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Ear Canal Properties of Children: Dimensions of Ear Canals and Simulation of the Input-Impedance*

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Summary
Today, only a few standardized couplers (i.e. a 2 ccm coupler (IEC 60126)) are used to fit hearing aids for infants, children, and adults. If we want to develop couplers that improve the fitting process for different age groups, we have to study the ear canal properties of infants and children in detail. The smaller ear canal of children leads to different input impedances than those of adults. In this study CAD-models were generated using CT-scans (computed tomography) of young children and adults. Using the CAD-models the ear canal properties and geometry are studied. A simulation of the ear canal impedance using FEM (Finite-Element-Method) was performed and analyzed in this study.

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1. Introduction

The ear canal dimension and impedance play an important role, especially when it comes to sound sources which are coupled to the ear (such as head phones, in-ear phones or hearing aids). Since those sources are attached to the ear and the ear canal, the load impedance changes. The ear canal (meatus acusticus externus) is a tube that runs from the pinna to the eardrum. A typical adult ear canal is about 2–3 cm long and has a diameter of 0.6–0.8 cm. The ear canal is slightly convexly curved in the back and upper direction (for protection). The outer half to two thirds of the canal is surrounded by cartilage and has glands that produce cerumen (ear wax), while the inner third to half is surrounded by bone.

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. Thus the ear canal properties (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 with a real human ear. This is especially true for children. Researchers found out that the deviation from standard 2 cm^3 coupler-data is about 15–19 dB (SPL) for infants (cf. [4]). For reasons of robustness and production tolerances, however, this coupler is still in use. The only existing coupler for children is the "Freiburger Konische Kinder Kuppler" (FKKK - a cone-shaped coupler for children made in Freiburg by Keller [5, 6]). This coupler has a volume of 0.6 cm^3 and is intended for three to five-year old children. The geometrical data of this coupler is based on a study by Pfeil [7]. When this coupler was introduced, it was for the first time possible to fit hearing aids for children without using correction factors.

A direct connection between the values of the growth-dependent differences in the ear canal impedances and studies of the organ of hearing is postulated by Keefe [8]. In order to gain more insights and to obtain more data, this study focuses on the investigation of ear canal properties, i.e. dimensions and impedances of children.

2. Data acquisition and simulation of ear canal impedances

For this article the Finite Element Method (FEM) was used to calculate the ear canal impedance. CAD models of the ear canals were reconstructed for a simulation based on CT scans (computed tomography) of the petrous bone. The construction of the CAD models is the major challenge when simulating ear canal impedances of children. Whether the reconstruction is finely detailed or not depends on the resolution of the CT scans. The transition between air and tissue is clearly visible on each scan. The

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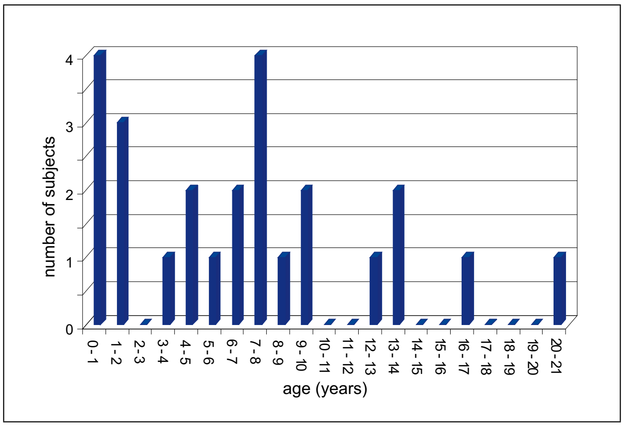

Figure 1. Age distribution of subjects.

eardrum is visible as a thin membrane. In each slice, the contours of the ear canal and the eardrum are extracted manually by drawing splines along the transition between air and tissue.

As the risks of a CT-scan are very high, it was not possible to use volunteers. Thus, this study uses CT-scans that have been provided for research use by the University Hospital Aachen. A total of 25 CT-scans was available for the data acquisition that was performed for this study. The subjects were not examined at the hospital because of any hearing diseases. The test group consisted of 12 male and 13 female subjects aged between three weeks and 20 years. The age distribution of the subjects is plotted in Figure 1.

Due to the limited resolution of the CT scans, very narrow spaces might be neglected. The step size (resolution) of the CT-scans was between 0.75 mm and 1 mm.

Every scan of the CT is loaded into the program MicroStation (this program was created by Bentley using the photogrammetry-plugin PHIDIAS[1] [9]). The program automatically shifts each scan into the correct distance and angle. Figure 2 shows a screenshot to illustrate this approach. Afterwards the CT-scans are loaded and the contours are extracted.

At the ear canal entrance all splines are cut to define the reference plane. This plane results from the transition zone between cavum conchae and ear canal (similar to a blocked or sealed ear canal entrance plane). This reference plane is not necessary perpendicular to the middle axis of the ear canal, as the ear canal might turn in a different direction. Using these layered splines a closed volume model can be generated (see Figure 3). The volume is discretized using tetrahedral-elements with a length of 1 mm to 3.1 mm (maximum) (corresponding to $d_{\max} = \lambda/6$ with λ = minimum wave length according to the highest calculated frequency).

Vallejo [10] calculated the impedance of one ear canal at the ear canal entrance using a simulation technique and compared his results with other authors. Stinson and Daigle [11] used the Boundary Element Method (BEM) to study the sound field in the human ear canal. Schmidt

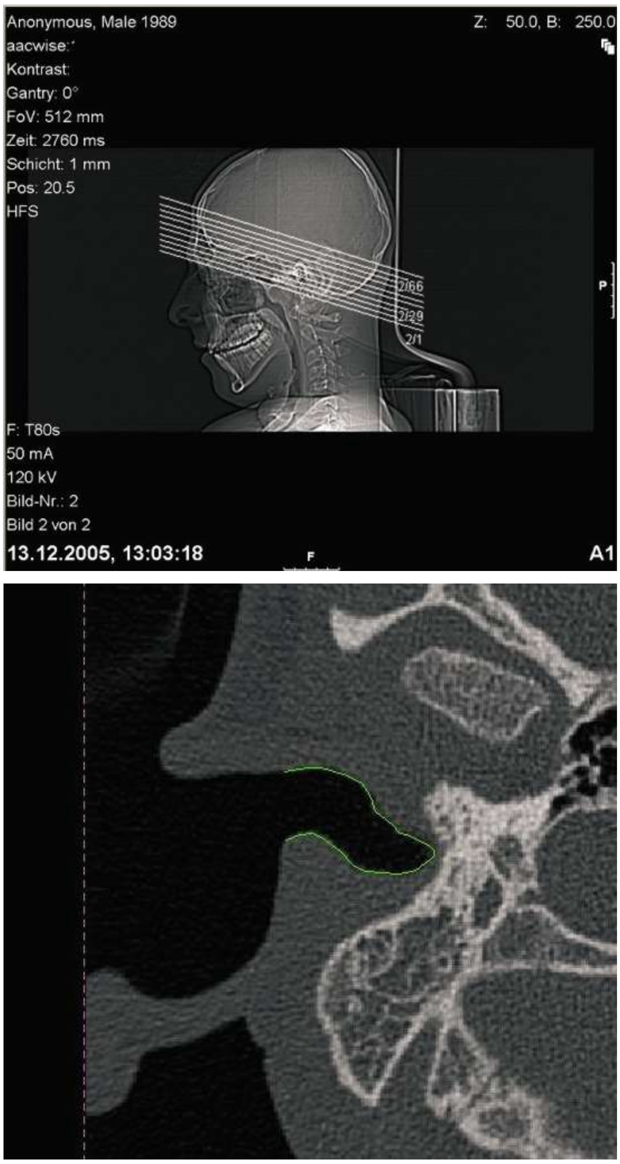

Figure 2. Generating CAD models of the ear canals using CT-scans. Top: Overview of the scans. Bottom: Shape (contour) of the ear canal in one scan.

[12, 13] studied the wave field in the ear canal using the Finite Element Method (FEM).

Using the Finite Element Method the ear canal impedance can be derived up to frequencies of 16 kHz, corresponding to the $d_{\max} = \lambda/6$-rule. The input impedance of the ear canal, however, depends on the impedance of the middle ear. The middle ear is not modeled and simulated in this work. The impedances are calculated using the geometrical data and the boundary conditions of the surfaces (ear canal and eardrum) chosen in the simulation. The solver *SoundSolve* used for this study was developed at the Institute of Technical Acoustics (RWTH Aachen University) (cf. [14, 15]).

The ear canal entrance plane is used as a well-defined interface between the outer ear functions and the ear canal properties, but also as an excitation area for the FEM. Since the ear canal is sealed with this plane any reflections caused by this plane have to be avoided.

[1] phocad.de

The FEM simulation in this study uses a second order isoparametric tetrahedral discretization of the time-harmonic wave equation. The source is modeled with a prescribed constant particle velocity distribution across the ear canal entrance plane along with a planar nonreflecting impedance boundary condition. Therefore an impedance of $Z = \rho_0 c_0$ (characteristic impedance of air) is applied to the entrance plane. The solution of the complex sound pressure field is obtained with direct or iterative solvers for the resulting system equations.

The input impedance is independent from the radiating impedance in the other direction. Furthermore, the acoustic properties of the other surfaces (ear canal wall and eardrum) need to be defined.

In general, the fibrocartilaginous part forms the outer third of the canal; a bony part forms the inner two thirds. The bony part is much shorter in children. Studies of the acoustic impedance on skin show that skin can be regarded as rigid (see for instance [16, 17]). It is, however, not easy to determine the acoustic properties of the eardrum. It is hence necessary to model every detail accurately for a correct simulation. There is a myriad of studies dealing with the acoustic properties of the eardrum, especially the eardrum impedance.

From 1956 to 1977, Morton and Jones [18], Zwislocki [19], Blauert and Platte [20], and Mehrgardt and Mellert [21] collected different data of human adults. Additionally, measurements of corpses were carried out by Onchi [22] and Fischler *et al.* [23]. However, the findings of these studies vary tremendously. This is caused on the one hand by different measurement techniques and subjects (since ears of deceased subjects are not comparable to ears of living subjects) and on the other hand by the assumption that an ear canal is a tube of constant cross section. Hudde [24] showed that the eardrum impedance depends on the variation in the cross-sectional area along the ear canal axis. Hudde explains in [25] that in-vivo measurements are only valid up to frequencies of 2 kHz. The latest results are published in [25, 26, 27]. The results are based on measurements of ear canals of corpses. The ear canals were measured as soon as possible (the measurements were carried out no later than two days after the person had passed away) and stored in sodium chloride solution. Hudde determined an eardrum impedance based on these measurements. Due to a lack of more recent data, this impedance is used in this study in addition to the rigid definition of the eardrum. It is still uncertain whether these values can be used for children and infants as well or not.

The results of the Finite Element Method show the sound pressure at a definite point on the ear canal entrance plane (cf. Figure 3). In this study the point at the center of the ear canal entrance plane is chosen.

With the boundary condition of the ear canal entrance plane ($\underline{Z}_0 = \rho_0 c_0$), the intended ear canal impedance equals, according to the equivalent circuit diagram in Figure 4,

$$\underline{Z}_e = \underline{p}/\underline{v}_2, \tag{1}$$

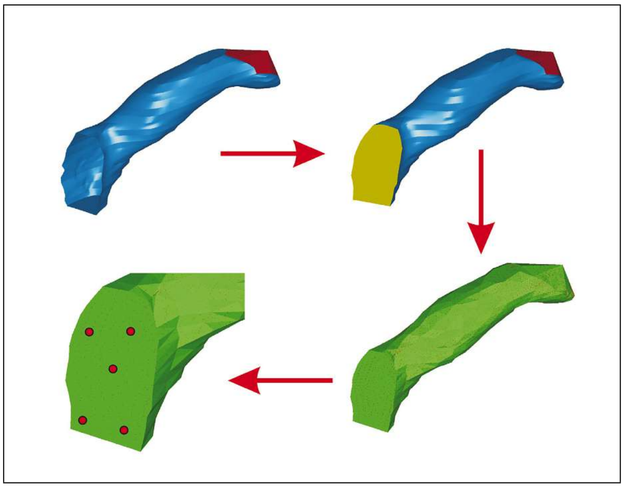

Figure 3. CAD modeling of the ear canals showing the process from a surface model (generated out of splines) to a discretized volume model. The ear canal entrance plane is defined in the second step. Possible points on the entrance surface area to read out the input impedance are shown in the last step.

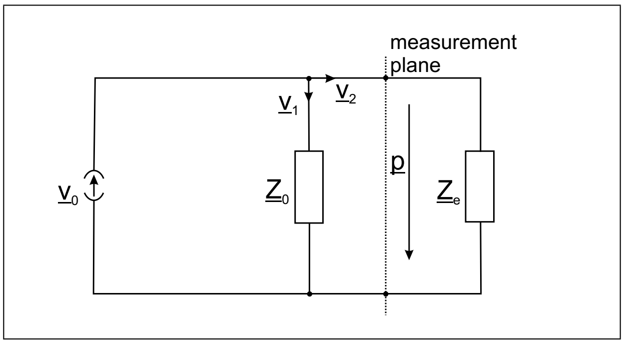

Figure 4. Equivalent circuit diagram for the calculation of the ear canal impedance based on the sound pressure of the simulation.

with

$$\underline{v}_2 = \underline{v}_0 \frac{\underline{Z}_0}{\underline{Z}_0 + \underline{Z}_e} \tag{2}$$

($\underline{v}_0$ = particle velocity of excitation).

Thus, the ear canal impedance can be calculated according to

$$\underline{Z}_e = \frac{\underline{p}}{\underline{v}_0} \frac{1}{1 - \underline{p}/(\underline{v}_0 \underline{Z}_0)}, \tag{3}$$

with

$$\underline{Z}_0 = \rho_0 c_0 = 414\,\mathrm{Ns/m^3}. \tag{4}$$

In this case the density of air is $\rho_0 = 1.204\,\mathrm{kg/m^3}$, and the speed of sound is $c_0 = 344\,\mathrm{m/s}$, which corresponds to a temperature of approx. 20 °C according to [28]. The temperature within the ear canal is higher, however, $\underline{Z}_0$ is applied at the ear canal entrance, thus it is coupled to the room temperature.

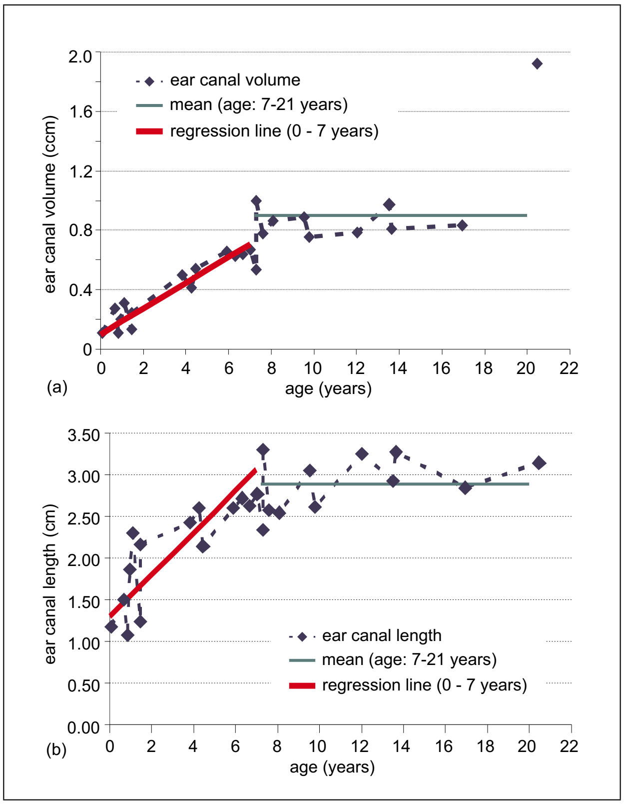

Figure 5. Ear canal parameters as a function of age. (a): Ear canal volume, (b): Ear canal length.

The ear canal impedances and corresponding figures in this study are normalized to the characteristic impedance of air according to

$$\underline{Z}'_e = 20\log\left(\frac{|\underline{Z}_e|}{\underline{Z}_0}\right) \tag{5}$$

Thus, in this study the specific impedance is used. Another possibility would be to use the acoustic impedance. The difference is that using the volume velocity the acoustic impedance at low frequencies is proportional to the volume of the ear canal. Using the cross-sectional area of the ear canal entrance plane the acoustic impedance can be calculated or vice versa. The authors tend to use the specific impedance because this makes it possible to compare measurement results of ear canal impedances using a calibrated source with simulation results without taking the ear canal entrance plane into account.

3. Anthropometric data of ear canals

The CAD models created for the simulation can be used for a data analysis of the geometrical features of the ear canals. The parameters ear canal volume, length and the surface area of the eardrum are calculated and discussed. The uneven age distribution and limited data inhibits complete statistics, however, the geometrical data are examined in terms of correlation to growth. Input Impedances mainly reflect to the ear canal volume and the length of the ear canal. The length of an ear canal characterizes the poles and zeros of the ear canal impedance. The surface area of the eardrum has no direct impact on the impedance, however, this area is shown since the boundary conditions of the surface area differs from the other boundaries in the ear canal.

3.1. Ear canal volume

Many different values of the ear canal volume can be found in relevant literature. Brunner [29] determines a volume of 1.5 cm^3, Stinson *et al.* [30] published values between 0.91 cm^3 and 1.725 cm^3 for subjects with an average age of 55 years (male subjects) and 65 years (female subjects) respectively. Pfeil [7] determines an average value of 0.343 cm^3 for 31 children (and 59 ear canals) aged between two and ten years.

Twentyfive ear canals were measured for this study. For subjects younger than seven years of age, the mean value is 0.365 cm^3, which is very close to the values obtained by Pfeil. With advancing age (over seven years) the volume increases to approx. 0.90 cm^3 (see Figure 5a). This corresponds to results of [30]. When taking a closer look at the volume as a function of age, it can be observed that the volume ranges from 0.1 cm^3 to approx. 0.65 cm^3 over the first seven years. This fact underlines that these values are strongly correlated to growth. Almost no age-dependent alteration can be observed for children who are over seven years old. The same applies to the growth of the skull cranial bone. At the age of six 95% of the growth is completed and at the age of seven the growing process comes to an end [31]. There is only one outlier in terms of volume in the dataset (the subject is 20.5 years old). The ear canal of this subject has an extremely large diameter compared with the other subjects. This reflects in a large volume while the length of this ear canal and the surface area of the eardrum within the range of the other subjects in this age group.

During the calculation based on the CAD models some information might get lost, since the CT scans are created with a layer thickness of 0.75 to 1 mm. Therefore, the models do not match precisely. The correlation coefficient defined by Bravias-Pearson (cf. [32]) is calculated to test the correlation between age and volume. However, the correlation between two criteria describes a necessary but not sufficient condition for a causal connection. The correlation coefficient for the group of subjects aged between zero and seven years is $r_{0-7} = 0.949$. This allows the assumption that the ear canal volume correlates with age. Figure 5a also shows the regression line (bold) for a perfect correlation ($r = 1$). This regression line fits the determined ear canal volumes very well. Taking a closer look at the subjects who are over seven years old, we can see that the correlation coefficient for this group is $r_{7-21} = 0.715$. Without the outlier the correlation coefficient is $r_{7-20} = 0.298$, which suggests that there is no connection between volume and age. All numerical values are provided in Table I.

3.2. Ear canal length

Determining the ear canal length turned out to be more difficult. There are different possibilities to determine a curved ear canal. For this study the mean value between two splines on the surface was calculated. The curved central axis is approximated by two splines positioned oppositely on the ear canal walls. The result is similar to the length of the curved central axis of the ear canal. Using this procedure several middle axes can becreated, depending on the position of the splines. However, the deviations turned out to be very small.

The length of the ear canal is often given as approx. 3.0 cm [29]. Stinson *et al.* [30] determined values between 3.5 cm and 2.7 cm for subjects with an average age of 55 (male subjects) and 65 years (female subjects) respectively. Stinson *et al.* determined the length of the curved central axis of the ear canal.

For the subjects over seven years of age the mean value of the ear canal length is 2.88 cm. Figure 5b shows that not only the volume depends on the age, but that there is also length of the ear canal. The correlation coefficient for subjects under seven years is $r_{0-7} = 0.814$. Although the number of subjects available in this age-group and the uneven age distribution, it can be stated that regression line for a perfect correlation is fitting, although there are some outliers. The correlation coefficient for subjects who are over seven years old is $r_{7-21} = 0.434$ and the ear canal length stabilizes at the age of seven.

3.3. Surface area of the eardrum

The surface area of the eardrum has a total area of 85 mm^2 according to [29]. The eardrum surface areas of children under the age of three are, except for one outlier, just between 10 mm^2 and 17 mm^2. The values of the older subjects do not differ much from the values published by other authors. The mean of the subjects older than seven years is 66.1 mm^2. The correlation coefficient for subjects under seven years is $r_{0-7} = 0.763$. The regression line for a perfect correlation is also plotted in Figure 6. In this case, greater deviations can be observed. However, a general trend is noticeable when it comes to the growth dependency of the eardrum surface area. There is no correlation to the age since the correlation coefficient for subjects older than seven years is $r_{7-21} = 0.079$.

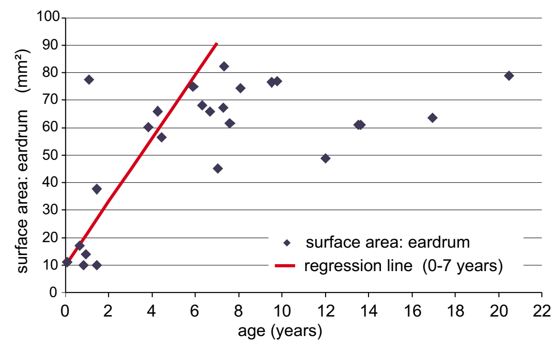

Figure 6. Surface area of the eardrum vs. age.

Table I. First resonance of the input impedance and geometrical data of the ear canals for all subjects. f_f: first resonance in kHz; ℓ: ear canal length in cm; V: ear canal volume in cm^3; S: eardrum surface area in mm^2.

age	f_f	ℓ	V	S
3 weeks	11.0	1.18	0.110	11.2
0 Y 08 M	6.7	1.51	0.273	17.0
0 Y 10 M	9.1	1.08	0.111	10.0
0 Y 11 M	3.9	1.87	0.199	14.0
1 Y 01 M	2.6	2.30	0.310	77.4
1 Y 05 M	4.1	1.25	0.133	10.0
1 Y 05 M	9.2	2.17	0.243	37.7
3 Y 10 M	3.9	2.43	0.501	60.2
4 Y 03 M	2.4	2.60	0.415	66.0
4 Y 05 M	3.9	2.15	0.539	56.5
5 Y 11 M	3.3	2.61	0.656	75.0
6 Y 04 M	3.5	2.72	0.624	68.1
6 Y 08 M	2.9	2.63	0.636	65.9
7 Y 00 M	3.5	2.77	0.671	45.1
7 Y 03 M	3.8	2.34	0.533	67.2
7 Y 04 M	3.5	3.31	0.995	82.4
7 Y 07 M	3.6	2.58	0.781	61.6
8 Y 01 M	3.7	2.55	0.865	74.4
9 Y 06 M	2.9	3.05	0.887	76.5
9 Y 09 M	3.4	2.62	0.755	77.0
12 Y 00 M	2.0	3.25	0.784	48.9
13 Y 06 M	3.6	2.93	0.972	61.0
13 Y 08 M	3.0	3.27	0.811	61.0
16 Y 11 M	3.5	2.85	0.833	63.6
20 Y 06 M	3.2	3.15	1.920	79.0

4. Ear canal impedances of children and adults

Figure 7 shows the simulated ear canal impedances separately for four age groups. At first, these simulations were carried out assuming a rigid eardrum. Hence, all boundary conditions are rigid.

The impedances mainly reflect the volumes and the lengths of the ear canals. The lengths of the ear canals produce the transmission line characteristics given by poles and zeroes. The area function across the ear canal produces some shift of the poles and zeroes.

One can easily see that there is a large variation in the age group under 1.5 years (Figure 7a). The youngest child in this age group is three weeks old. The resonance frequency is at 10.1 kHz and differs clearly from a typical adult one. Even though there are subjects of similar age (e.g. 8, 10, and 11 month old subjects) the resonance frequencies differ tremendously with approx. 4 kHz (11 month-old), 6.8 kHz (8 month-old) and 9 kHz (10 month-old). This correlates with the geometrical features of the ear canal (cf. Table I).

The same is true for subjects who are approx. 1.5 years old. The first resonance of these subjects varies between

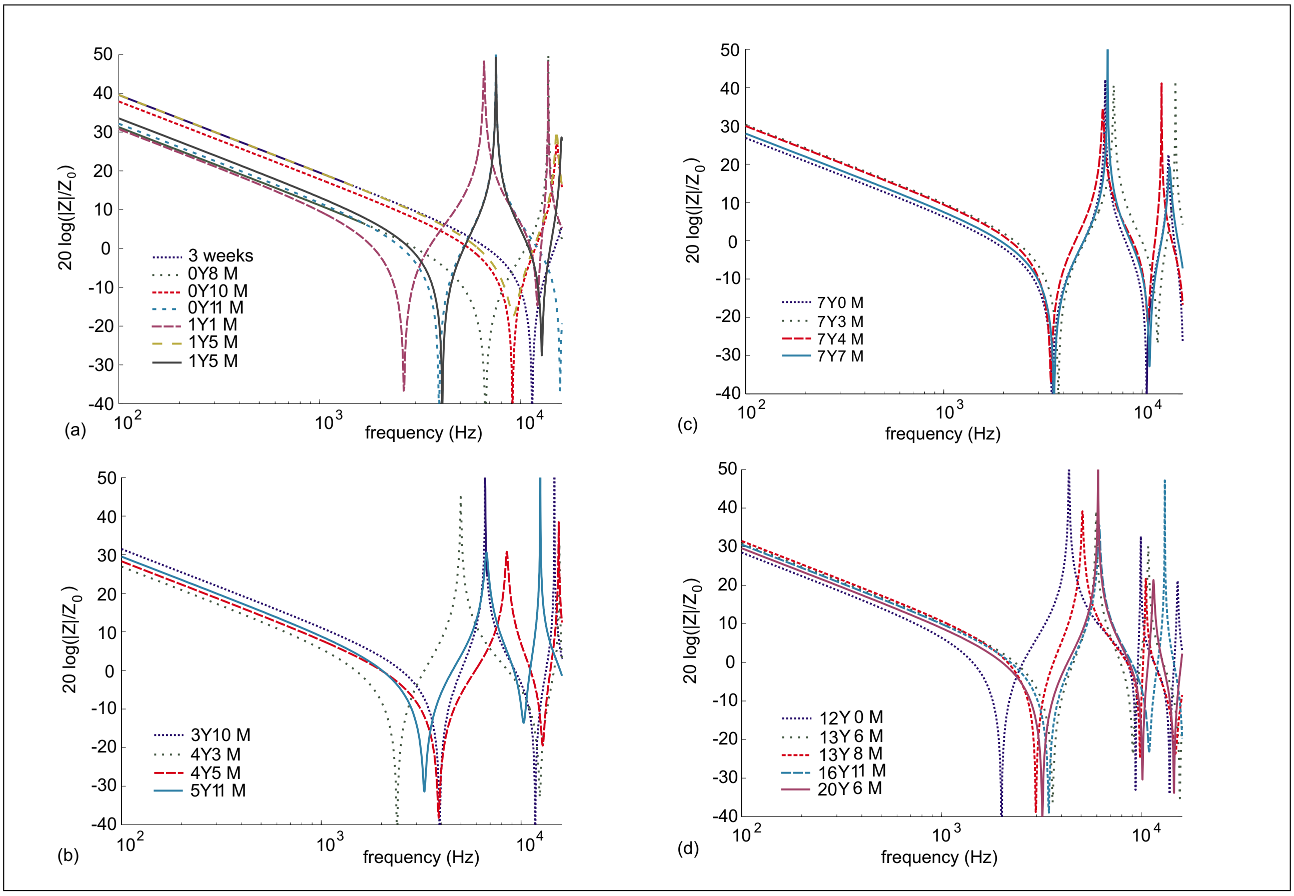

Figure 7. Simulated ear canal impedances. (a) Age group: 3 weeks–1.5 years, (b) Age group: 3–6 years, (c) Age group: 7 years, (d) Age group: 12–20.5 years.

2.6 kHz and 9.2 kHz. The test subject who is 1 year and 1 month old has the lowest first resonance from all 1 year-old children and accordingly this child has the largest ear canal. In contrast to this subject, there is one subject who is 1 year and 5 months old and the volume of the ear canal is only a third compared to the ear canal the 1-year and 1-month old subject.

Figure 7b shows the simulated ear canal impedances for four subjects who aged between 3 years and 10 months and 5 years and 11 months.

In contrast to the very young subjects, who show a large individual spread, the ear canal impedances of this age group are increasingly similar. The spread is substantially smaller compared with the younger subjects. The first resonance wavers between 2.4 kHz and 3.9 kHz. The geometrical data are also in the same order of magnitude.

The results for the age group of subject who are seven years old are very similar (Figure 7c). The first resonance of the subjects is between 3.5 and 3.8 kHz.

The last group consists of all subjects who are over 12 years old. Figure 7d shows the simulated ear canal impedances. The youngest subject has, however, the longest ear canal. The ear canal of the 20-year old subject has the largest volume of all ear canals. It is, however, shorter than the ear canal of the 12-year old subject, and the eardrum surface area is larger (factor 1.6) which causes the higher first resonance frequency.

4.1. Influence of the eardrum impedance

As described in section 2, many different values for the eardrum impedance can be found in relevant literature. The influence of the eardrum impedance defined by Hudde [25, 26, 27] for the frequency range from 100 Hz to 16 kHz was used for the simulations described in this study. The ear canal of a 16-year old male subject is used as an example. The values determined by Hudde have been fitted with the correct eardrum surface area of 63.6 mm^2 for the whole eardrum surface area.

Figure 8 shows the impedance of this ear canal once calculated with rigid boundary conditions and once with the eardrum impedance applied. The difference caused by the eardrum impedance is clearly visible. Only a very slight influence of the eardrum impedance can be detected at frequencies above 4 kHz, for higher frequencies the results are identical. The ear canal impedance with eardrum impedance taken into account is approx. 10 dB lower than with rigid boundary conditions for frequencies between 100 Hz and 1.0 kHz. At approx. 1.2 kHz the impedance increases to a small maximum and above 1.2 kHz the impedance shows slightly higher values than with rigid boundary conditions. Additionally, the quality factor is not as large at the resonance frequencies.

Figure 9 shows the simulated ear canal impedance (solid lines) of subjects who are over 12 years old. In

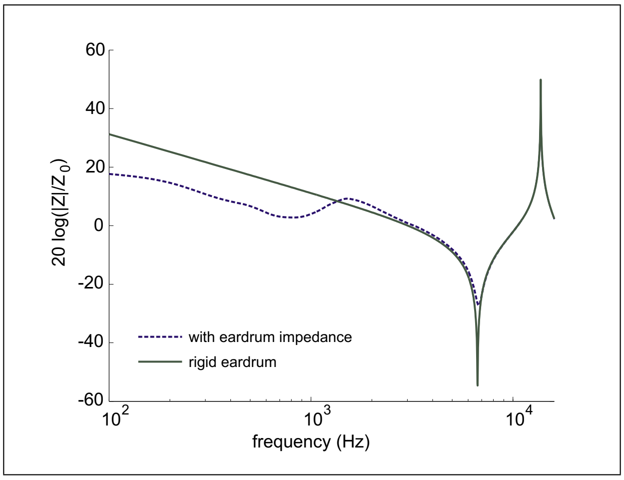

Figure 8. Simulated ear canal impedance with and without eardrum impedance.

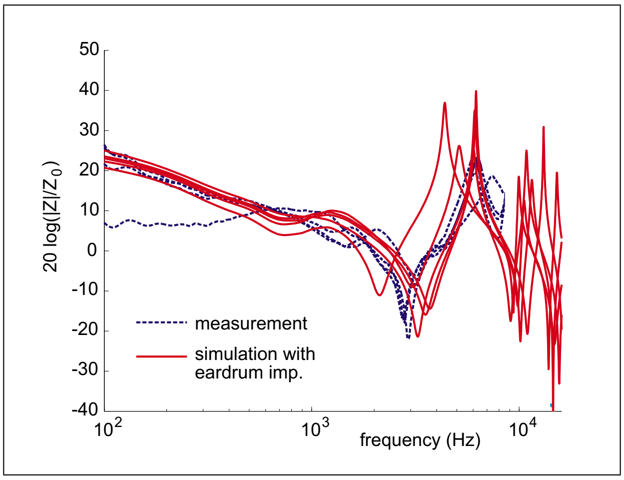

Figure 9. Selection of subjects: measurement results (dashed lines) and simulation results (solid lines) with eardrum impedance (subjects more than 12 years old).

this case the eardrum impedance after Hudde was taken into account according to the above described procedure. While comparing the results with the rigid simulations (Figure 7d) one can see that the main differences are the alteration in the level at low frequencies (now approx. 22 dB instead of 30 dB), the small maximum at approx. 1.2 kHz, and the lower quality factor.

In order to verify the correct values for the boundary conditions, an attempt was made to compare simulation and measurement results of subjects older than 6 years of age. Figure 9 shows a selection of measurement results (dashed lines) using a calibrated source (6, 7, 10 and 11 year old subjects, cf. [33]). This selection is plotted together with simulation results of the age group above 12 years.

Measurement and simulation results show a good concordance, although no identical subjects are compared. The typical features are depicted in this case. The first minimum is reproduced well; however, the first maximum is higher and sharper than the measured data. The characteristic maximum which is caused by the eardrum impedance can also be detected in the measurement. The eardrum impedances, however, are obtained with the help of grown-up subjects. Therefore we do not have sufficient information to know how eardrum impedances of children differ from adults. It is hence unclear whether the values determined by Hudde [25, 26, 27] are valid for children as well or not. It was not possible to examine a subject for this study who was able to participate in both a measurement and a CT scan. However, if one subject had been available for measurements and simulations, one would certainly have found out more about the damping and other physical issues. This still needs to be done.

5. Summary and conclusion

The ear canal properties were determined for various subjects of different age groups.

The ear canal volume and ear canal length increase from the age of zero to seven years more or less linearly and stagnate above seven years of age at a certain level. This correlates with the growth of the skull cranial bone. The same holds true for the surface area of the eardrum.

The simulation, however, lacks some physical properties to achieve more realistic results. The ear canal wall properties have to be defined exactly and the eardrum properties for children still need to be studied in detail.

The ear canal impedances of very young subjects aged between zero and three years vary significantly, although their anatomical features are quite similar. In this age group a small deviation of the ear canal volume, eardrum surface area or ear canal length yields enormous deviations of the ear canal impedances. From the subjects available in this study, the ear canal lengths of very young children show a large variance that no clear dependence on age can be seen. This reflects in the ear canal impedances. However, in these first years, the ear canal impedances differ significantly from typical ear canal impedances of adults.

Even though individual differences may occur, subjects aged between three and six years already have similar ear canal impedances. At the age of seven, the ear canal impedance seems to reach the characteristics that are usually found in adults. This is in line with the anatomical ear canal parameters. The ear canal impedances of subjects who are more than seven years old are already very similar to adults ones.

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