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Application of a finite element model in the diagnosis process of middle ear pathologies

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Abstract

The ear is a complex organ that can be affected by various pathologies that are still fairly misunderstood. This work tests the possibilities of studying the ear and its pathologies using a virtual environment and thus bypassing expensive and time-consuming clinical trial. A previous validated finite element model of the middle ear was employed to study two pathological states of the middle ear. It was shown that the model obtained results very close to the clinical evaluation thus proving of being a proper tool for further investigations of middle ear pathologies.

Keywords: middle ear, myringosclerosis, eardrum perforation, finite element model of the ear.

Introduction

The tympano-ossicular system constitutes the anatomical basis of sound transmission of the middle ear and is formed by the tympanic membrane, the middle ear ossicles (malleus, incus and stapes), their suspending ligaments and joints and the accommodation muscles (tensor tympani and stapedius muscle). It represents the transmitting mechanism of sound vibrations from the external ear channel to the inner ear. This sound transmitting mechanism can be influenced by different pathologies which can affect its integrity and its mobility. Studies of middle ear pathologies are of great importance to further the accuracy of diagnosis and treatment. Investigation of the human middle ear is usual done by *in vivo* and *in vitro* experiments on temporal bone specimens. These are in many cases time-consuming and expensive. A virtual tool that can be used to model various pathological cases of the ear could help medical research broaden its knowledge of disease without employing a clinical trial, thus being able to obtain results in a less time-consuming and more cost-effective way [1].

To test and follow this hypothesis, two pathologic cases of the eardrum were selected, these were modeled using a previous validated finite element model of the middle ear and otological exams were carried out for both cases in order to compare results.

Tympanosclerosis is a histological process occurring in the mastoid and middle ear mucosa characterized by hyalinization, which may progress to calcification or ossification. Acute, chronic or recurrent inflammation can cause this process of middle ear lamina propria, characterized by progressive infiltrate of fibroblasts, causing an increase in collagen, followed by hyaline degeneration and calcium deposits, which may lead to formation of cartilage or bone. The tympano-ossicular unit can be damaged causing conductive hearing loss. When tympanosclerosis affects only the tympanic membrane, the pathology is called myringosclerosis (MS) [1–3].

Tympanic membrane perforations appear following acute or chronic otitis media where a subsequent inflammation of the middle ear mucosa can occur, creating mucosal edema and afterwards mucosal ulceration and damaging of the epithelial lining [4, 5].

Aim

The aim of this research was the use of a previous validated finite element model of the ear to evaluate two real pathological cases of the eardrum and thus show that a virtual environment is a handy tool to obtain information about a disease without having to undergo expensive and time-consuming clinical trials.

Materials and Methods

Two cases of myringosclerosis were selected for this study: a myringosclerotic plaque in the usual form of arcus senilis affecting an intact eardrum and a myringosclerosis combined with a small perforation in the antero-inferior quadrant. Both cases had no other known underlying pathologies.

An otological exam was carried out, for each of the two selected pathologies, and the resulting otoscopy and audiogram provided the tools to model and evaluate the cases using the Gentil *et al.* finite element model of the ear [6] (Figure 1).

The finite element model consists of all the three ossicles of the middle ear, the eardrum and the simulated cochlea. It also includes the superior, lateral and anterior ligaments of malleus, the superior and posterior ligaments of the incus, the annular ligament of

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the stapes and two muscles, the tensor tympani muscle and the stapedius muscle.

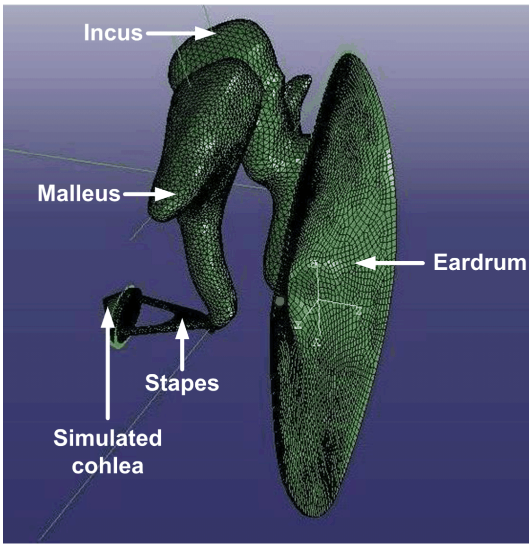

Figure 1 – *Finite element model of the middle ear, Gentil* et al. *[1].*

The eardrum respects the anatomical structure and is formed of two different zones (pars flacida, pars tensa) and the three layers of different material properties such that the inner layer is orthotropic and the outer layers are isotropic.

The incudomallear and incudostapedial joints were simulated using contact formulation. The development of the model, material properties and validation is thoroughly explained in the work of Gentil *et al.* [6].

Using the otoscopy images, the two pathologies were modeled, in ABAQUS finite element software package [7], using a unique method to model MS based on the rule of mixtures for composite materials with uniformly distributed particles. This method has been explained in the work of Berdich [8]. The otoscopy images and the resulting models are shown in Figures 2 and 3.

After modeling of the two pathologies, each model was run in ABAQUS and the results were compared to the before mentioned audiograms. For both pathologies, the sound pressure level used was 80 dB.

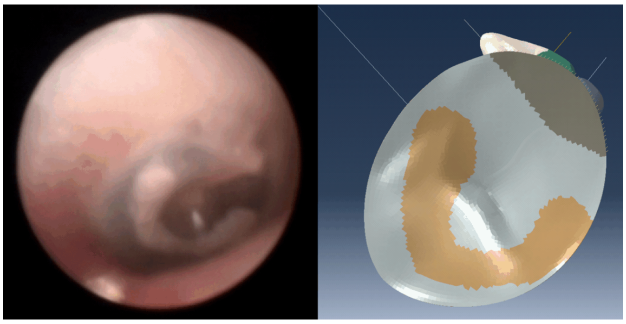

Figure 2 – *Myringosclerosis in the form of arcus senilis: left the otoscopy image and right the model obtained in ABAQUS.*

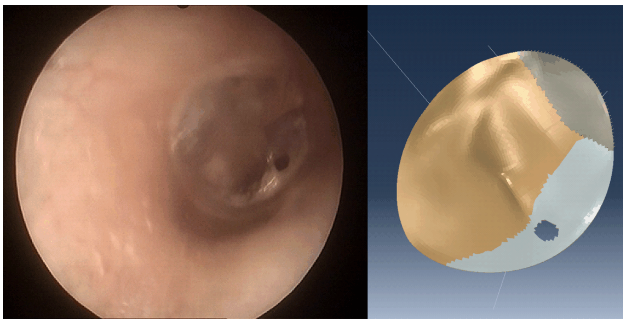

Figure 3 – *Myringosclerosis with perforation: left the otoscopy image and right the model obtained in ABAQUS.*

Results

The resulted displacement of the stapes footplate for each studied case was compared to the audiogram as shown in Figures 4 and 5. The first case presented a myrinogosclerotic plaque in form of an arcus senilis on an intact eardrum. Myringosclerosis is a common finding in many tympanic membranes consisting of irregular white patches generally located around the malleus handle. The pathologic lesion consists of thickening of the lamina propria of the tympanic membrane containing abnormal hyalinized collagen, cartilaginous or calcified deposits. The etiology of tympanosclerosis is not completely understood but it is generally accepted that it follows recurrent inflammation of the middle ear. The etiology is most likely an immune reaction of the lamina propria. Hearing loss is uncommon unless the majority of the tympanic membrane or the ossicular chain is involved. In this case, the pure tone audiogram showed a decrease of hearing in the 0–1000 Hz range of 10 dB. This mild hearing loss was observed also in the result of the finite element model as seen in Figure 4.

The second case is a patient with a chronic otitis media. The lesions on the eardrum consisted in a small perforation in the antero-inferior quadrant and multiple myringosclerotic lesions. It is known that recurrent inflammations of the middle ear during the evolution of chronic otitis media may lead to eardrum perforation and myringosclerotic plaques. This may influence the vibrations of the tympano-ossicular system, affecting hearing. For the myringosclerosis with perforation, a decrease of 20 dB could be registered in both the audiogram and the displacement of the stapes footplate of the finite element model (Figure 5). In this case, the two curves differ greatly above 6000 Hz with a progressive fall of the audiometric curve, in higher frequencies, reaching a 60 dB loss at 8000 Hz in the audiogram. This could be due to other complications of the ear that were not considered when modeling this specific case, like the involvement of the ossicular chain affected by tympanosclerotic deposits.

Discussion

The finite element model of the ear reported by Gentil *et al.* [6] was used to study two diseased middle ears. The first case was a myringosclerotic plaque in the usual form of arcus senilis affecting an intact eardrum, while the second case was myringosclerosis combined with a small perforation in the antero-inferior quadrant.

The myringosclerotic plaques were modeled using the rule of mixture for composite materials and considering the plaques are formed from uniformly distributed particles of hydroxyapatite within an isotropic matrix of normal eardrum tissue as defined for the two outer layers [8]. Thus, the area covered by the myringosclerotic plaque lost its orthotropic properties. Hydroxyapatite was chosen based on the histopatologic findings of Bonnaud [9], Buyanover *et al.* [10] and Doner *et al.* [11] regarding the calcification of myringosclerotic plaques and the good resemblance of hydroxiapatite to bone tissue [12, 13].

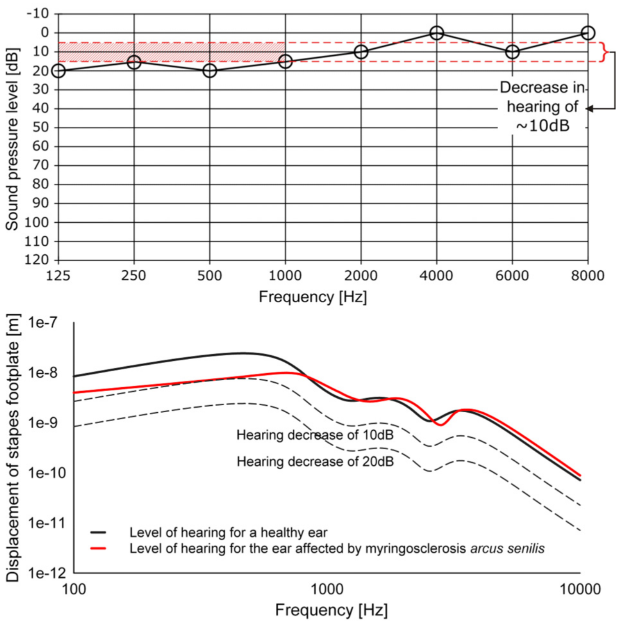

Figure 4 – ***Comparative results showing the same decrease in hearing for the myringosclerosis in the form of arcus senilis: up the audiogram and down the results from ABAQUS.***

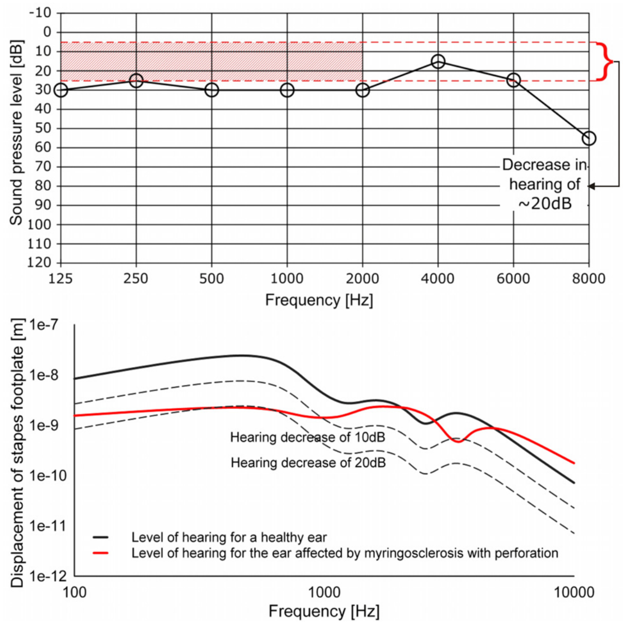

Figure 5 – ***Comparative results showing the same decrease in hearing for the myringosclerosis with perforation: up the audiogram and down the results from ABAQUS.***

Evaluation of the two pathologies using the finite element model showed similar results to the clinical evaluation, thus proving that this model could be engaged as a tool to further analyze pathologies of the middle ear at a greater scale and avoid a clinical trial.

The necessity to remove all of the myringosclerotic plaques from the eardrum during tympanoplastic surgery is still an issue of debate. Studying the influence of myringosclerosis, in the functioning of the tympanic membrane, on finite element models could provide valuable information in this field. Developing an easy to use, very accurate model, that can simulate the dynamics of the tympano-ossicular system, is thus a must for the otorhinolaryngology field and further research needs to be allocated to this goal.

When we analyze the dynamic behavior of biological elements, the finite element method is a powerful tool that makes it possible to model the complicated irregular geometries of biological structures and to understand their dynamics without *in vivo* experiments [14].

During the last decades there were several computer models created, simulating the dynamics of the middle ear elements and also other segments of the human body in the field of biomechanics, *e.g.*, Grecu *et al.* constructed a 3D virtual model of a normal hip joint using the finite element method [15], Tarniţă *et al.* created a three dimensional model of the human elbow joint with the help of finite element method based on CT images [16]. The function of the human middle ear was also studied by Beer *et al.* who constructed a finite element model using 3D measurements of the surfaces of the tympanic membrane and of the auditory ossicles. He studied separately the two components of the middle ear: the eardrum and the ossicular chain and concluded that the human auditory ossicles are elastic bodies, which can be regarded as rigid bodies only in a restricted frequency range, from 0–3.5 kHz [17].

Koike *et al.* also created a three dimensional model of the human middle ear applying the finite element method. He studied the vibration patterns of the tympanic membrane and ossicles, the effect of the middle ear cavities on the tympanic membrane vibration and the characteristics of the pressure transmission in normal and pathologic middle ears [18].

Williams *et al.* developed a finite element model of the middle ear and compared the vibration manner to that found experimentally in animal and human cadaver material and concluded it was similar. He was the first to study different pathologies of the ear by modifying parameters in the model. Still the model was not complete as it did not have suspensory ligaments and tendons [19].

In the last years, different models of greater accuracy were developed and the entire ear was completely modeled using the finite element method [20–26]. All data gathered is of great importance in studying the hearing mechanism and the influence of pathologies upon the middle ear function, especially in those pathologic situations, which can be treated by prosthetic implantation. Outcomes of treatment and accuracy of diagnosis is still an issue and the use of such models could provide handy tools to obtain innovative developments in challenging areas, like the design of new ossicular implants, for reconstructive surgery of the middle ear [27–29].

One important parameter in order to achieve a most accurate simulation of the middle ear dynamics and to realize clinical applications of finite element models is the multidisciplinary collaboration of medical engineers, ENT and audiology specialists.

The goal to achieve greater knowledge regarding middle ear pathologies is still time-consuming and expensive. This work has shown that efforts should be made to improve such tools not only for research but also for better diagnosis and treatment. Still there is need of further validation and study using this finite element model on other real cases like the ones presented herein.

Conclusions

This work proposed the use of a finite element model of the middle ear to evaluate two pathologies of the eardrum: myringosclerosis and tympanic membrane perforation. Results were compared to otological evaluation through audiograms and it was shown that the model predicted the hearing loss with good accuracy. Employing such a model instead of a clinical trial to study various pathologies could be a way to obtain new information regarding the development and outcome of diseases.

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