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Journal of Biomechanics ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Journal of Biomechanics

journal homepage: www.elsevier.com/locate/jbiomech
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Effects of the fibers distribution in the human eardrum: A biomechanical study

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ARTICLE INFO

Article history:
Accepted 17 March 2016

Keywords:
Biomechanics
Finite element method
Eardrum quadrants
Eardrum fibers

ABSTRACT

The eardrum separates the external ear from the middle ear and it is responsible to convert the acoustical energy into mechanical energy. It is divided by *pars tensa* and *pars flaccida*. The aim of this work is to analyze the susceptibility of the four quadrants of the pars tensa under negative pressure, to different lamina propria fibers distribution. The development of associated ear pathology, in particular the formation of retraction pockets, is also evaluated. To analyze these effects, a computational biomechanical model of the tympano-ossicular chain was constructed using computerized tomography images and based on the finite element method. Three fibers distributions in the eardrum middle layer were compared: case 1 (eardrum with a circular band of fibers surrounding all quadrants equally), case 2 (eardrum with a circular band of fibers that decreases in thickness in posterior quadrants), case 3 (eardrum without circular fibers in the posterior/superior quadrant).

A static analysis was performed by applying approximately 3000 Pa in the eardrum. The *pars tensa* of the eardrum was divided in four quadrants and the displacement of a central point of each quadrant analyzed. The largest displacements of the eardrum were obtained for the eardrum without circular fibers in the posterior/superior quadrant.

1. Introduction

The tympanic membrane, is a thin piece of tissue that separates the external ear from the middle ear. The acoustical energy is here transformed in mechanical energy and transmitted to the three ossicles of the middle ear. The tympanic retraction pockets are an ear disorder whose pathophysiology is still not completely understood. The retracted segment of eardrum is often known as a retraction pocket. The pathology occurs in 40% of cases in the *pars flaccida* (the flaccid portion of the tympanic membrane, located in the upper portion of the eardrum, which shows more fragility, due to the lack of the fibrous middle layer, present in the *pars tensa*) and in 36% of cases in the posterior/superior quadrant of the *pars tensa* (Paço et al., 2009). Otalgia is occasionally a feature and is due to changes in middle ear pressure or infection. The hearing loss is typically conductive in nature. Several factors are important in the formation of this pathology, including Eustachian tube dysfunction Danner (2006) and structural changes to the membrane, secondary to repeated bouts of inflammation (Ruah et al., 1992). Three factors must occur for the eardrum to become retracted: (i) negative middle ear pressure; (ii) weakness of the eardrum and (iii) increase in surface area of the eardrum (Ikeda et al., 2011). The first factor can result from an inadequate opening of the Eustachian tube, the pressure within the middle ear can be less than atmospheric pressure and the eardrum can become sucked into the middle ear space. The second one can be related with weakness of the middle layer of the pars tensa in the postero-superior quadrant, or alternatively, after the perforation by grommet, predisposing these areas to retraction. The third factor, associated with an unusual development of new cells on the surface of the eardrum, which migrate over the surface and move out along the ear canal. This process of proliferation and migration can result in increase of a retraction pocket. Most common complaints are infected pockets causing otorrhea and conductive hearing loss and can reach up to 45–55 dB in some cases. Progressive retraction of pars tensa may cause the atrophic membrane to drape over the incus and stapes, often resulting in necrosis of these ossicles. It is usually regarded to be a

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http://dx.doi.org/10.1016/j.jbiomech.2016.03.030
0021-9290/

Please cite this article as: Gentil, F., et al., Effects of the fibers distribution in the human eardrum: A biomechanical study. Journal of Biomechanics (2016), http://dx.doi.org/10.1016/j.jbiomech.2016.03.030

sequel of chronic otitis media with effusion. A small portion of these retraction pockets may progress and become cholesteatoma. Surgical treatment includes resection of the eardrum. The most common sites of retraction pockets are *pars flaccida* and postero-superior parts of the eardrum (Ars, 1991). Diagnosis is entirely clinical and requires a visual examination of the tympanic membrane. As part of an assessment of a patient with a tympanic membrane retraction, audiometric evaluation with a pure tone audiogram and tympanometry is usually performed. Surgery should be performed to prevent cholesteatoma formation.

In studies of the temporal bone, Paço et al. (2009) found some anatomical aspects that may be related to a greater susceptibility of this quadrant to pressure changes. One of the factors mentioned was a different constitution of the lamina propria in different quadrants. According to Paço (2003), although the radial fiber layer remains the same for all quadrants, the circular fiber layer is always distributed in the periphery and differentially in the various quadrants. The same study identified three possible scenarios: in 45% of cases the circular fibers involve all quadrants, in 30% of cases the band decreases in thickness in posterior quadrants and in 25% of cases circular fibers are not identified in the posterior/superior quadrant.

The aim of this work is to analyze, based on the finite element method, the effects of the distribution of the fibers of the lamina propria, namely the susceptibility of the four quadrants of the *pars tensa* to negative pressure. It will be investigated the influence of this aspect on the development of ear pathologies, particularly the retraction pockets.

2. Material and methods

In this study, a geometric model of the tympano-ossicular chain (Gentil et al., 2011) was used to model the middle ear. The eardrum was adapted (Garbe et al., 2009, 2010) to the dimensions described in the study of Paço (2003). It was divided (topographically) into six quadrants. The *pars tensa* is composed by four quadrants: posterior/superior, posterior/inferior, anterior/superior and anterior/inferior. The *pars flaccida* is composed by the remaining two quadrants. After this division, a representative node was chosen from the finite element mesh (Fig. 1) for each quadrant and the displacements for each node were analyzed.

Fig. 2 shows the dimensions of the eardrum model. The height of the eardrum (vertical axis) is 9.7 mm. This is the distance that separates the upper and lower limits along the malleus. The width of the eardrum (horizontal axis), determined as the transversal distance at the umbo, is 8.8 mm. The eardrum has an elliptical shape (Fig. 2a).

Taking into account the dimensions of the *pars tensa*, the umbo was taken as the reference region. The distance from the umbo to the anterior edge of the eardrum is 3.9 mm. The distance from the umbo to the posterior edge of the eardrum is 5.2 mm, and from the umbo to the eardrum lower edge is 4.3 mm (Fig. 2b).

Regarding the dimensions of the *pars flaccida*, the anterior part has a value of 1.6 mm. The dimension of the posterior part is approximately the double of the previous, with an average of 3.0 mm. The height of the *pars flaccida* has a value of 1.7 mm (Fig. 2c).

The discretization of the model was made using ABAQUS software (Hibbit et al., 2004), starting with the discretization of the eardrum and then the ossicles.

The eardrum was discretized using three-dimensional hexahedral elements of eight nodes, of type C3D8, and divided into two parts: the *pars flaccida* (located at the top and representing 10% of the eardrum total area, approximately) and the *pars tensa* (responsible for the vibration of the eardrum and representing near 90% of eardrum total area).

The *pars tensa* of the eardrum was considered to be divided into three layers (Garbe et al., 2009) according to its anatomy: layer 1, the external; layer 2, the intermediate; layer 3, internal. From the biomechanical point of view the intermediate layer is very important because it is primarily responsible for the stiffness of the eardrum, with radial and circular fibers. The inner layer is continuous with the mucosa of the middle ear, and the external one continues into the external auditory canal.

The intermediate layer of the eardrum has two planes of fibers: an external, located in contact with the epidermis which is composed of radial fibers available, and another, arranged in contact with the mucosa that consists of circular fibers. The radial fibers are found throughout the surface of the *pars tensa*, since the circular fibers are away from the umbo. The plane of radial fibers radiates its fibers, beginning from the malleus to the periphery of the eardrum. The distribution of radial fibers in every quadrant is identical (Paço et al., 2009).

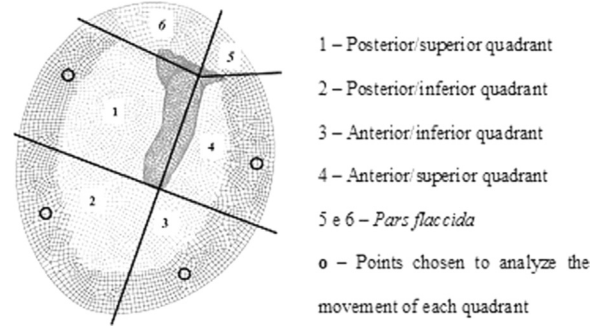

Fig. 1. External face – eardrum and respective quadrants.

The plane of circular fibers is available from within the radial fibers. According to Paço (2003), the distribution of circular fibers occurs in three different ways (Fig. 3): Case 1 represents the eardrum with a circular band of fibers surrounding all quadrants equally; Case 2 represents the eardrum with a circular band of fibers that decreasing in thickness in posterior quadrants; Case 3 represents the eardrum without circular fibers in the posterior/superior quadrant.

The properties of the eardrum were set according to their anatomy. The *pars flaccida* is always considered in the same way, isotropic elastic. For the *pars tensa* (Table 1) different properties were used for each layer. The central layer properties were characterized by different types of fibers distribution. The material properties were based on previous works, where E is the Young's modulus, the index θ indicates circular direction and $r$indicates radial direction. The Poisson's ration is assumed equal to 0.3 for all materials and the damping coefficients as $\alpha = 0\ s^{-1}$ and $\beta = 0.0001$ s (Prendergast et al., 1999; Sun et al., 2002). The density of the eardrum is 1.20E+03 Kg/m^3.

For the discretization of the ossicles, tetrahedral elements of type C3D4 were chosen, instead of hexahedral as in the eardrum. This takes into account the strongly irregular geometries of the ossicles.

The ossicles were divided into regions according to their properties. The malleus was divided into three parts (head, neck and handle); the incus (body, short process and long process); for the stapes, the same properties were applied to its constituent parts (head, neck, anterior and posterior cruras and stapes footplate). The ossicles are assumed as having isotropic behavior, with linear elastic properties obtained from literature (Ferris and Prendergast, 2000; Sun et al., 2002). The Young's modulus of all ossicles of the middle ear was considered 1.41E+10 Pa. The density varies according to the constituent parts of the ossicles themselves.

The simulation of the joints between the ossicles, malleus/incus and incus/stapes were made through mathematical formulations representative of contact (Wriggers, 2002), with a friction coefficient equal to 0.9 (Gentil et al., 2007).

The group formed by the three ossicles (malleus, incus and stapes) is attached on the outside to the eardrum and inside to the oval window by the stapes footplate.

Based on the Yeoh model (Yeoh, 1990), the present work uses hyperelastic non-linear behavior for the ligaments (Gentil et al., 2006, 2011; Holzapfel, 2000) being the Hill model (Martins et al., 1998) used for the muscles (Gentil et al., 2013).

Related to the boundary conditions, the eardrum is constrained in order to simulate the tympanic sulcus. Anatomically, the *pars flaccida* is free. The *pars tensa* is attached at its periphery and in the posterior/superior quadrant the eardrum was constrained in layer 3. In other quadrants the eardrum was fixed in layer 1 and layer 3, using the nodes shown in the scheme of Fig. 4.

The ossicles are suspended by ligaments and muscles to the tympanic cavity walls. The malleus is attached by the superior, lateral and anterior ligaments and the tensor tympanic muscle; the incus by the superior and posterior ligaments; the stapes by the stapedius muscle and surrounding the periphery of the stapes footplate, 78 bar elements were fixed, simulating the annular ligament.

To analyze the retraction pockets formed in the pars tensa a static analysis was performed by applying 3000 Pa in the eardrum. With the sole objective of analyzing the influence of different types of fibers distribution in the eardrum central layer on the behavior of the eardrum (umbo), the simulations were carried out applying a uniform sound pressure level (SPL) of 70 dB SPL in the eardrum. The frequency range investigated covers the interval of 100 Hz to 10 kHz (the audibly range).

3. Results

To simulate an internal pressure in the tympani cavity, a pressure of 3000 Pa was applied in the eardrum and a static analysis was performed allowing to obtain the displacements of the eardrum. Fig. 5 shows these displacements of a central point of the posterior/superior, posterior/inferior, anterior/inferior

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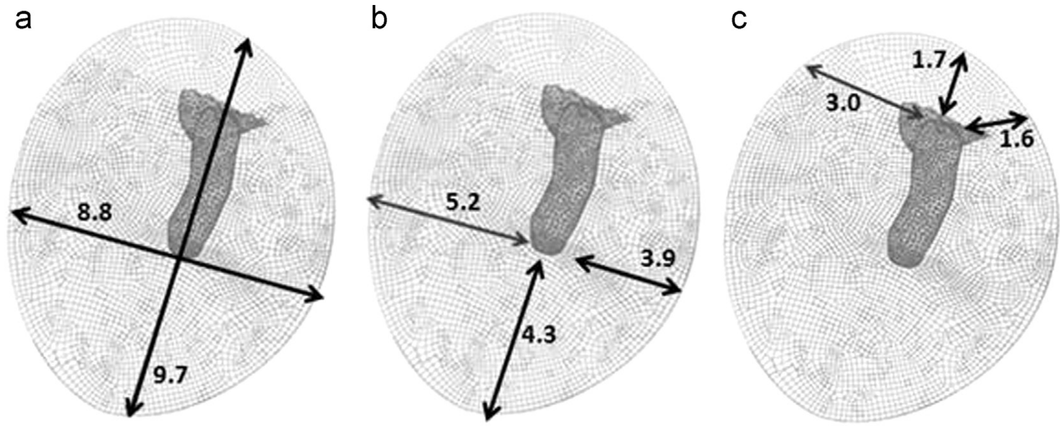

Fig. 2. Dimensions of eardrum in reference to the handle of the malleus, in mm.

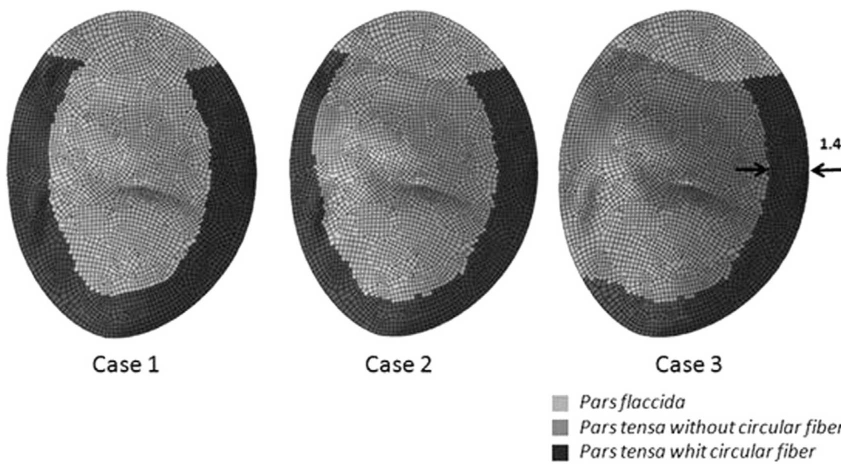

Fig. 3. External face – *pars flaccida* and *pars tensa* for Case 1 (eardrum with a circular band of fibers surrounding all quadrants equally), Case 2 (eardrum with a circular band of fibers that decreasing in thickness in posterior quadrants) and Case 3 (eardrum without circular fibers in the posterior/superior quadrant).

Table 1
Some material properties of *pars tensa* of the eardrum.

Material properties							
Layers		**Density**	**Model**		**Poisson's ratio**	**Young's Modulus (N/m^2)**	
Pars tensa						$E(\theta)$	$E(r)$
Layer 1		1.20E+03	Elastic	Isotropic		1.00E+07	
Layer 2	With circular fibers	1.20E+03	Elastic	Orthotropic	0.3	2.00E+07	3.20E+07
	Without circular fibers	1.20E+03	Elastic	Orthotropic	0.3	0.50E+07	3.20E+07
Layer 3		1.20E+03	Elastic	Isotropic	0.3	1.00E+07	

and anterior/superior quadrants of the eardrum (according to the scheme presented in Fig. 1), for the three fibers distribution cases considered, and with the eardrum without any particular fibers distributions. The biggest displacements occur in the posterior/superior quadrant and the smallest on the anterior/superior one.

Thereafter, a dynamical study was made and the frequency range was considered between 100 Hz and 10 kHz. The sound pressure level applied in the eardrum was 70 dB SPL for all results. For the analysis of the results, the displacements obtained in four frequencies of that range (100, 782.8, 1807 and 9659 Hz) were registered and their differences were checked. Fig. 6 shows these displacements of a central point of each quadrant of the eardrum for the three fibers distributions cases considered, and with the eardrum without distribution of fibers. In all results, on average, it was consistently observed that the displacements obtained with the eardrum without distribution of the fibers have lower amplitude than the fibered cases. The major differences occurred in two posterior quadrants, not showing significant differences in two anterior quadrants comparing the 3 cases described. In the case where the central layer of the eardrum lacks the range of circular fibers (case 3), the posterior/superior quadrant has greater mobility when compared with the other cases. We can also observed that displacements decrease for higher frequencies.

Fig. 7 shows the displacements of the umbo for all analyzed cases. Despite the displacements in each of the quadrants, in the three considered cases, are different, for the umbo the results obtained are very similar. It may be concluded that the transmission of energy for the considered eardrum fibers distribution does not interfere with the middle ear ossicles movement.

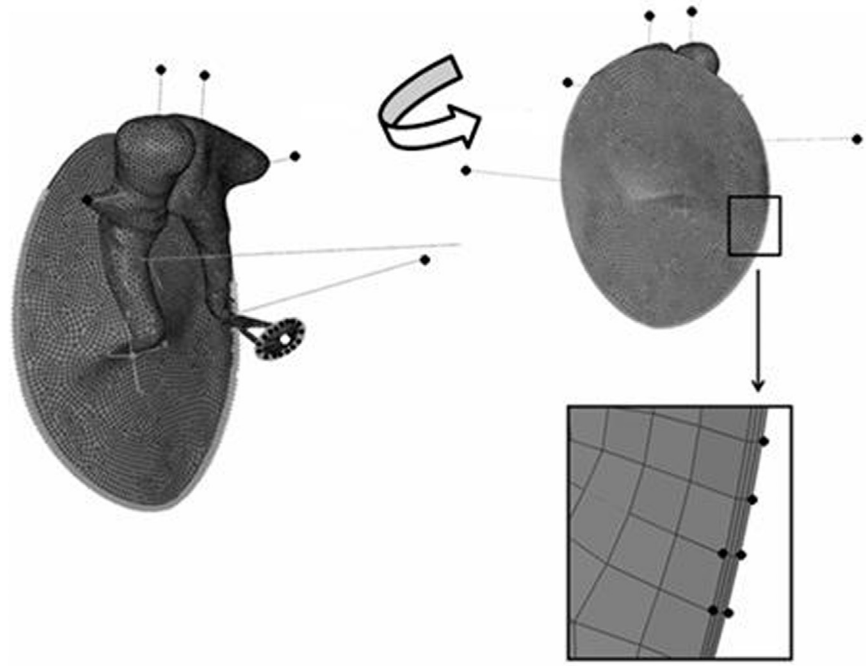

Fig. 4. Detail of the boundary conditions in the eardrum.

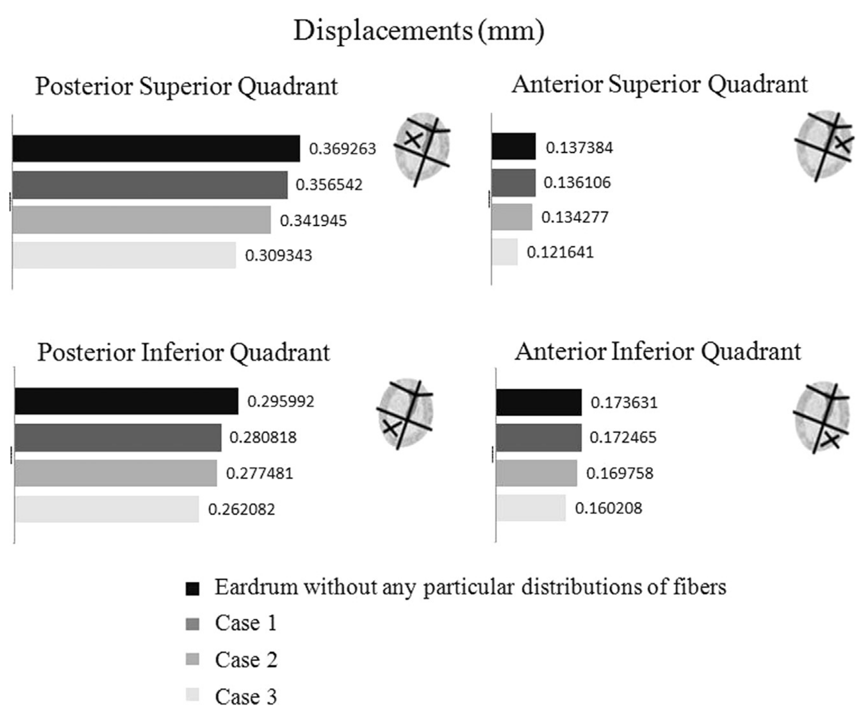

Fig. 5. Displacements of eardrum quadrants (3000 Pa), with Cases referred in Fig. 3.

4. Discussion

In all results, it was consistently observed that the displacements obtained with the eardrum without any particular distribution of the fibers have lower amplitude than the cases with fibers distribution was considered (Fig. 6).

The major differences occurred in two posterior quadrants, not showing significant differences in two anterior quadrants comparing the 3 cases described (Fig. 5).

It can be observed an increased order of magnitude of the eardrum displacements, as (Case 1) < (Case 2) < (Case 3) (Fig. 3). In the case where the intermediate layer of the eardrum lacks the range of circular fibers (Case 3), the posterior/superior quadrant has greater mobility when compared with the other cases. The movement of the eardrum in Case 1 and Case 2 is 92% and 96% of Case 3. The eardrum of Case 2 has higher mobility than on Case 1 (Fig. 6).

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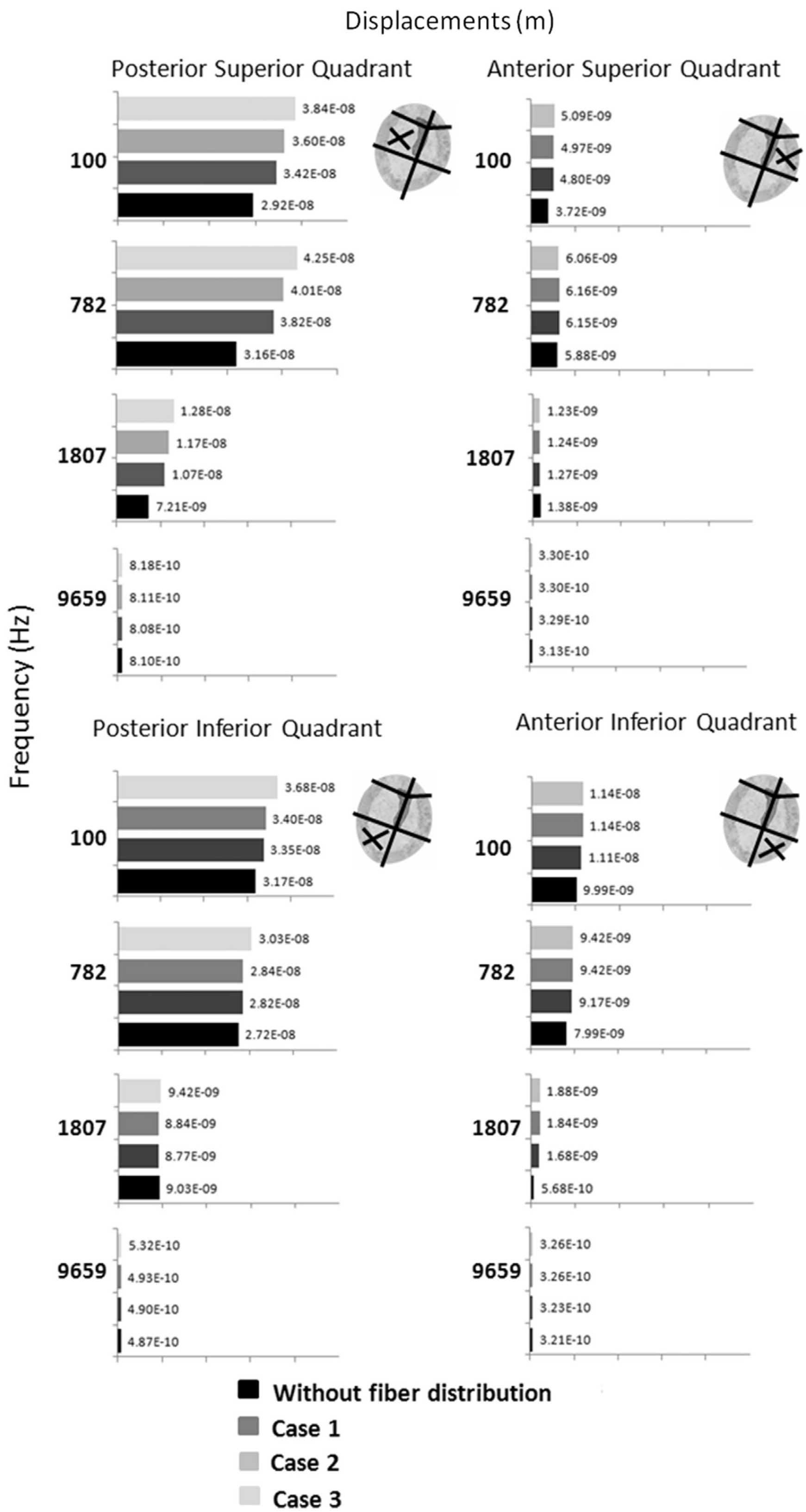

Fig. 6. Displacements of eardrum quadrants, for different frequencies, when 70 dB SPL is applied in the eardrum.

We have found that regardless of the composition of the lamina propria the posterior/superior quadrant suffered the greatest displacement with the application of negative pressure, which can be attributed to its largest size. Furthermore, it was also observed that the fewer the circular fibers, the greater the eardrum displacement.

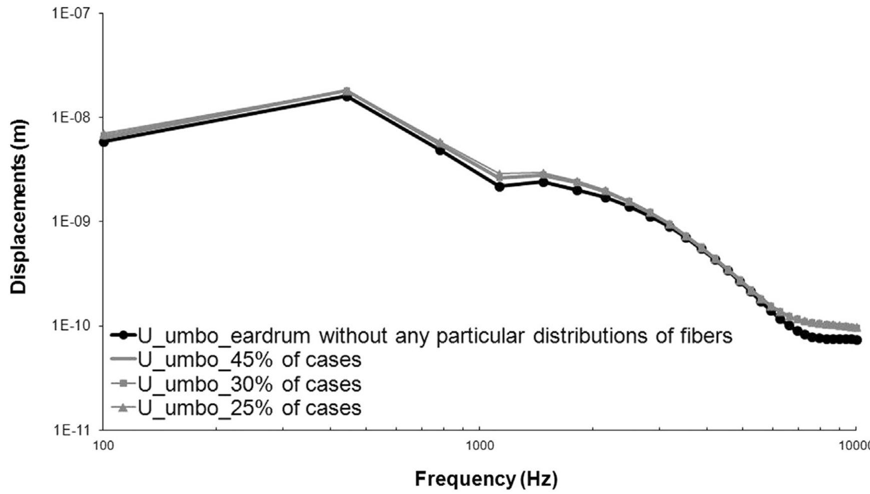

Fig. 7. Displacement of the umbo (70 dB SPL), comparing the eardrum without fibers distribution with 3 different cases considered.

Since the posterior/superior quadrant shows great variation in this aspect and may even present a lack of circular fibers in 25% of the population, this quadrant is inevitably more susceptible to the development of pathology related to pressure changes, including retraction pockets, as is observed clinically.

This study allows us to identify a group of patients more prone to developing this pathology, explaining the higher incidence of retraction pockets on the posterior/superior quadrant compared with the other quadrants of the *pars tensa*.

It also contributes to validate the finite element method to study the pathophysiology of human middle ear, opening a range of possibilities for simulation on future studies.

5. Conclusion

The transmission of energy for the considered eardrum fibers distribution does not interfere with the middle ear ossicles movement, since the displacements of the umbo are similar.

Comparing the 3 cases, the major differences occur in the two posterior quadrants and no significant differences are present in the two anterior quadrants.

Regarding the composition of the lamina propria the posterior/superior quadrant suffer the greatest movement for a negative pressure, which can be attributed to its largest size. It should also be noted that as a result of this investigation, it was seen that the fibers distribution has a significant importance on the formation of retraction pockets.

Conflict of interest

The authors declare that they do not have conflict of interest.

Acknowledgment

The authors acknowledge the funding of the Project UID/EMS/50022/2013 of LAETA, from Fundação para a Ciência e Tecnologia (FCT) of Ministério da Educação e Ciência, Portugal and the support of FCT and Fundo Social Europeu (FSE) under programs POPH-QREN and Grant SFRH/BPD/71080/2010 and SFRH/BD/108292/2015 are gratefully acknowledged.

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