ABSTRACT
Acoustic impedance measurements of the human ear canal enable us to understand the function of the middle and the inner ear as well as to recognize possible dysfunctions. Additionally, the ear canal impedance is an important parameter which has to be taken into account when hearing aids are adjusted. Hearing aids for infants, children, and adults are all fitted using only a few standardized couplers (i.e. 2 ccm coupler (IEC 60126). The measurement of individual real-ear-to-coupler differences (RECD) is required since these couplers yield insufficient data as far as children are concerned. However, couplers suitable for different age groups can be developed for an improved fitting process if the knowledge about ear canal impedances and the ear canal volumes of infants and children is increased.

Two different methods to obtain ear canal impedances will be discussed in this article. The first one is a classic measurement technique in which a one-microphone-impedance probe is used. Different coupling techniques have been tested with regard to repeatability and measurement uncertainty. Later on, the impedance probe is tested on adults and on children.

The second method is the simulation of the ear canal impedance using FEM (Finite-Element-Method). The required CAD-models are generated with the help of CT-scans (computed tomography) of young children and adults.

INTRODUCTION
The acoustic measurement of impedances on the human ear canal is nowadays often used to identify possible dysfunctions of the middle and inner ear. Special couplers are used to emulate the input impedance and the residual volume of the ear canal with the inserted hearing aid in the fitting process. By adjusting for the individual hearing loss, the ear canal impedance plays a vital role in avoiding mismatches, which could result in a device that is either too loud or too quiet for the patient.

When it comes to fitting processes of hearing aids for children and infants, the commonly used couplers do not emulate the childlike ear canal sufficiently. Besides the smaller residual volume for children, the resonance frequencies are also shifted towards higher frequencies. This causes high uncertainties in the fitting process of hearing aids for the auditory system of children influencing the children’s linguistic development. Additionally, infants are not able to give any feedback on their hearing aid adjustments; therefore, an objective assessment method is inevitable.

Hence, detailed data on the ear canal impedance of children has to be gained and is the main focus of this work. Two different techniques to determine ear canal impedances are proposed. Measurement and simulation results are going to show that even data from very young infants can be achieved. With the help of this data the fitting process for hearing aids of children can be significantly improved.
SIMULATION OF EAR CANAL IMPEDANCES

The geometry of the ear canals is reconstructed on the basis of CT-scans (computed tomography).

The contours of the ear canals are drawn with splines on the CT slides using the program MicroStation™ with the photogrammetry-plugin PHIDIAS [1]. Figure 1 shows a screenshot to illustrate this approach. Consecutively, the CT-scans are loaded and the contours (green) are extracted. The position of the eardrum is marked red. A closed volume model can be generated on the basis of these layered splines. Therefore a plane in the transition of cavum conchae to the ear canal needs to be defined. The volume is discretized using tetrahedra-elements with a length of 1 mm to 3.1 mm (maximum). Using the Finite-Element-Method (FEM) the ear canal impedance can be derived up to frequencies of 16 kHz (cf. Vallejo [2] and Stinson [3]).

MEASUREMENT OF EAR CANAL IMPEDANCES

The measurement of ear canal impedances is carried out using a method introduced by Lodwig and Hudde [4]. This method consists of a one-microphone impedance probe using the principle of the calibrated source. This arrangement includes one loudspeaker mounted on a tube with an adapter. The loudspeaker injects the sound into the tube. Lateral on the tube there is a small hole for the microphone (Sennheiser KE-4). This microphone measures the sound pressure \( p \), which depends on the attached load.

This measurement technique is based on the description of the loudspeaker with respect to a reference measurement plane M by an ideal source with a series impedance \( (\overline{Z}_0, \overline{Z}_0) \). Once
these parameters are known, the source is fully described and the impedance of the ear canal can be measured by only one measurement of the sound pressure on the reference plane M. The operating range of the probe is between 100 Hz and 8.5 kHz.

There are different possibilities to connect the probe and the ear canal. Ear-plugs and soft plugs for tympanometry turned out to be insufficient, while individual formed otoplastics turned out to be the best option. Therefore an impression of the ear is taken, which is usually used to create an ear mold for hearing aids. This impression is used to fit the probe in the ear. Figure 2 shows the probe with an individual ear mold. The picture on the right shows the probe during a measurement.

VERIFICATION OF THE TWO APPROACHES ON A WELL-DEFINED TEST VOLUME

To compare the two approaches used to determine the ear canal impedance, the impedance of a well-defined test volume is once simulated using FEM and once measured with the measurement probe.

The test volume is a compact aluminium cylinder with an inner diameter of 8 mm. The length of the cylinder is 35 mm. After mounting the impedance probe, an effective length of 25 mm is left. This arrangement is similar to the real position on a human ear. The length of 25 mm corresponds to a not yet complete full-grown ear canal. Placing the probe on the test volume causes a cross-sectional jump which is in accordance to the real ear situation with the probe mounted and connected to the ear canal.

Figure 3 shows the magnitude (left) and the phase (right) of the impedance observed during simulation (red) and measurement (blue). The frequency and phase responses of the simulation and the measurement show a good agreement. The results of the measurement, however, show a lower quality factor than the simulation. Thus, the phase-jumps in the phase response of the measurement are not so steep. If a little damping is applied in the simulation (1 %), the two approaches become more similar. Nevertheless, in the further results of this study no damping is assumed since in the literature no data is available about the correct value of the damping in the ear canal.

EAR CANAL IMPEDANCES OF CHILDREN AND ADULTS

The construction of the CAD models is the major challenge when it comes to simulating ear canal impedances of children. Whether the reconstruction is finely detailed or not depends on the resolution of the CT-slides. In general the simulation is working for adults as well as for very young children. For this study 25 CT-scans in total were available for the simulation. The test group consists of 12 male and 13 female subjects aged between three weeks and 20 years. Once the CAD-models of the ear canals are created, detailed data about the length and volume of the ear canal can be calculated easily.

Figure 4 shows the ear canal length and the ear canal volume as a function of age (blue dotted line). The red line shows the regression line for the age group of zero to 7 years. The green line indicates the mean value for the age group above 7 years. In case of the ear canal volume
(right) the regression line fits very well ($r = 0.95$). The volume varies from values of 0.1 ccm to approx. 0.65 ccm within the first 7 years strongly correlated to the growth. Above 7 years, the ear canal approaches a volume of 0.9 ccm, however, there is one outlier.

In case of the ear canal length (left) similar trends can be observed. A strong dependence on the age for subjects younger than 7 years can be detected. Although, there are some outliers, the ear canal length grows up to 7 years ($r = 0.81$) and above 7 years, the ear canal stabilizes to a length of approximately 2.9 cm. This correlates with the literature that the petrosal is full grown with an age of 6-7 years.

Figure 4.- Left: Ear canal length in [cm] as a function of age (blue); Right: Ear canal volume in [ccm] as a function of age (blue); Regression line for the age group of 0 – 7 years (red) and mean value of the age group of 7 – 21 years (green)

Figure 5.- Selection of ear canal impedances of children and adults.
Upper left: Measured impedances of 6–7 year-old children.
Upper right and lower row: Simulated results of diverse age-groups.
The measurement approach has been already studied by Hudde [4] and has been applied to ears of adults. Now for the first time the practicability of this approach is tested on children.

22 children took part in this study. Therefore a probe with an inner diameter of 3.5 mm and an outer diameter of 5 mm was used. No problems occurred while using this method even when tests were carried out on three-year-olds. If younger children need to be measured a smaller probe will have to be used.

Figure 5 (upper left) shows a selection of measured ear canal impedances for children in the age from 6 to 11 years. Figure 5 (upper right and lower row) shows a selection of simulated impedances of very young children up to adults. In comparison to the measurement, again, the simulation shows a higher quality factor. One can easily see, that there is a large variation in the age below 1 ½ year. When it comes to an older age, the resonance frequencies are closer together. These simulations were carried out without any impedance applied on the eardrum.

SUMMARY
It has been shown, that ear canal impedances can be determined using measurements and simulations for adults as well as for very young children. The simulation technique, however, provides certain advantages in regard to infants. Moreover, data about the shape, volume, and length of the ear canal has been achieved by constructing a CAD model of the ear canal. Results show high variations of the ear canal impedances of children younger than 6 years. For children in the age of 3 weeks up to 1.5 years the data are even more divergent. This correlates well with the obtained geometrical data of the ear canal. Variations of the resonance frequencies of children older than 6 years are in the same order of magnitude as the variations of adults. Thus, subsequent future work needs to focus on the age-group below the age of 6 years in more detail, to provide methods for the development of adequate couplers for children.

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