DEVELOPMENT OF A 3D FINITE ELEMENT MODEL OF THE HUMAN EXTERNAL EAR FOR SIMULATION OF THE AUDITORY OCCLUSION EFFECT

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1. INTRODUCTION

Approximately 120 million workers worldwide are at risk of developing professional hearing loss (WHO, 2001). Hearing protection devices, such as earplugs (EP), are a frequently used short term solution to protect workers from hazardous noise. Wearing EPs, however, causes distortion of the wearer's voice and amplification of physiological noises; also referred to as the occlusion effect (OE). The OE, as well as other auditory and physical limitations, reduces the comfort of an EP. Consequently, workers often only wear EPs for short periods of time (Berger, 2000; Lusk et al., 1998; Morata et al., 2001). This leaves them prone to hearing loss. Numerical models present a valuable means to improve the outlined shortcomings because they can aid to better assess and design hearing protectors. The present study describes the development of a novel coupled linear elasto-acoustic 3D finite element model of the human external ear. This genuine model is employed to simulate the auditory OE. In the following, preliminary research findings are presented.

2. METHODS

Simulation of the OE was carried out in three steps. First, the geometry of the human external ear was reconstructed. Secondly, a model of an earplug was coupled to the open ear model. Lastly, the sound pressure levels (*SPL*) at the tympanic membrane of the open and occluded ears were subtracted to determine the OE.

2.1 Model geometry

To ensure high model authenticity, 100 transverse-axial anatomical images of a female cadaver head (age = 59 years) were used for 3D reconstruction. All images were obtained via the Visible Human Project® database (NLM, MD, USA). 3D reconstruction of the ear canal as well as the bony, cartilaginous and skin tissues was carried out in slicOmatic 4.3 (TomoVision, QC, Canada). The obtained voxel model (voxel height = 0,33mm, length = 0,33mm, depth = 0,33mm) was imported into CATIA V5 (DS, France) for further processing.

2.2 Material properties

The biomaterial properties of the bony and cartilaginous tissues were approximated using literature findings. The skin tissue of the ear canal entrance and walls was modeled using soft rubber.

2.3 Boundary conditions

To account for the interaction with neighbouring tissues, as well as the environment, several boundary conditions were included in the model. The unoccluded ear canal entrance was expressed through a frequency dependent impedance of a flat disc. The skin tissue around the ear canal entrance was free in its movements. Circumferential (perpendicular to ear canal entrance) and medial (parallel to ear canal entrance) tissue boundaries were modeled using roller constraints. Finally, the eardrum impedance was expressed through a two-piston model (Shaw, 1977; Shaw & Stinson, 1981).

2.4 Model excitation

A surface distributed force of magnitude $1 \mathrm{Nm}^{-2}$ was introduced normal to the circumferential boundaries of the bony tissue. This method was chosen to simulate a bone conducted excitation which is required to trigger an OE upon EP insertion.

2.5 EP model

It was assumed that the insertion of an EP would only deform the EP and that the ear canal would keep its original shape. Following this initial hypothesis, the model of a moulded silicone earplug of known material properties was inserted into the model. First, the insertion depth of the EP was set to 7mm to simulate a shallow insertion. Secondly, the EP model was inserted 22mm into the ear canal to model a deep insertion scenario.

2.6 Model resolution

All model domains were imported into COMSOL 4.0 (COMSOL, Inc., Sweden) for 3D finite element analysis. Each domain was meshed individually (according to the four elements per wavelength criterion ($\lambda/4$)) using tetrahedral elements. Sound pressure levels (*SPL*) of the open and occluded ear models were calculated as follows:

$$SPL_{open} = 20*\log_{10}(|p(x,y,z)|/p_{ref}) \text{ with } p_{ref} = 2\text{e-}5 \text{ Pa}$$

$$SPL_{occluded} = 20*\log_{10}(|p(x,y,z)|/p_{ref}) \text{ with } p_{ref} = 2\text{e-}5 \text{ Pa}$$

Finally, OEs were calculated by subtracting open and occluded *SPL*s:

$$\text{OE} = SPL_{occluded} - SPL_{open}$$

3. PRELIMINARY RESULTS

Figure 1 and Figure 2 illustrate the OEs that were calculated using the 3D finite element model for shallow and deep occlusions respectively (solid lines). In addition to that, each figure illustrates two dash-dotted graphs that were taken from the literature (Stenfelt & Reinfeldt, 2007). These graphs represent envelopes of objective, forehead-bone conducted OEs of 20 subjects. Experimental occlusion depths equalled 7mm and 22mm. Literature results were adjusted to the present frequency range.

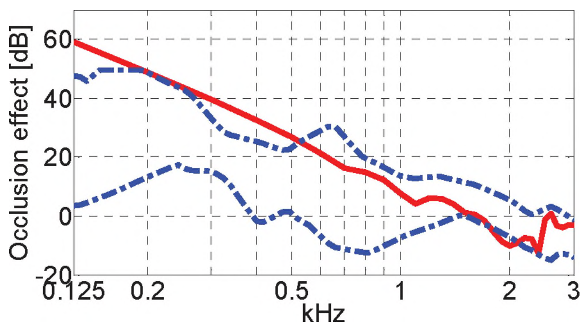

Figure 1: Simulated OE (solid line) and experimental envelope curves (dash-dotted lines) for a shallow (7mm) occlusion. The experimental reference data can be found in Stenfelt & Reinfeldt, 2007.

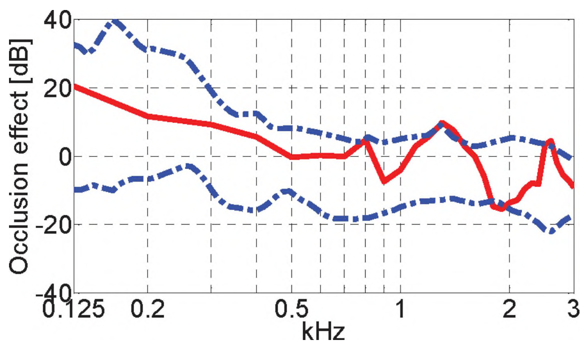

Figure 2: Simulated OE (solid line) for a deep insertion (22mm). Dash-dotted lines represent the envelopes of 20 objective, forehead bone-conducted OE measurements. The original data can be found in Stenfelt & Reinfeldt, 2007.

For a shallow insertion (7mm) the highest OE (60dB) occurs at 0.125 kHz. Afterwards, the modeled OE decreases by about 20dB/octave until 0.7 kHz is reached. At 1.7 kHz the simulated occlusion effect crosses the 0dB line. Afterwards it gets negative (1.7 kHz to 2.6 kHz). The OE vanishes a second time at 2.6 kHz and remains negative at the highest frequencies. Compared to the literature findings (dash-dotted lines) the model overestimates the OE by about 15dB at the frequencies below 0.2 kHz. At the frequencies between 0.2 kHz and 0.3 kHz the modeled OE and the upper limit of the experimental envelope curve are superimposed. Between 0.3 kHz and 0.5 kHz the model deviates by about 10dB from the upper bound of the experimental envelope curve. At the frequencies above 0.5 kHz the modeled OE stays within the boundaries that are set by the experimental data.

For a deep insertion (22mm) condition the OE is overall smaller in magnitude. At 0.125 kHz the simulated OE equals 20dB. Afterwards it decreases by about 10dB/octave. Between 0.5 kHz and 0.7 kHz the simulated OE disappears. Subsequently, the OE progresses in a zig-zag-like manner. Further 0dB crossings occur at 0.85, 1, 1.6, 2.5 and 2.7 kHz. The simulated OE stays within the experimentally determined bounds throughout the entire analyzed frequency range.

4. DISCUSSION AND CONCLUSIONS

The obtained results indicate that the implemented 3D finite element model can be employed to calculate the auditory OE. Obtained OEs vary as a function of insertion depth and are plausible when compared to literature findings. For a shallow insertion, the model overestimates the OE in two frequency bands below 0.5 kHz. This might be due to leakage or noise phenomena. In order to further validate the model, it is planned to conduct experimental work on an equivalent physical model to be able to compare the numerical model predictions to experimental results that are independent of the materials properties, tympanic membrane impedance and excitation location. Comprehensive tests regarding the influence of each of these factors have yet to be completed. Preliminary results suggest that the OE model is very promising. Nevertheless, further testing should be conducted.

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