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Research Paper

Effects of model definitions and parameter values in finite element modeling of human middle ear mechanics

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ABSTRACT

Background: Despite continuing advances in finite element software, the realistic simulation of middle ear response under acoustic stimulation continues to be challenging. One reason for this is the wide range of possible choices that can be made during the definition of a model. Therefore, an explorative study of the relative influences of some of these choices is potentially very helpful.
Method: Three finite element models of the human middle ear were constructed, based on high-resolution micro-computed tomography scans from three different human temporal bones. Interesting variations in modeling definitions and parameter values were selected and their influences on middle ear transmission were evaluated. The models were compared against different experimental validation criteria, both from the literature and from our own measurements. Simulation conditions were restricted to the frequency range 0.1–10 kHz.
Results: Modeling the three geometries with the same modeling definitions and parameters produces stapes footplate response curves that exhibit similar shapes, but quantitative differences of 4 dB in the lower frequencies and up to 6 dB around the resonance peaks. The model properties with the largest influences on our model outcomes are the tympanic membrane (TM) damping and stiffness and the cochlear load. Model changes with a small to negligible influence include the isotropy or orthotropy of the TM, the geometry of the connection between the TM and the malleus, the microstructure of the incudostapedial joint, and the length of the tensor tympani tendon.
Conclusion: The presented results provide insights into the importance of different features in middle ear finite element modeling. The application of three different individual middle ear geometries in a single study reduces the possibility that the conclusions are strongly affected by geometrical abnormalities. Some modeling variations that were hypothesized to be influential turned out to be of minor importance. Furthermore, it could be confirmed that different geometries, simulated using the same parameters and definitions, can produce significantly different responses.

1. Introduction

The development of a finite element (FE) model of the human middle ear (ME) is not straightforward. Many choices need to be made by the researcher, from the early stages of temporal bone imaging and the construction of the geometry, to the choice of physics to be included in the model, the applied material parameters, and the boundary conditions. Since the mechanics of the system are complicated, it is often very difficult to accurately and confidently predict the consequences of the possible choices that need to be made. This results in different model definitions for different research groups throughout the research community (De Greef et al., 2014a; Fay et al., 2006; Ferrazzini, 2003; Gentil et al., 2014; Hoffstetter et al., 2010; Homma et al., 2010; Tuck-Lee et al., 2008; Zhang and Gan, 2011a; Zhao et al., 2009).

In this paper, the aim is to determine the importance of some of

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Abbreviations: ME, middle ear; TF, transfer function; FE, finite element; TB, temporal bone; µCT, micro-computed tomography; TM, tympanic membrane; PT, pars tensa; PF, pars flaccida; TMC, tympanomallear connection; M, malleus; I, incus; S, stapes; IMJ, incudomallear joint; ISJ, incudostapedial joint; SAL, stapedial annular ligament; TT, tensor tympani; SM, stapedius muscle; SFP, stapes footplate

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the choices made throughout the development of a middle ear FE model. This was done by studying the influence of different variations in the model description on the transfer function (TF) of three different FE models, based on the geometries of three different temporal bones. In addition, by applying the same model definitions to different human ME geometries, this study will bring insight into the isolated effect of geometry on the sound transmission of the ME.

2. Materials and methods

2.1. Study strategy

After evaluating the variations that are described further on, a final model description was constructed that represents a trade-off between agreement with experiments, structural/morphological observations, effort necessary to implement, and computational cost. For example, if a certain feature did not produce a significant change but improves the resemblance to microstructural observations, it was included in the model only if the required effort to implement it and the additional computational cost were relatively small. An example of this is the incudostapedial joint (ISJ) microstructure (see results and discussion).

Sections 2.2 and 2.3 describe how the final models, referred to as the ‘base models’ of this paper, were built and defined and which material parameters were used in them. Since three geometries from three different donors were constructed, there are three base models and most variations were studied for all three geometries.

2.2. Geometry

The three temporal bones (TB's) used in this study were a subset of the six TB's used for the morphologic study in De Greef et al. (2015). Therefore, all procedures up to and including the image segmentation are identical to that paper and only a condensed description of the procedures is provided here. Samples 1, 2, and 3 from the current paper are samples 2, 3, and 4 from De Greef et al. (2015), but we will use numbers 1, 2, and 3 from here on in this paper. Some morphological parameters for the three samples are listed in Table 1 to allow the reader to appreciate how the geometries vary. The geometries were selected so that they represent a large (sample 1), small (sample 2), and average (sample 3) ME from our population of six samples.

The three fresh human TB samples were acquired from Cochlear Technology Centre Belgium. Samples 1 (male, 75y) and 2 (male, 73y) are right TB's; sample 3 (male, 73y) is left. The samples were stained using phosphotungstic acid (PTA) before they were imaged using a micro-computed tomography (μCT) system at the Centre for X-ray Tomography of Ghent University (UGCT) facility (Masschaele et al., 2007). The resulting dataset of the scans had an isotropic voxel pitch of 18.5 μm (sample 1) or 22.8 μm (samples 2 and 3). After 2D-reconstruction of the μCT scans, the image data were segmented using Amira® 6.1 (FEI Visualization Sciences Group, Hillsboro, Oregon, USA). The segmentation procedure was a combination of automatic and manual segmentation tools and is described in more detail in De Greef et al. (2015). The influence of segmentation operator bias was investigated by Buytaert et al. (2014) and the authors concluded that the results of a manual segmentation are only marginally dependent on the operator.

After image segmentation, the labeled volumes were converted into triangulated surface models using a generalized marching cubes algorithm (Hege et al., 1997). Initially very fine (more than 1M triangles), the surfaces were simplified and remeshed using an adaptive remeshing algorithm (Zilske et al., 2008) to approx. 18,000 triangles. Both algorithms are natively implemented in Amira®. The final surfaces were exported to the FE software as ASCII .stl-files (STereoLithography).

The final models contained the following separate structures: pars tensa (PT) of the TM, pars flaccida (PF) of the TM, tympanomallear connection (TMC), malleus, incus, stapes, incudomallear joint (IMJ), incudostapedial joint (ISJ) capsule, ISJ interior, anterior mallear ligament, lateral mallear ligament, posterior incudal ligament, stapedial annular ligament (SAL), tensor tympani (TT) tendon, and stapedius muscle (SM) tendon.

A noteworthy feature of our three geometries is the morphology of the lenticular process of the incus. In all samples, only a thin bony core connected the long process of the incus to the lenticular plate. This core was surrounded by soft tissue, which was labeled as ISJ capsule in our models. A close-up image of this is presented in Fig. 1.

2.3. Finite element analysis

For all FE simulations in this study, Comsol Multiphysics 5.2 (COMSOL AB, Stockholm, Sweden) was used, extended with the Structural Mechanics Module. Once imported into Comsol, the surface models were converted into a tetrahedral volume mesh, to be used in the FE calculation. A mesh refinement study indicated that a surface model of approx. 18,000 triangles, corresponding to a volume mesh containing approx. 120,000 tetrahedral elements, provided an acceptable trade-off between result accuracy and computation time (the difference in the TF between this mesh and a mesh containing almost twice the number of elements (220,000) was at most frequencies less than 1 dB, and at the most 2.2 dB (around the resonance)). The entire model consists of second-order (quadratic) elements. Using this mesh, most of the TM's interior was adequately meshed using a single layer of quadratic elements, except near the TM's edge. A frequency-domain analysis sweeping over 24 frequencies between 0.1 and 10 kHz took approximately 25 min to calculate on a PC (CPU: Intel Xeon E5-2630 v3 @ 2.40 GHz, 8 cores (2 processors installed) – RAM: 128 GB – OS: Windows 7). The 24 frequencies were logarithmically evenly spaced at four frequencies per logarithmic decade below 562 Hz and 16 frequencies per logarithmic decade above 562 Hz.

2.3.1. Boundary conditions of the base models

The following description applies to the base models of this paper and, if not stated otherwise, to all variation models.

The stimulating load on the model was a uniform sound pressure of 1 Pa on the lateral side of the TM. A contiguous selection of triangular faces at the edge of the TM, as well as the end surfaces of

Table 1
Selection of relevant morphological parameters of the three selected samples. The last column contains statistical parameters from the dataset of 6 samples in De Greef et al. (2015).

Parameter	Sample 1	Sample 2	Sample 3	Mean ± St. Dev. (N = 6)
TM surface area (mm^2)	65.9	58.1	60.0	59.4 ± 6.9
IM joint angle (°)	22.5	15.8	12.5	17.5 ± 4.4
IM complex volume (mm^3)	27.6	23.5	23.8	26.7 ± 2.4
Stapes volume (mm^3)	1.44	1.18	1.23	1.24 ± 0.13

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