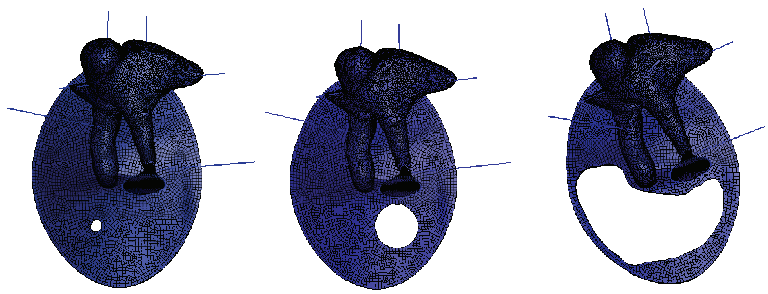


Figure 2: The three different sizes of perforated eardrum.

Table 2: The first 20 eigenvalues for normal and perforated eardrums.

	Normal	Small	Middle	Bigger		Normal	Small	Middle	Bigger
1	602,98	601,70	592,90	537,27	11	2605,40	2590,90	2546,30	2537,30
2	825,84	825,82	825,08	802,80	12	2694,80	2685,50	2635,80	2614,40
3	933,25	932,98	931,54	883,43	13	2720,80	2719,90	2716,10	2690,70
4	1273,70	1265,80	1210,60	1172,00	14	2810,20	2796,30	2741,90	2798,60
5	1900,70	1905,60	1892,40	1939,80	15	2884,50	2882,70	2874,40	2978,90
6	2153,50	2152,70	2061,30	2062,00	16	3137,70	3133,70	3073,70	3100,40
7	2194,30	2197,90	2182,80	2090,90	17	3228,00	3223,60	3183,60	3369,40
8	2227,40	2227,30	2244,30	2263,00	18	3357,40	3367,10	3404,40	3429,10
9	2403,80	2398,10	2401,40	2354,70	19	3432,70	3439,40	3489,20	3635,30
10	2414,60	2407,30	2496,90	2402,40	20	3603,60	3598,80	3675,50	3795,50

presented. Appling 2 Pa acoustic pressure value (100 dB SPL), the results obtained, for three different sizes of perforations are compared with the results of the normal eardrum.

For the umbo displacement (Figure 3) there are not differences between normal eardrum and a small perforation. If we compare the normal eardrum with the perforation with 2 mm, we can see that the perforated eardrum has fewer displacements for the middle frequencies. Significant differences occur for the bigger perforation and for low and middle frequencies, having the perforated eardrum fewer displacements.

For the stapes footplate displacement (Figure 4) we can also verify that there are not differences between normal eardrum and small perforation. For the middle perforation there are only little differences (not significant) for low and middle frequencies. Significant differences occur on low frequencies for the bigger perforation.

These results are in compliance with our clinical practice. We can conclude that the stapes footplate displacements can be related with hearing loss. Microperforations, usually, aren't associated with hearing loss (Figure 5-a)). By the other side, big perforations can result in low frequencies hearing loss, as it can be seen in

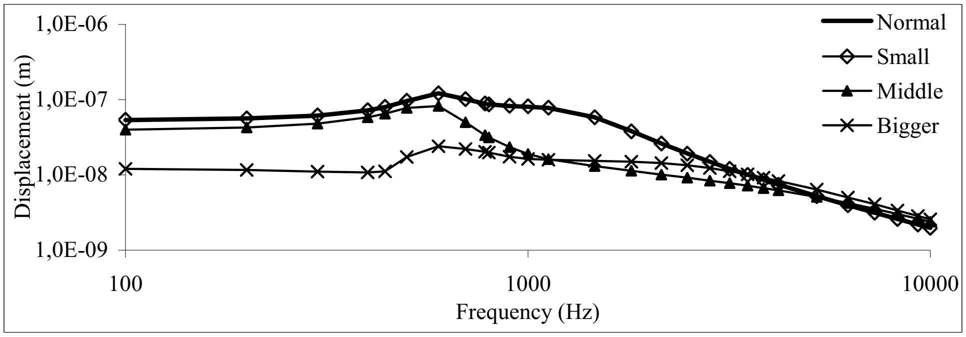


Figure 3: Umbo displacement for normal and perforated eardrums.

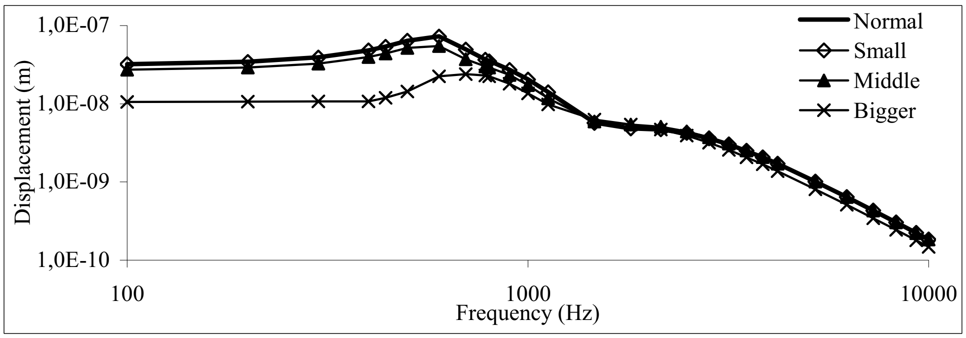
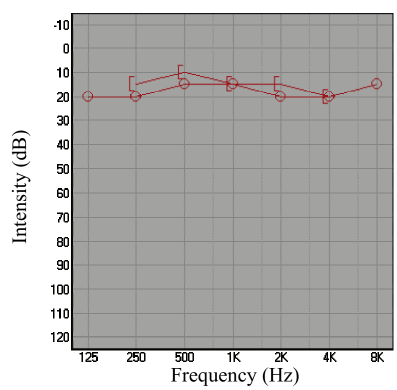
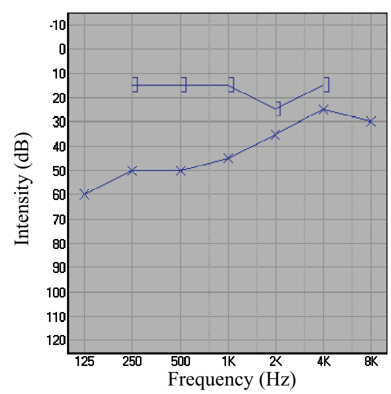


Figure 4: Footplate displacement for normal and perforated eardrums.

the Figure 5-b).



a)



b)

Figure 5: Audiogram: right ear, normal (a); left ear, conductive hearing loss (b).

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