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MODELLING OF THE IMPACT OF EAR IMPLANTS TO EAR ACOUSTICS

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Abstract

The article presents methodology of creating a model of human ear for the purposes of finite element analysis. Following steps of building geometry and mesh are shown. There is listed number of geometry variables which allows to fit the model to the individual anatomical characteristics connected with hearing system. Model created enables application various types of hearing implants as well as investigation of mechanical and electrical interactions between human ear tissues and applied implants. Number of material properties of human ear elements which have a significant impact on its performance are shown.

Key words: human ear, parametric model, hearing implants, finite elements method, material properties

Modelowanie wpływu implantów usznych na akustykę ucha

Streszczenie

W artykule przedstawiono metodykę tworzenia modelu ucha ludzkiego dla symulacji numerycznej stopnia oddziaływania wprowadzanych implantów usznych na jego akustykę metodą elementów skończonych. Wyszczególniono główne jego zmienne geometryczne umożliwiające dopasowanie modelu do indywidualnych cech anatomicznych układu słuchowego człowieka. Opracowany model ucha umożliwia aplikację różnego rodzaju implantów słuchowych oraz realizację badania interakcji mechanicznych i elektrycznych pomiędzy tkankami ucha ludzkiego i implantami. Przedstawiono charakteryzację właściwości fizycznych elementów ucha ludzkiego mających istotny wpływ na jego działanie.

Słowa kluczowe: ucho ludzkie, model ucha, model parametryczny, implanty słuchowe, metoda elementów skończonych, właściwości fizyczne

1. Introduction

Hearing impairment can be caused by diseases of the external auditory canal and middle ear (conductive hearing loss) or caused by damage to the inner ear and auditory nerve (sensorineural hearing loss) [1]. The mixed hearing loss is when the sensorineural hearing loss coexists with conductive hearing loss.

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Depending on the type of the disease, various methods of medical treatment are used. In the case of a minor hearing loss, the effective is pharmacological treatment (approximately 10% of patients). For other damages, hearing aids or surgical intervention are necessary [2]. Surgical intervention may include:

- implantation of prosthesis,
- implantation of electro-stimulated cochlear implant.

Placing the implant requires understanding of its influence on the process of hearing. So far, this understanding has been primarily based on the experience and intuition of the surgeons. The recent progress in the modeling methods opens path for computer-aided planning of the surgical operations. In this context, the present paper describes the results of an interdisciplinary research on modelling implants effect on the human hearing.

The rapid development of computer methods allows today to carry out complex simulations and visualization as well as complex data acquisition. In the present study an attempt has been made to employ computer modelling for investigations of the reaction of the human organism to the implantation of the middle/internal ear implant.

To this end, a computational model of the middle and inner ear was developed which was based CT images of a head. This model was used to compute acoustic properties of the system with different types of implants via finite element method. A method of defining of input data for the calculation and the results of the analyzes are described hereinafter.

2. Model – the geometry of the components of the ear

The human ear as an object of modeling is an item of particular complexity and diversity due to its intricate architecture and patient to patient variability. The ear geometry substantially differs from the relatively simple shapes or surfaces which can be described analytically. Therefore, an experimental method was used, based on CT scans of respective parts of the skull, to acquire the geometry of the ear. This visualization of the skull fragments was carried out in collaboration with the Institute of Physiology and Pathology of Hearing of the Polish Academy of Science.

Fragments of the temporal bone of the healthy ear and the temporal bone with the pathological changes have been visualized by MicroXCT-400. The reconstruction steps are shown in Fig. 1.

The CT methods allow to obtain three-dimensional reconstruction of the examined structures by analyzing a large number of images of the respective object, recorded at different angles. Based on the set of projections, 3-D image of the object is obtained, which is subjected to digital image processing. This objective of this image processing is to separate contrast of the studied item from the background noise. Finally, the 3-D image is used to calculate a set of digital images of item cross-sections.

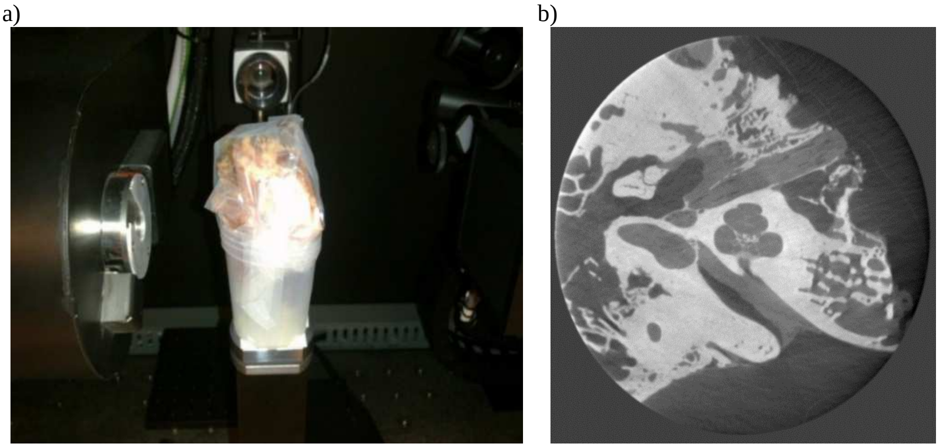

Fig. 1. The sample prepared for CT (a) and an example of CT image (b)

For the purpose of this paper it is assumed that the analyzed object is composed of three main components:

- external ear,
- middle ear,
- inner ear.

The external ear consists of auricle and external acoustic meatus. The tympanic membrane is a barrier between the external and middle ear. The middle ear is a set of bones (malleus (hammer), incus (anvil) and stapes (stirrup)) located in the tympanic cavity. Cochlea with semicircular channels are parts of the inner ear.

3. Model – processing of CT images

The final step in the reconstruction of the scanned fragment is the preparation of a three-dimensional, stereo lithography model from previously obtained sections. Then the model is rebuilt to a geometric CAD formats. The method used for processing of CT images enables to identify the elements of inner and middle ear, and also to check the correctness of their position in relation to other organs. Detailed CT data enabled to prepare parametric description of the geometry of the ear.

The parametric model developed in this study and one of the CT images used for preparation of the model are shown in Fig. 2. This figure confirms that the developed model retains the full complexity of the ear and takes into account all its components relevant in the context of acoustic functions.

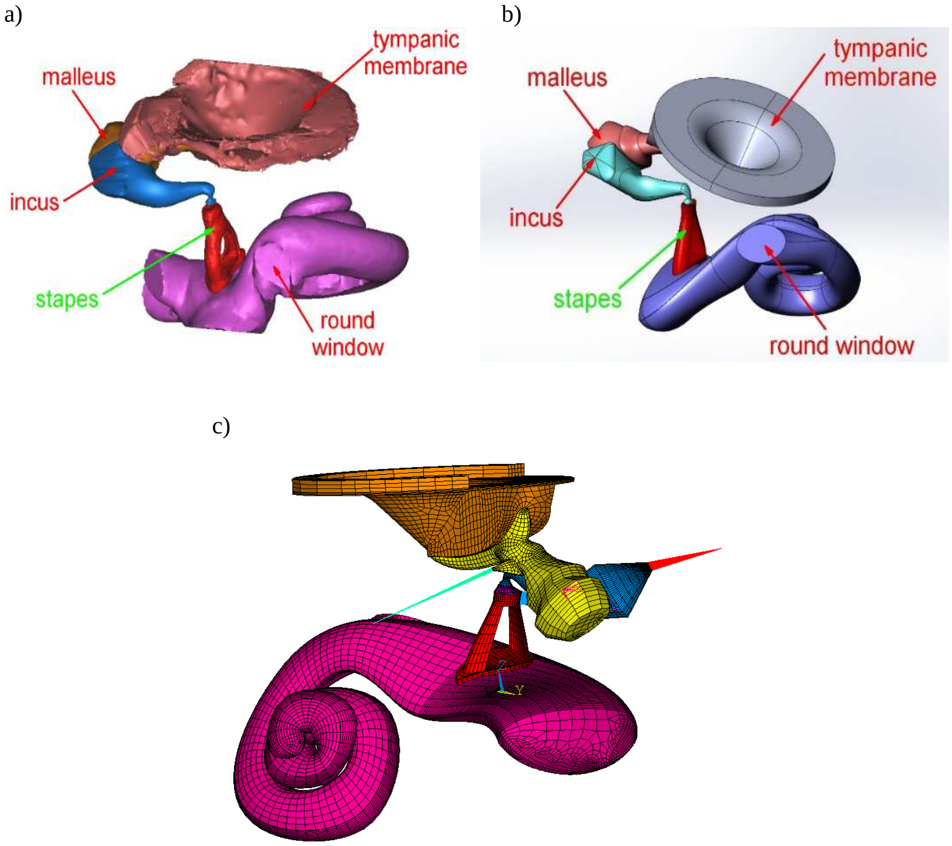

Fig. 2. CT visualization of model components with description (a), CAD model developed for the need of this study (b), the finite element mesh (c)

During development of the parametric model of the ear on the basis of CT images the particular attention was paid to precise mapping of attachment points of the ligaments and joints between auditory ossicles, i.e. synovial joint between the incus (anvil) and the stapes (stirrup) and the synovial joint between malleus (hammer) and incus (anvil). The joint between the malleus and incus (articulatio incudomallearis) is saddle, screw or "barrage" (braking) one. Synovial joint between the incus and the stapes (articulatio incudostapedia) is the spherical joint (the head of the joint is the surface of the lenticular of incus and the acetabulum is the head of the stapes) [3-7]. The individual steps of the modeling process of the auditory ossicles are shown in Fig. 3. The data processing was carried out in the MIMIC.

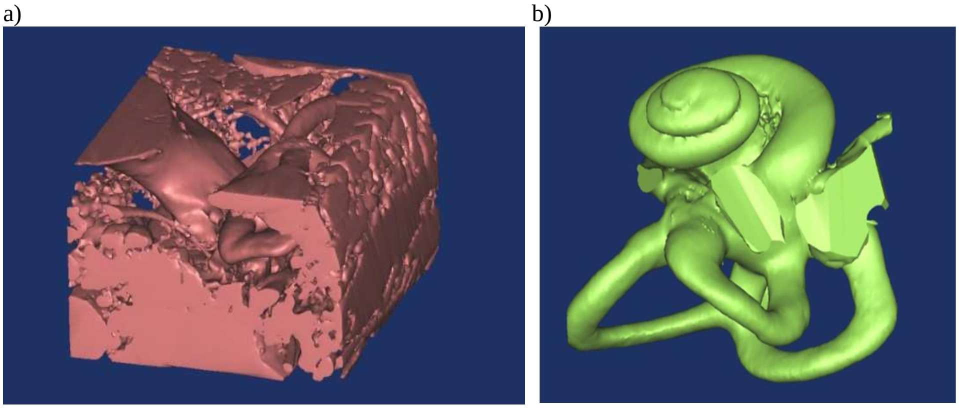

Fig. 3. The processing steps of data obtained in the CT imaging for model development:
a) components of the middle ear, b) components of the inner ear

The adopted parametric model enables to modify the geometry of individual elements of the ear and geometry of the implants. At the same time, adopted calculation method enables to analyze the system taking into account different boundary conditions and variable material properties.

4. The basic components of the model

In connection with the purpose of the analyzes, particular attention was paid to the components of the developed model, which are the elements of the auditory system [6-11]. These elements are: the tympanic membrane, hammer, anvil, stapes and cochlea. The parameters describing these components are shown in Fig. 4-9. Parameters which describe tympanic membrane [8-13] are shown in Fig. 4.

Explanation of the designations assumed in the description of the tympanic membrane model: D – diameter; h_b-height; g1, g2 – membrane thickness in the specific areas; b_s - the width of the attachment zone of the membrane in the outer ear canal; h_s – the thickness of the attachment zone of the membrane in the outer ear canal; h_m – the height of malleolar prominence which is the area of connection with the hammer; a – the length of the arc portion of the pars flaccida of tympanic membrane.

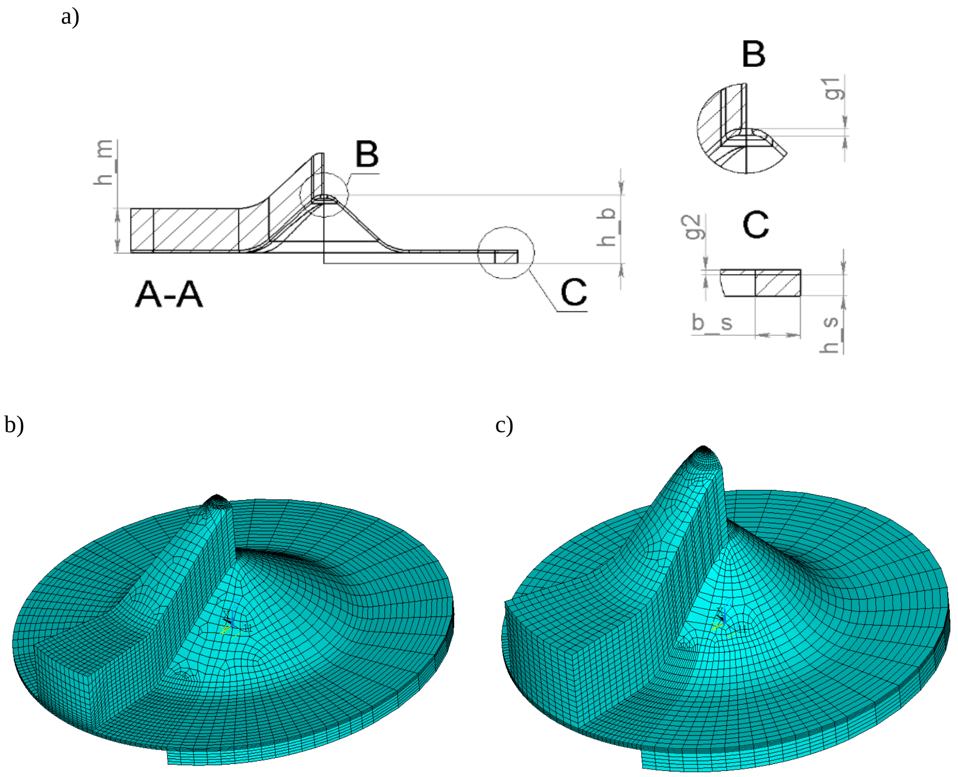

Fig. 4. Basic geometry variables for tympanic membrane (a), finite elements mesh for tympanic membrane (b), tympanic membrane mesh after modification of h_m, h_b, h_s, g1, g2 (c)

The malleus can be divided into the manubrium, lateral part, anterior part, neck and head, as shown in Fig. 5. The geometry of the malleus can be described by the dimensions of the semi-axis of the ellipses for a few sections of each of the specified elements – Fig. 5b. The position of each of the sections is parameterized. In addition, the outline of the head is consistent with the geometry of the anvil in the area of the joint between the malleus and incus (articulatio incudomallearis). Figure 5 also shows the visualization of the model for the two sets of data describing the geometry of the malleus.

Anvil can be divided into a long crus, body and short crus [3-5], as shown in Fig. 6. The following parameters that define the geometry of the anvil [8-11] are assumed: L_ok – the size of a short crus and a, b – the size of the head. The geometry of the long crus of the anvil can be described by a description of the position and contour of sections describing the geometry of the component. The outline of the body of the anvil is consistent with the geometry of malleus and the area of the joint between the malleus and incus (articulatio incudomallearis).

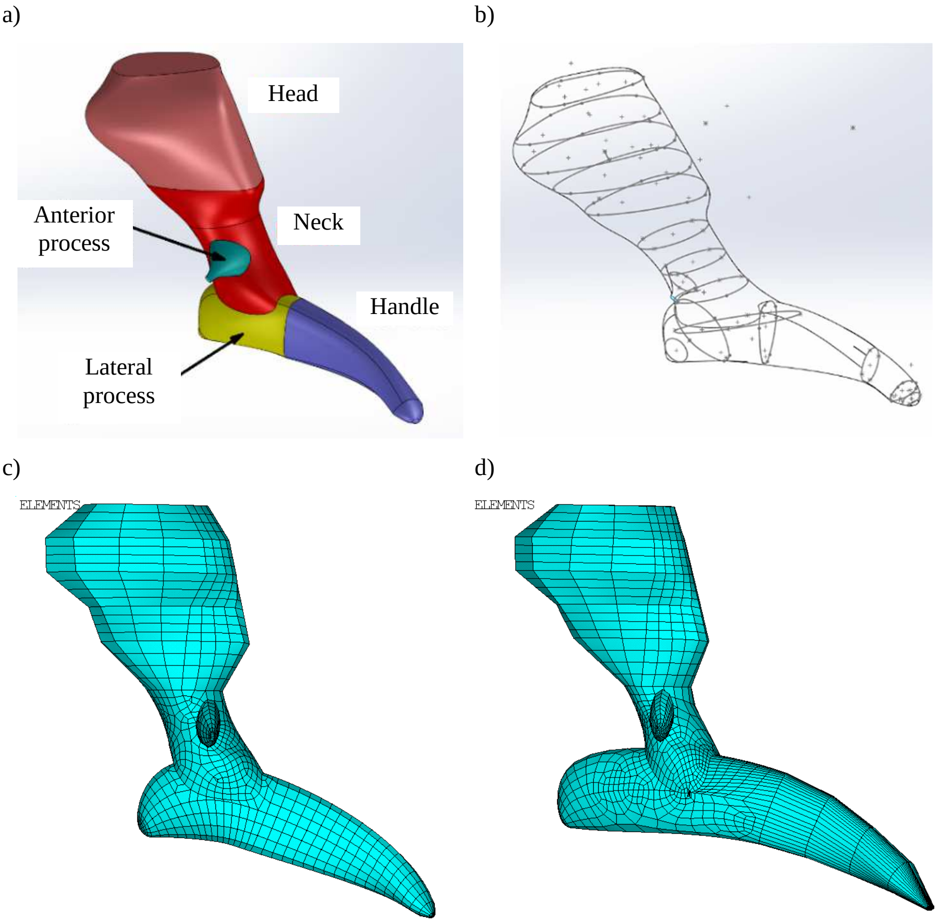

Fig. 5. Model of malleus: description of anatomy (a), sections defining the geometry of the malleus (b), finite elements mesh for malleus (c), finite elements mesh for malleus with modified diameter of neck, length of handle and lateral process (d)

The parameters describing the stapes [8-11] are shown in Fig. 7. The following parameters that define the geometry of the stapes are assumed: g_podst – the thickness of the plate; h_top – the height of the head, h_c – total height, a_podst, b_podst – axis of the ellipse of the base a_top, b_top – axis of the ellipse of the head. The figure also shows examples of models of stapes for different geometrical parameters. It should be stressed that the geometry of the base is matched to the shape of the oval window.

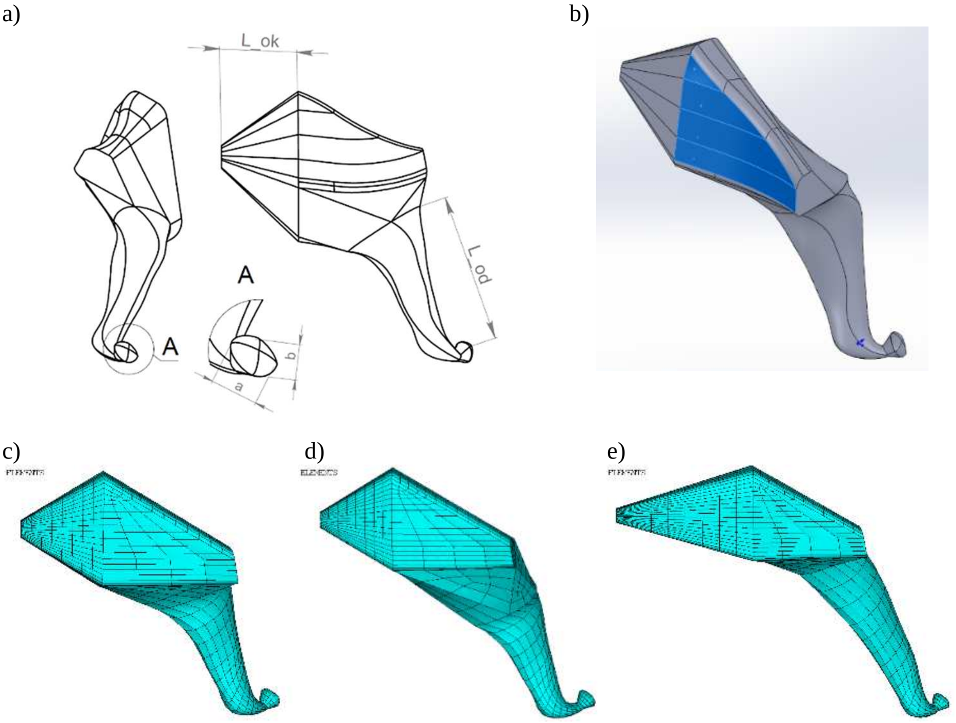

Fig. 6. Model of the anvil (a), the definition of adopted characteristic dimensions (b), finite elements mesh (c), finite elements mesh for anvil with modified L_od (d), finite elements mesh for anvil with modified L_ok, L_od (e)

The outer contour of the cochlea is described in the thirteen control cross-sections shown in Fig. 8. The fourteenth cross-sections define the position and dimensions of the round window. Each of the section of the developed model can be assigned a set of parameters which enable to change its position and dimensions. The cochlea channel is divided with osseous spiral lamina of different thickness and span and with the Reissner and basement membrane [8, 14-16]. These anatomical components are also included in the developed model.

The geometry of the implant and the finite element mesh is shown in Fig. 9. The curvature of the branches of the implant are adapted to the anatomy of the individual elements of the middle ear. The length of the branches results from the size of the planned series of types of implants. This figure also shows a model of the ear with the implant.

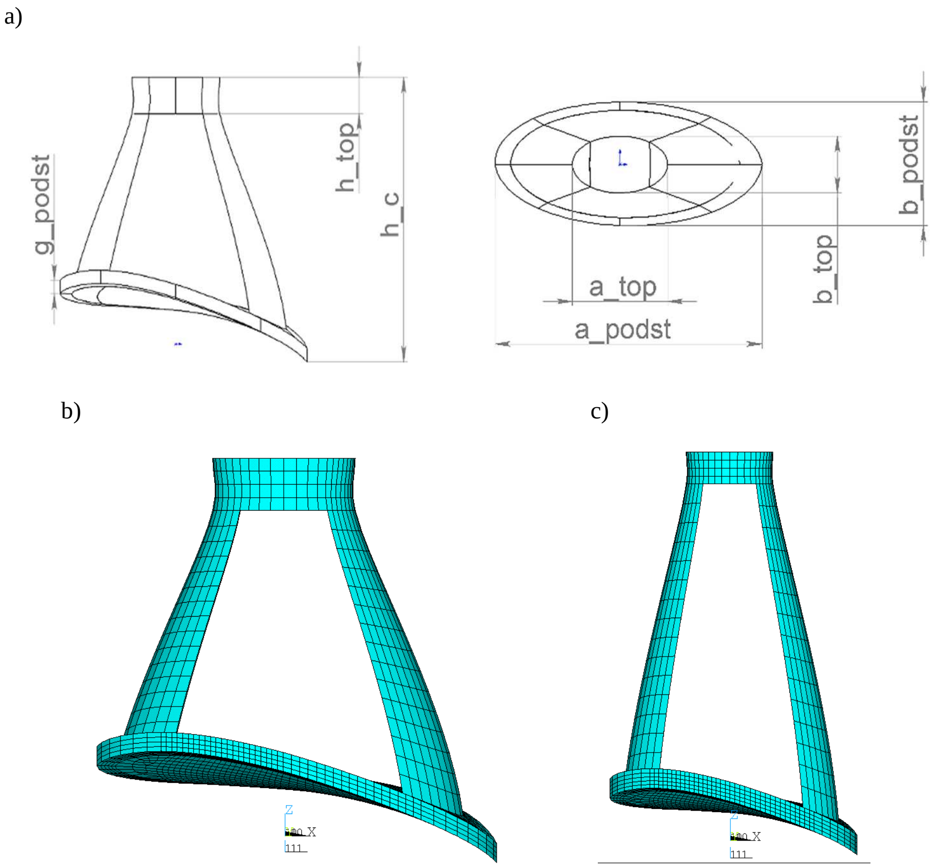
a)
b)
c)

Fig. 7. Model of the stapes: a) the definition of geometric parameters, b) finite elements mesh, c) finite elements mesh for stapes with modified h_c, h_top, g_podst

Computational model gives possibility for virtual application of various types middle and inner ear implants. Based on the manufacturer data, several types of inner ear implants were considered. The geometry of the inner ear implants and the finite element mesh are shown in Fig. 9.

The generated model geometry of the cochlear implant enables to control the parameters such as:

- The number of control sections,
- The diameter and the contour (circle/ellipse) of each of the sections,
- The length of the implant,
- Number of electrodes,
- Electrode size (depth, thickness, width),
- Spacing of electrodes,
- The diameter of the inner channel.

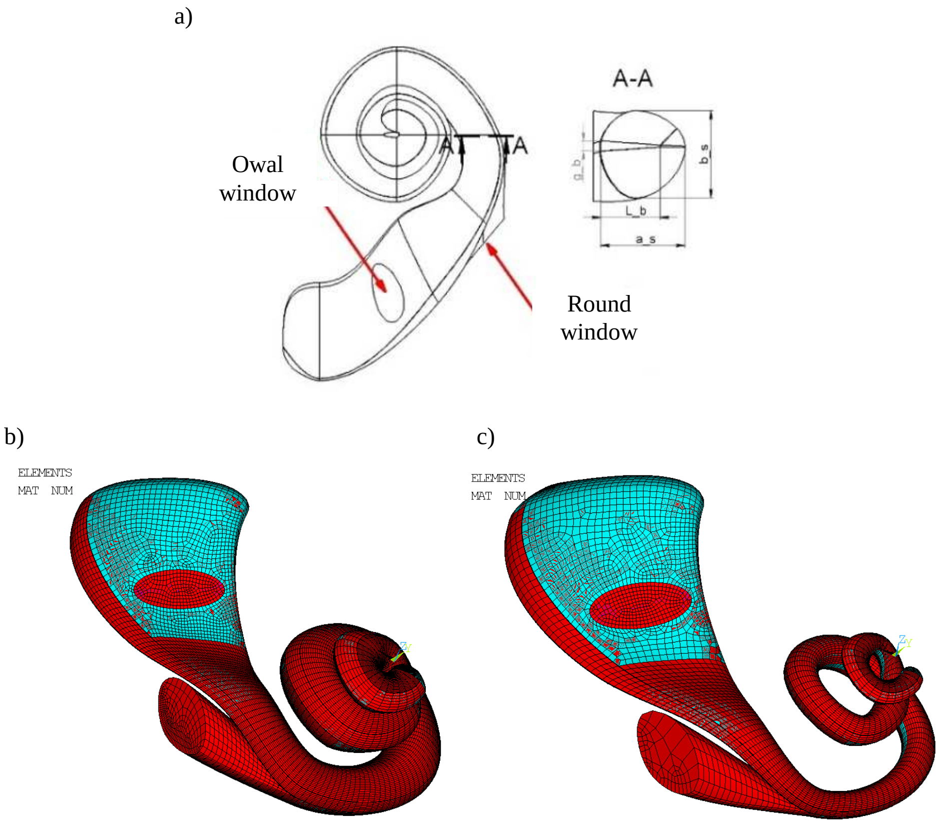

Fig. 8. Geometry of cochlea: a) geometry parameters which describe cross section of cochlea, b) cochlea finite elements mesh, c) finite elements mesh for cochlea with modified dimensions of control cross-sections

Explanation of the designations assumed in the description of the cross section of cochlea: g_b – the thickness of the osseous spiral lamina, L_b – the width of the osseous spiral lamina, a_s, b_s – size of the cochlea channel.

5. Finite element computations

Finite element method has been used in the past to analyze a number of complex materials science systems in the context of materials strength, heat transfer, fluid flow [17-18] .In the present study it has been assumed that this method can also be used to simulate performance of the human ear. Respective model of the middle ear with the division into finite elements is shown in Fig. 10.

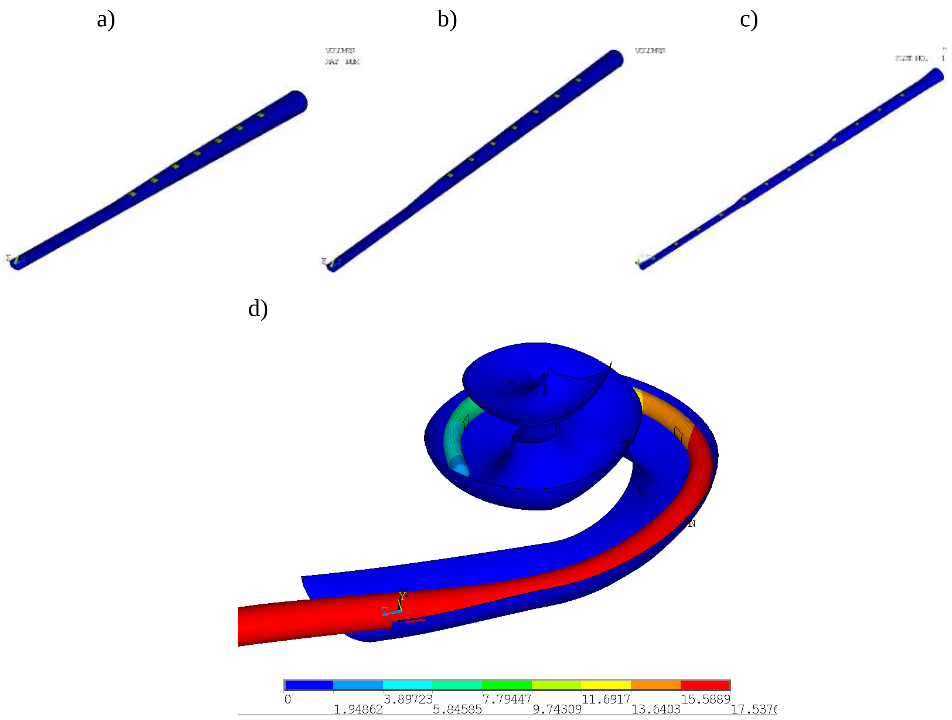

Fig. 9. Various models [19] of cochlear implants: a) Flex 20, b) Flex EAS, c) Flex 28 and d) simulated location of the implant in the cochlea channel

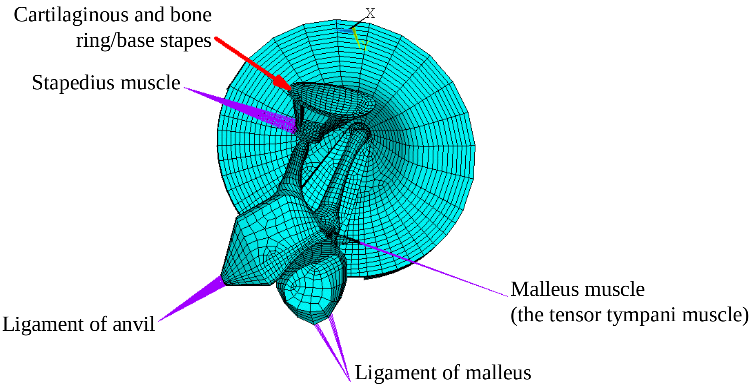

Fig. 10. The middle ear

When the computational mesh of tissues and bones is created, the solid185 elements are used, and the tendons and muscles are modeled with beam188 elements. A fluid which behavior is described with fluid 30 elements is inside the cochlea. The mesh of finite elements inside the cochlea is shown in Fig. 11.

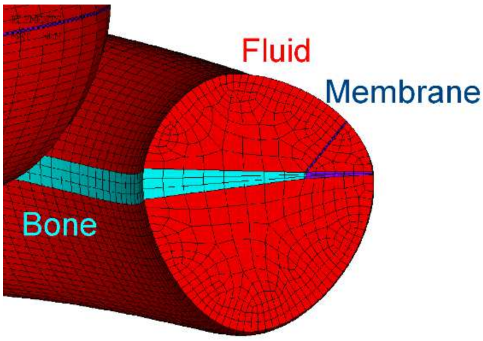

Fig. 11. The inner ear, the computational mesh

Joint connection and the connection of the gripping elements of the implant with tissues are mapped through frictional contact by contact elements conta173 and target170 [20]. The total number of elements of the grid is 34 000 elements for the middle ear and 150 000 elements for the inner ear. The computational model was built using ANSYS program. The input data in the form of material properties of each ear tissues are listed in Table 1 [8-11, 21-23].

Table 1. Physical properties adopted in the computations

Component of model	**Young modulus E, MPa**	**Poisson number ν**	**Density δ, kg/mm^3, $\times 10^{-6}$**
The tympanic membrane	35	0.3	1.2
Malleus/head	$14.1 \cdot 10^3$	0.3	2.55
Malleus/neck	$14.1 \cdot 10^3$	0.3	4.53
Malleus/handle	$14.1 \cdot 10^3$	0.3	3.7
Anvil/head	$14.1 \cdot 10^3$	0.3	2.36
Anvil/long crus	$14.1 \cdot 10^3$	0.3	5.08
Stapes	$14.1 \cdot 10^3$	0.3	2.2
Ring of the oval window	0.2	0.3	2.2
Connection of tympanic membrane/malleus	35	0.3	1
Lateral malleal ligaments	0.067	0.3	1.2
Superior malleal ligaments	0.049	0.3	1.2
Posterior ligament of incus	0.065	0.3	1.2
Ligament of stapes	0.052	0.3	1.2

Summary

The subject of this paper is a complex anatomical-electro-mechanical system of a human ear with an implant for improving hearing functions. The degree of complexity of this system is shown by the number of anatomical components with complex geometry, which also has individual variables. Moreover, the geometry of the individual components of the ear, probably shaped via the process of evolution, can not be described by well-known geometric relationships, so the computer methods of visualization must be used. In fact, to obtain a three-dimensional description of the geometry of the anatomical components of the ear, X-ray tomography was used, which recently is more widely used in materials science and engineering.

The components of the model developed show a large degree of variation of structure and properties. Some of them have typical anatomical features of hard tissue and the other ones have typical anatomical structure of soft tissue. The developed model is also characterized by a high degree of complexity in the context of the modeled phenomena such as mechanical, acoustic and electric ones. Achieving the results described in this paper was possible thanks to the cooperation of specialists in materials engineering and medicine. Interdisciplinary approach was crucial to achieve the intended results, namely the development of the ear model enabling to optimize surgical intervention conducted for the improvement of hearing.

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