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Measurement of Children's Ear Canal Impedances*

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Summary
The ear canal impedance is an important parameter which has to be taken into account when adjusting hearing aids. 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. 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 for 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. This paper describes a measurement technique using a one-microphone-impedance probe. Different coupling techniques were tested with regard to their repeatability. The measurement technique was verified using a test volume and was compared with a FEM simulation. Afterwards the impedance probe was tested on adults and children.

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1. Introduction

Couplers (sometimes also referred to as "ear simulators" or "artificial ears") are used as a standardized (cf. IEC 60318-5 [3]) replica of the ear canal and impedance. The ear canal volume and impedance are reproduced using several cavities. These standardized couplers (as well as standardized artificial heads) can only provide a "mean ear", which means that individual properties cannot be considered.

However, a standardized coupler for children is not available. The standardized 2 cm^3 coupler does not reproduce the human ear very well since the cavity of this coupler is too large compared to a real human ear. This is especially true for children. For reasons of robustness and production tolerances, however, this coupler is still in use.

Thus, the measurement of the ear canal impedance on real ears can be used as input data for the development of appropriate couplers for children.

2. Determination of ear canal impedances

Morton and Jones [4] measured the acoustical impedance as early as 1956. Numerous studies were carried out by Hudde from 1983 to 1999. Different measurement techniques were discussed in [5], but in most cases the focus was put on the eardrum impedance of adults. Rabinowitz [6] measured the acoustic immittance in the human ear canal for frequencies ranging from 62 Hz to 4 kHz. Stinson [7] collected data of the acoustic energy reflection coefficients at the eardrum for frequencies between 3 and 13 kHz for 20 ears. Ciric and Hammershøi [8, 9] used an impedance tube to measure the acoustic impedances of the ear canal. This method yields very reliable results, but it would be impossible to apply this method while working with children, since one cannot use the apparatus with children easily.

Only a few studies addressed the issue of ear canal properties of children: Kruger and Ruben [10] measured the acoustic properties of infants and toddlers. The subjects were between 0 and 40 months old. A probe was inserted 2 mm in front of the eardrum. The results show that the resonance frequency is a function of age. The resonance frequency of newborn children is at about 7 kHz while the one of 20 to 37 month-old children is about 2.7 kHz, which is already similar to an average adult. Pfeil [11] chose an indirect method to obtain ear canal parameters. The ear canals of 31 children, who were between two and ten years old, were filled with a cold curing synthetic material up to the eardrum while they were undergoing surgeries under general anesthetic. The negatives of the ear canals were measured regarding their geometrical features. The average volume was 0.6 cm^3.

Keefe *et al.* [12] made a comprehensive study of ear canal impedances and reflection coefficients of infants and

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[1] Parts of this work were presented at the 19th International Congress on Acoustics, ICA 2007 in Madrid [1] and are published in the dissertation of the author [2].

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Figure 1. Impedance Probe: Left: Model of the impedance probe with loudspeaker and microphone; Middle: Open impedance probe: Aluminum calotte and connecting tube; Right: Closed impedance probe.

adults. Measurements of an adult group and groups of infants who were 1, 3, 6, 12, and 24 months old, were carried out over a frequency range of 125 to 10700 Hz. Keefe *et al.* [12] underlined the growth dependency of the measured parameters. The ear canal impedances decrease by 6 dB/octave until they reach their minimum at 6 kHz. In case of higher frequencies the impedances increase by 6 dB/octave. The impedance functions of the 1 to 24 month-old children do not run in that straight line. Their functions, however, increasingly resemble the adults' functions the older the children are.

Helle [13] analyzed different procedures to determine the effective gain of hearing aids when measured at the IEC 60711 coupler compared with the child's ear. He also developed correction factors for this kind of measurement.

Very little data is available on ear canal impedances of children and adults that describe the impedance at the ear canal entrance that is located at the intersection of the cavum conchae and the ear canal. In this study the ear canal impedances according to the general definition of the field impedance $\underline{Z}$, which is the ratio between the sound pressure $\underline{p}$ and the particle velocity v are determined.

3. Measurement technique

The measurement of ear canal impedances is carried out using a method introduced by Lodwig and Hudde [14]. They applied this method to ears of adults. Now, for the first time, the feasibility of this approach is tested on children. This method features a onemicrophone impedance probe using the principle of the calibrated source.

For this measurement a one loudspeaker mounted onto a tube with an adapter (see Figure 1). The loudspeaker injects the sound into the tube. Lateral on the tube there is a small hole for the microphone. This microphone measures the sound pressure $\underline{p}$, which depends on the attached load.

This measurement technique is based on the description of the loudspeaker with regard to a reference measurement plane M by an ideal source with a series impedance ($\underline{p}_0$, $\underline{Z}_0$), cf. Figure 2. Once these parameters are known, the source is fully described and the impedance of the ear canal can be measured by performing only one measurement of the sound pressure on the reference plane M.

Afterwards the impedance at the measurement position is transformed to the ear canal entrance plane. At least two

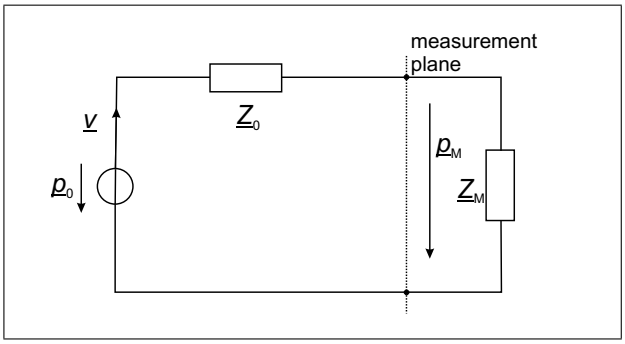


Figure 2. Impedance probe: Equivalent circuit diagram with source sound pressure $\underline{p}_0$.

measurements with known terminators are required to determine the source parameters $\underline{p}_0$, $\underline{Z}_0$. The simplest approach is to use terminators of two different lengths which are easily described mathematically. The advantage of this measuring method is that the measurement probe is small, which makes it possible to use it when working with children. Furthermore, it is easy to handle the calibration. Figure 1 shows the set-up of the impedance probe. The loudspeaker which is used is an aluminum calotte loudspeaker. The dimensions of the housing are selected such that the loudspeaker operates against a small amount of air. This causes even at low frequencies a high sound pressure level in the connecting tube.

A Sennheiser KE4-211-2 capsule (electret condenser microphone) is placed lateral onto the tube into a small hole. The distance between loudspeaker and microphone must be large enough so that higher order modes are decayed. Additionally, the part of the tube between loudspeaker and microphone is damped using damping wool to avoid high resonances in the tube. The probe used for this study has an inner diameter of 3.5 mm and an outer diameter of 5 mm. The tube is 25 mm long. Additional tests were carried out with smaller tubes for very young children [15]. A sweep (order 16 = 32768 samples, sampling rate = 44100 Hz) is used as excitation signal. A low-shelf-filter is integrated in the excitation signal to improve the signal-to-noise ratio.

Figure 2 shows the equivalent circuit diagrams of the impedance probe. In the following section the diagram de-

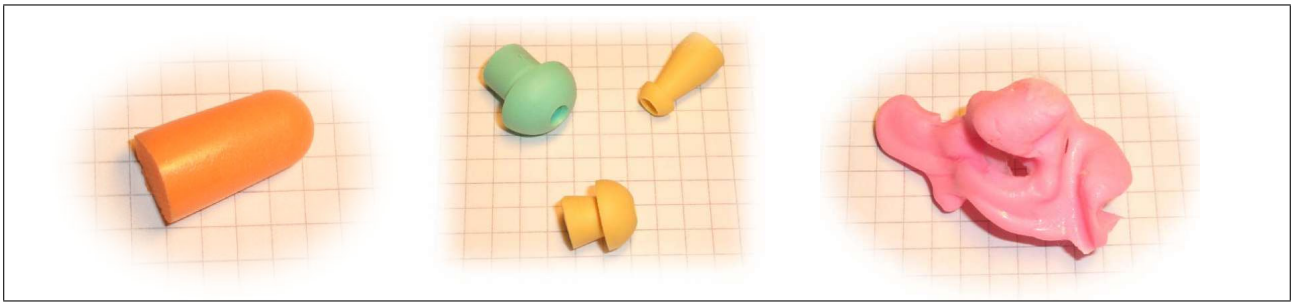


Figure 3. Coupling Devices: ear protection plug, tympanometry olives, and individual ear mold (otoplastic).

scribing the source using the source sound pressure $\underline{p}_0$ and series impedance $\underline{Z}_0$ is described.

Two different terminators have to be measured to determine the source parameters pressure $\underline{p}_0$ and $\underline{Z}_0$. Two rigid aluminum terminators (cylindrical tubes) of different lengths were created for this study.

The transmission line equations

$$\underline{p}(l) = \underline{p}(0)\cos(kl) + \mathrm{j}\rho_0 c\underline{v}(0)\sin(kl) \tag{1}$$

and

$$\underline{v}(l) = \mathrm{j}\frac{\underline{p}(0)}{\rho_0 c}\sin(kl) + \underline{v}(0)\cos(kl) \tag{2}$$

yield the impedance version of the transmission line equation

$$\underline{Z}(l) = \frac{\underline{Z}(0) + \mathrm{j}\rho_0 c\tan(kl)}{\mathrm{j}\underline{Z}(0)\tan(kl) + \rho_0 c}, \tag{3}$$

where $\underline{Z}(l)$ the impedance 'seen' at the input of a loss free transmission line of length l, terminated with an impedance $\underline{Z}(0)$ with

$$k = \frac{2\pi f}{c} = \frac{\omega}{c}. \tag{4}$$

Applied to the impedance probe, where $\underline{Z}(0)$ equals the demanded ear canal impedance, is $\underline{Z}(0)$ given by

$$\underline{Z}(0) = \frac{\mathrm{j}(\rho_0 c)^2\tan(kl) - \underline{Z}(l)\rho_0 c}{\mathrm{j}\underline{Z}(l)\tan(kl) - \rho_0 c} \tag{5}$$

With the rigid terminators for the calibration, we have $\underline{Z}(0) = \infty$, and thus $\underline{Z}(l)$ is given by

$$\underline{Z}(l) = \mathrm{j}\rho_0 c\cot(kl). \tag{6}$$

According to the equivalent circuit shown in Figure 2

$$\underline{p}_0 = \underline{v}\left(\underline{Z}_0 + \underline{Z}_M\right) \tag{7}$$

and

$$\frac{\underline{p}_0}{\underline{p}_M} = \frac{\underline{Z}_0 + \underline{Z}_M}{\underline{Z}_M}. \tag{8}$$

If the probe is applied to two different terminations, A and B, $\underline{Z}(0)$ are given by

$$\underline{Z}_0 = \frac{\underline{p}_{\text{measurement}B} - \underline{p}_{\text{measurement}A}}{\frac{\underline{p}_{\text{measurement}A}}{\underline{Z}(l_A)} - \frac{\underline{p}_{\text{measurement}B}}{\underline{Z}(l_B)}} \tag{9}$$

with

$$\underline{Z}(l_{A,B}) = \mathrm{j}\rho_0 c\cot(kl_{A,B}). \tag{10}$$

The operating range of the probe is between 100 Hz and 8.5 kHz. The lower limit can be put down to the loudspeaker, since creating a sufficient sound pressure level at low frequencies in the thin connecting tube is rather complicated. The upper limit can be put down to the calibration with the two different rigid terminators. The rigid termination yields a pole on the basis of the cotangent-function. Using these equations the impedance probe can be fully described and the impedance can be calculated with just one measurement of the sound pressure. Finally the results need to be transformed from the measurement plane to the ear canal entrance plane. The impedance must be multiplied with the ratio of the surface area of the tube to the surface area of the ear canal entrance where the probe is attached to.

3.1. Connecting the probe to the ear canal

There are different possibilities to connect the probe and the ear canal. Ear-plugs and tympanometry olives (Figure 3) turned out to be unsuitable [16].

It is very complicated to handle the foam of the ear-plugs. The probe needs to be fixed into the ear-plug, but they do not seal neither the probe nor the ear canal entrance sufficiently. This causes problems regarding the repeatability of the measurement. The same holds true for tympanometry olives.

Individually 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 into the ear. The individual ear mold is created with the help of a hearing aid consultant. First, he checks whether the ear canal is healthy and clean and studies the curvature of the ear canal. Then he places a small wad of cotton wool into the ear canal in front of the eardrum. A piece of thread is tied to the wad to retrieve it from the ear canal. The ear canal and the

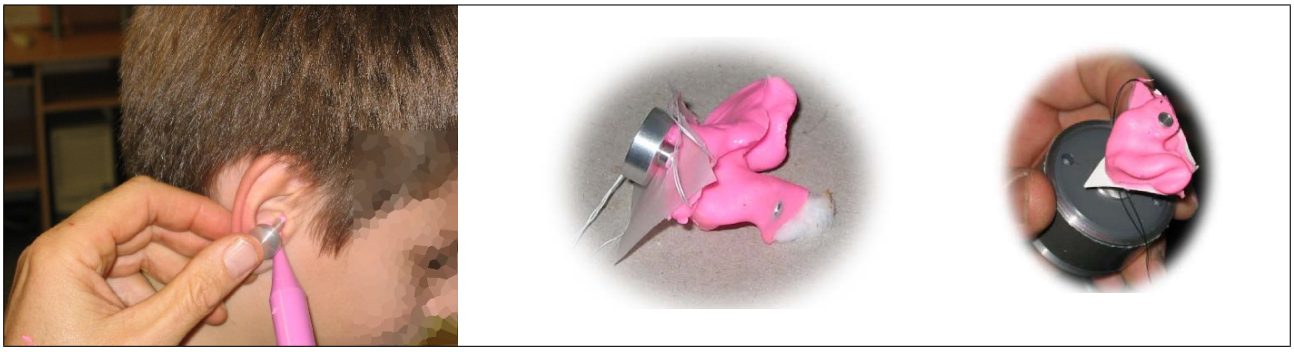


Figure 4. Creation of an individual ear mold, Individual ear mold with pin (in the dimensions of the probe) inside, Impedance probe ready to measure an individual subject.

complete cavum conchae are filled with a twocomponent cold-curing composition (Figure 4). A pin resembling the size of the impedance probe is placed in the direction of the ear canal and is fixed to the ear mold before curing. The ear mold is cured and can be taken off five minutes later. Figure 4 shows an individual ear mold directly after taking the ear mold out of the ear canal.

The individual impression allows a very exact definition of the ear canal entrance plane since the transition from cavum conchae to the ear canal entrance is clearly visible. The pin is taken out of the ear mold and the ear mold is cut to the desired length using a scalpel. Then the impedance probe can be placed into the hole of the pin. Figure 4 (right) shows the impedance probe with an individual ear model ready for measurement. The ear mold is covered with a thin oil film to seal the ear mold to the cavum conchae for the measurement.

The measurement procedure is evaluated and the repeatability of the measurement is tested on adults prior to the measurements on children.

The soft ear plugs and tympanometry olives show how the ear canal impedance is distorted, if the impedances probe does not seal the ear canal entrance properly. In this case the impedance or the measured sound pressure is equivalent to a measurement with the open impedance probe (with no coupling to the ear canal) at very low frequencies. In this case the impedance is very low at low frequencies. This might also occur when an individual ear mold does not seal the cavum conchae and the ear canal entrance sufficiently. However, if for each subject the measurement is repeated several times, the flawed measurements can be rejected.

If the measurement is correct, the impedance shows a spring-like behavior for low frequencies. The influence of the quality and repeatability of different individual ear molds is tested on one subject. The hearing aid consultant created an individual ear mold three times. The factor, which may cause differences, is, in this case, the placing of the pin during the curing of the ear mold. However, the repeatability of the measurement is very satisfying. Figure 5 shows the sound pressure levels (a, c, relative values) and phase responses (b, d) for the three individual otoplastics. The maximum deviation is about 2 dB between 100 Hz and 6 kHz.

Choosing the right ear canal entrance plane is crucial. The latter is tested on one subject. The individual ear mold was shortened in steps of 1 mm. Thus, at first the ear mold extended 5 mm into the ear canal. Figure 5 shows the relative sound pressure levels and phase responses of the five measurements. Most differences caused by the choice of the ear canal entrance plane occur below 2.5 kHz. However, this measurement also focuses on the measurement repeatability itself. The probe is replaced in the ear for each measurement. Thus, it is difficult to retrace the reasons why the measurement deviates. However, it can be observed that it is rather difficult to choose the entrance plane. However, when using an individual impression, it is comparatively easy to figure out how to define the ear canal entrance plane. Similar findings are observed in Finite Simulations of the ear canal by Schmidt [17, 18].

Each measurement is tested to make sure that the level of the measurement sweep is low enough so that the stapedius reflex does not occur. The stapedius and tensor tympani muscles of the ossicles contract when the sweep is presented with a high-intensity. This should be avoided in the measurement.

4. Verification of the Measurement with a Simulation

The impedance of a well-defined test volume is once simulated using FEM (see [19]) and once measured with the measurement probe to compare the two approaches used to determine the ear canal impedance. The test volume is a compact aluminum cylinder with an inner diameter of 8 mm. The cylinder is 35 mm long. After mounting the impedance probe the cylinder is still 25 mm long. This arrangement is similar to the real position on a human ear. The length of 25 mm corresponds to a not yet 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 6 shows a CAD model and a technical drawing of the test volume. The measurement and simulation results are discussed in the following paragraph. Figure 7

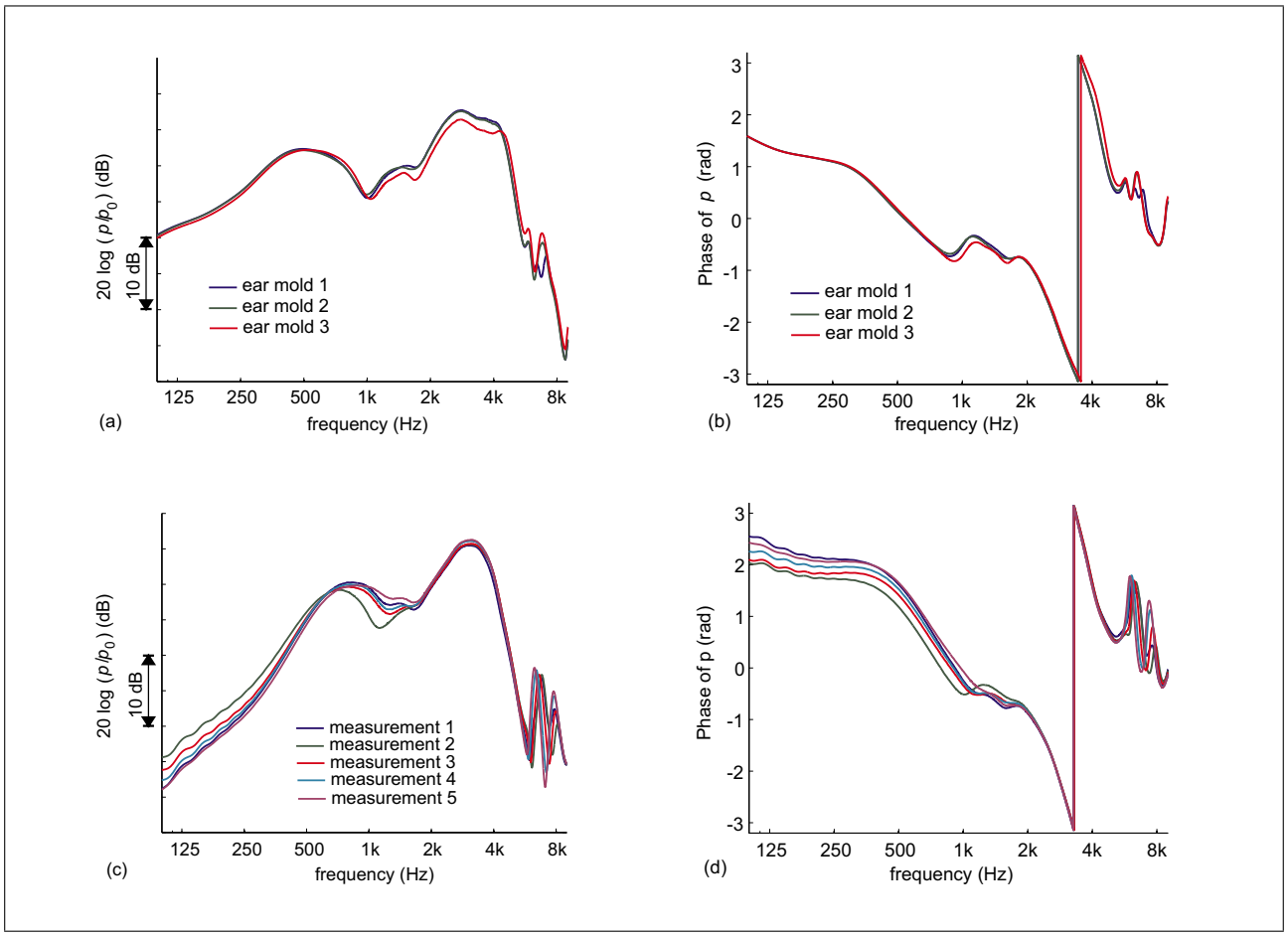


Figure 5. Repeatability of measurements with the impedance probe: Three different ear molds and variation of the ear canal entrance plane.

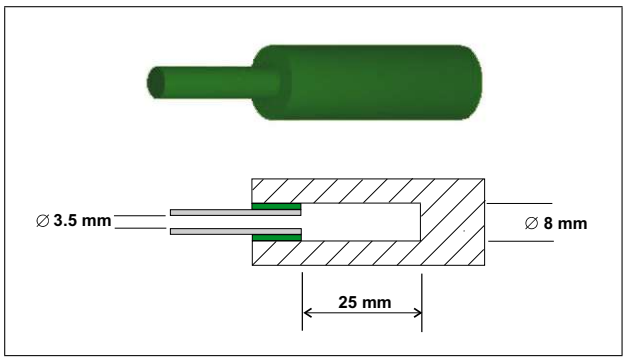


Figure 6. Test volume.

shows the magnitude (a) and the phase (b) of the impedance which were observed during simulation (dotted line) and measurement (solid line). The frequency and phase responses of the simulation and the measurement show a good concordance. 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. This might be due to damping, edge effects, or incorrect boundary conditions during the simulation. The simulation was carried out under ideal boundary conditions that can be assumed for the aluminum cylinder. But on the other hand the measurement procedure might be not as exact.

However, no damping is assumed in this study, since the relevant literature provides no data about the correct value of the damping in the ear canal. However, the impedances (magnitude and phase response) show a good concordance.

The damping effect increases, if the inner diameter of the probe becomes smaller. Studies on the loss effects in smaller tubes are carried out, since smaller tubes have to be used when measurements are performed on children who younger than approx. 3 years old. However, the probe used in this study has an inner diameter of 3.5 mm and the damping and loss effects can be neglected for the transformation of the impedance.

When smaller tubes are used the loss effects should be taken into account in order to obtain correct results for the impedance. The author could show that it is be possible to measure the impedance with a smaller probe (inner diameter of 2.5 mm) with satisfactory results [15]. However, in order to measure very young children (younger than 1.5 years of age) it turned out, that the probe needs to be even smaller than 2.5 mm. If, however, probes with smaller dimensions are used, measurement faults occur, that still have to be analyzed.

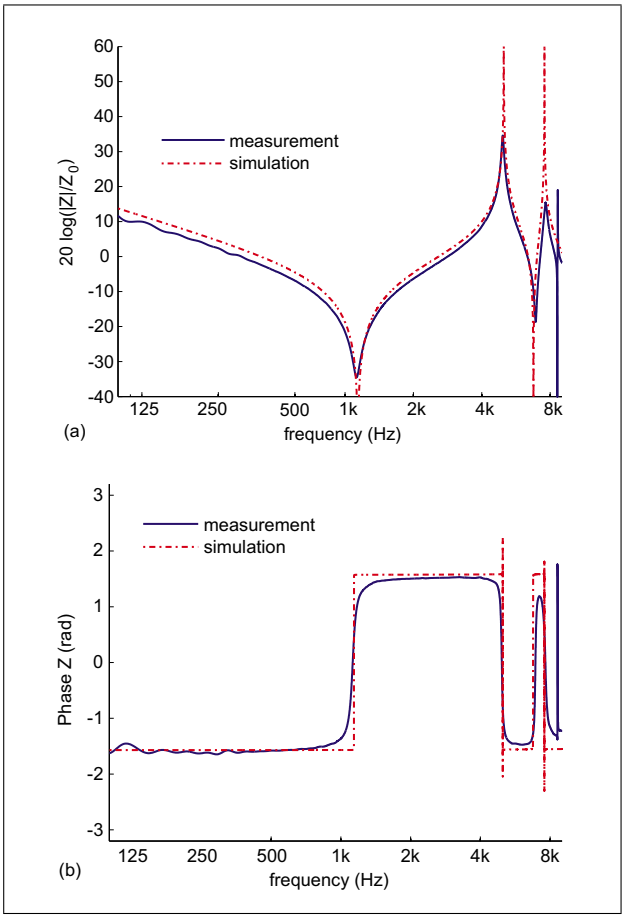


Figure 7. Magnitude and phase response obtained by measurement and simulation of a test volume.

5. Ear Canal Impedances of Children and Adults

For this study 22 children took part in the measurement. The age distribution of the measurement subjects are plotted in Figure 8.

For the measurement procedure children had to be found whose parents gave their consent so that they could take part in the study. The children are students of a special school (and pre-school) for deaf and hearing impaired children. There is no reason to consider the ear canals abnormal. However, there is a probability that the middle ear is not fully normal, which is not studied. This school was chosen for two reasons. First: the parents had to give their consent. As a two-component cold-curing composition is used to create the individual ear molds, parents are often concerned about the risks that this procedure might entail for their children. However, as the parents deal with hearing impaired people every day, they are often willing to give their consent as they are aware of the benefits of this study. The second reason was that it is a rather awkward feeling when the two-component cold-curing composition is injected into the ear canal during this procedure. Most of the children who attend this school wear hearing aids and are therefore used to this kind of procedure. These students undergo medical treatment regularly and are checked upon

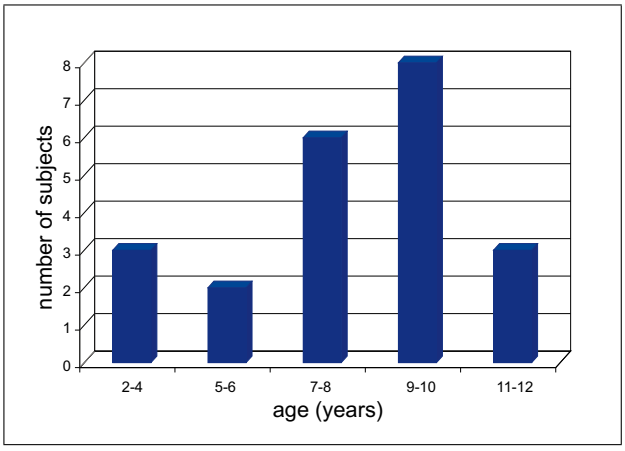


Figure 8. Age distribution of the test subjects.

every week by a hearing aid consultant. The consultant also knows whether the eardrum and ear canal is abnormal or healthy.

It was possible to measure 15 male and seven female students of this school. Before the individual ear mold was created, the children's height and age were registered. The measurement was repeated at least four times, with very patient children up to nine times. For each repetition the ear mold and impedance probe were taken out of the cavum conchae and inserted again. If a faulty measurement was found during the repeated measurement, this measurement was rejected and not taken into account. If the individual ear mold is manufactured with the whole impression of the cavum conchae up to the pinna fine structure, it is easy to replace the ear mold at exactly the same position with no degree of freedom.

No problems occurred while using this method on children even when tests were carried out on three year-old subjects. If younger children need to be measured, a smaller probe will have to be used. Since the diameter of the probe would be too large. Figure 9 shows the measured ear canal impedances for all subjects. When comparing these results with measurement results of Ciric and Hammershøi [9], the individual differences among the subjects are in a similar order.

The measured impedances of children aged four to nine years are shown in Figure 10. Compared with the geometrical ear canal parameters, children under the age of six years should show different ear canal impedances. The first resonance is relatively difficult to identify.

The resonance frequencies of the children under the age of six are slightly higher (around 3.8 kHz) than those obtained for adults. However, similar outliers are reported by other authors as well [9]. The age groups consisting of children who are over nine years old show an individual deviation, but a dependency on the age cannot be observed for subjects of this age. Furthermore, a correlation between the body height and the ear canal impedance could not be found, since the number of subjects in the age group under the age of six to seven is small.

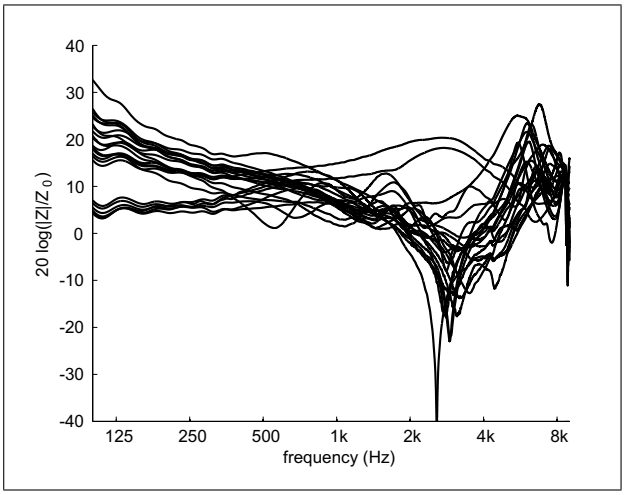


Figure 9. Measured ear canal impedances for all subjects.

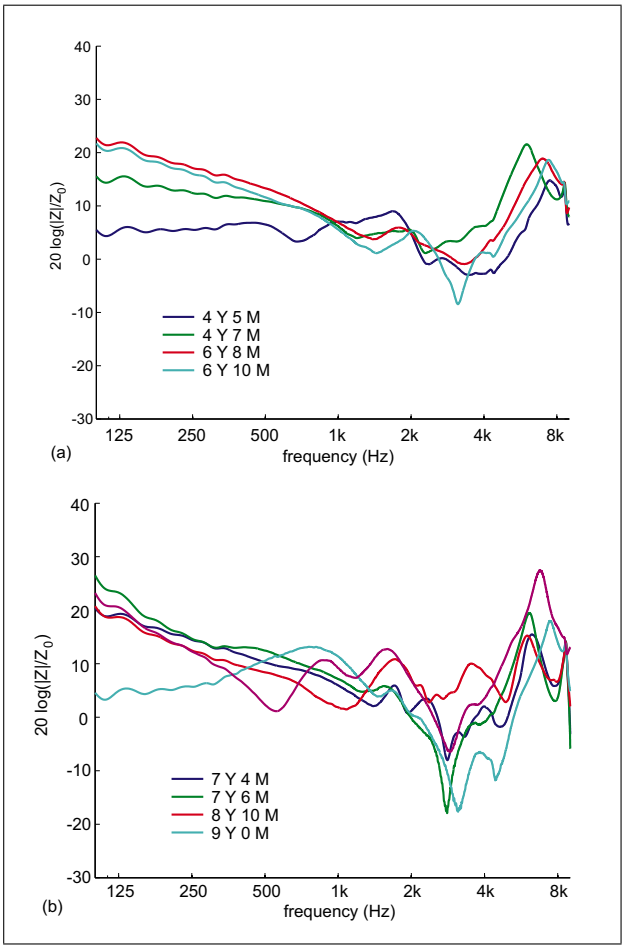


Figure 10. Measured ear canal impedances for the age group: 4–6 years (a) and 7–9 years (b).

6. Summary and Conclusion

The ear canal impedances were measured for various subjects of different ages. The measurement method used in this study was for the first time used to measure the ear canal impedance on children's ears. The coupling of the probe to the ear was examined and the measurement repeatability was discussed. The measurements results of the probe have been verified using a FEM simulation of a test cylinder. For real ear measurements, the probe diameter is with 3.5 mm too large to measure the most interesting age group (from newborn up to 5–6 years of age). The measurement method using smaller impedance probe is being now further developed (see [15]). However, a large database of children will have to be measured.

Another possibility is to simulate the ear canal impedances [19]. However, the simulation probably lacks some physical properties to achieve more realistic results. Ear canal properties such as the exact definitions of the ear canal wall properties and the eardrum properties still need to be studied in detail.

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