Variables affecting the real ear to coupler difference

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Abstract

The aim of this thesis was to compare real ear to coupler difference (RECD) values in different measurement configurations. To obtain fast predictions on the outcome of an RECD measurement, a plane wave transmission line model was made. Simulations of the effect of changes in different variables, makes it possible to investigate how these variables affect the RECD. These observations together with measurements in real ears and couplers can be used to explain how such variables affect the RECD. The model was validated by verification measurements in connection to a 2cc coupler, and an ear simulator, and proved its ability to accurately describe trends in RECD responses, where variables have changing parameters.

Main findings include a comparison of three different hearing aid receivers connected to hearing aid hooks to represent the acoustics in undamped hearing aids with different receivers, and an Etymotic ER3A insert ear phone were made, and revealed substantial differences in RECD. Interactions between hearing aid tubing and receivers were also found to be significant, in the simulation study.

The study concludes that the RECD response is affected by the entire acoustic system from the transducer to the medial end of the earmold’s sound bore. This knowledge is important to consider in the development of hearing aid fitting procedures and in regard to clinical practice.
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Chapter 1

Introduction

Approximately 15% of the population in Denmark live with a hearing loss. In many cases a hearing aid (HA) can help these people hear sounds and understand speech better. It is an electronic device which essentially amplifies sounds captured by its microphone and transmits the amplified sound to the ear via a speaker known as a receiver.

To ensure that a HA has the required gain to compensate for a hearing loss, its performance can be measured in a so called coupler. A common type of coupler for this purpose is the 2cc coupler, which has a small cavity of 2 cm$^3$. The 2cc coupler is defined in the IEC 60318-5 standard. The advantage of the coupler is that it may be part of a standardized measurement setup, it is therefore used as a calibration device for describing hearing aid’s performance.

However the 2cc coupler is not a very good approximation for an average adult ear canal, which usually has a smaller volume. Furthermore, the simple cavity does not reflect individual differences such as acoustic impedance of the ear, earmold acoustics and acoustic leakage between earmold and ear canal wall. For this reason, a hearing aid connected to a coupler, might produce a different sound pressure level (SPL) than in the real ear. This difference is known as the real ear to coupler difference (RECD). There is no general definition of how to measure the RECD but it is generally accepted to be the difference, in dB, of the SPL measured in the real ear relative to the SPL measured in the 2cc coupler, for the same sound generator. In other words, the RECD measurement consist of two components, a coupler measurement component and a real ear measurement component. Traditionally, an insert earphone has been used as the transducer. Several clinical studies have determined that the RECD is influenced by factors like: the earmold characteristics, age of the person and even the transducer type used for the measurement,(Bagatto et al. (2002); Munro & Toal (2005)). While these studies have determined that the RECD measurement depends on such factors, a systematic study has not yet been found in the literature.
The purpose of this work is to investigate variables that affect the RECD in a systematic way, by use of computer models and measurements in real ears. Simulations of the effect of changes in receiver type, tube dimensions and earmold dimensions makes it possible to investigate how some of these variables affect the RECD. These observations together with measurements in real ears and couplers can be used to explain how such variables affect the RECD.

In chapter 2 a more thorough description of the procedure for obtaining a real ear to coupler difference measurement is described. Results from previous clinical studies on variables that affect RECD are also presented.

Chapter 3 deals with the modeling of the RECD. A description of the theory used for modeling the various acoustic elements is given, and the method for building up the model, in order to simulate the RECD is described.

Chapter 4 concerns the measurements conducted in this project. A description of the measurements that have been made using ear simulators and couplers for computer model verification, and real ear measurements is presented.

Chapter 5 presents the results of simulations and measurements. The model is verified by comparing verification measurements and simulations. Next, a simulation study is conducted to investigate how the parameters in the acoustic circuit affect the RECD. At the end of the chapter, the results of the RECD measurements conducted with real ears are presented, and findings from the simulation study are compared with the RECD measurements.

Finally, the main findings are discussed and implications for future applications are described.
This chapter describes more in detail what the RECD is, how it may be obtained, and provides some findings from previous studies. Throughout the report, there will be references to parts of the outer and middle ear plus acoustic components in a hearing aid. To clarify matters, a short description is given here. Figure 2.1 shows a hearing aid in situ. The sound sensed by the microphone is processed by an electric circuitry and is then broadcast by the receiver via tubing to the residual ear canal, where the sound eventually excites the tympanic membrane. The tubing consist of a tube between the receiver and the hook, the hook itself, a tygon (silicone) tube and an earmold sound bore which acoustically is also a tube.

Figure 2.1: Typical behind the ear hearing aid used with a vented earmold.

Sound can enter the ear canal in three ways; (1) from the receiver via the hearing aid tubing and earmold, (2) directly through a ventilation canal (vent) and (3) as bone conducted sound generated in the ear canal when the person is speaking. The vent serves several purposes. It provides ventilation to the ear canal to avoid infections, it reduces over-and under pressure, at the eardrum, during insertion...
and removal of the earmold, and it reduces the so-called occlusion effect (OE). The latter occurs when an unvented earmold completely fills the outer portion of the ear canal. The person’s own voice might sound booming or hollow, which is referred to as the OE. The bone conduction sound generated in the ear canal cannot escape out of the ear since it is completely occluded and the sound is therefore forced to excite the tympanic membrane instead. This results in extra amplification of the low frequencies. For subjects with normal hearing at low frequencies this amplification will be an unwanted effect.

All these acoustical elements influence the sound in the ear, and a change in any of these parameters will therefore affect the SPL at the eardrum, and thereby affect the RECD.

### 2.1 Application of the RECD

A fitting rule is used to prescribe a certain real ear aided response (REAR), for a given hearing loss, based on predefined fitting objectives. The fitting targets are prescribed to obtain a certain SPL in an average ear. Real ears may deviate from this average, which means that a correction has to be made to ensure an accurate fitting of the hearing aid.

A measurement with a probe tube microphone placed in the ear canal and the HA in place and turned on, can be used to measure the SPL close to the eardrum, and verify that the SPL produced by the hearing aid results in the expected REAR. However, it may be more convenient to adjust the hearing aid in a 2-cc coupler instead. The hearing aid and coupler can be placed in a sound isolated box during the adjustments, to ensure a controlled environment.

Another advantage is that not all subjects can tolerate to have a probe inserted in the ear for a longer period of time. This goes especially for infants and children. The real ear measurement component of an RECD measurement can be performed within a few seconds, and very little cooperation from the child is needed.

To predict the REAR on an individual person, the output from the hearing aid measured in the 2-cc coupler is added with the RECD, head diffraction (HD) and microphone location effects (MLE) (Moodie et al. 1994),

\[
REAR = 2\text{cc response} + \text{RECD} + \text{HD} + \text{MLE}
\]

In clinical application, the values for head diffraction and microphone location effects are usually average values found in the literature, for example the publication by Bentler & Pavlovic (1989).
2.2 Measuring the RECD

A clinical procedure on how to measure the real ear to coupler differences is described by Moodie et al. (1994). The procedure requires a probe tube microphone connected to a hearing aid analyzer (a system designed to evaluate hearing aids), an insert earphone, a 2-cc coupler and the patients custom earmold. Figure 2.2 (left) shows the procedure for obtaining the 2cc coupler component of the RECD. A probe tube adapter substitutes the 1/2 inch microphone that is normally positioned in the bottom of the coupler. The insert earphone is attached to the tubing of the 2-cc coupler. A broadband or swept stimulus is presented via the insert earphone, and the SPL generated in the coupler is now measured by the probe microphone. To obtain the real ear response the probe tube is inserted into the ear. Moodie et al. (1994) suggests that the probe tube is placed at a standard insertion depth from the intertragal notch (for adult females, 28 mm; adult males, 31 mm; children 20-25 mm). A custom earmold with the insert earphone attached via the earmold tubing, is inserted into the ear canal, so that the probe microphone lies between the ear drum and the earmold. By presenting the same stimulus which was used for obtaining the coupler response, the response of the ear can be obtained, and the RECD can be determined as the difference in dB between the real ear -and coupler response.

By using the probe tube microphone in both the real ear and coupler measurements it is easier to compare the two spectrums, without the need for calibration of the microphone, assuming the probe tube does not affect the acoustics neither in the ear nor in the coupler.

Figure 2.2: Apparatus for measuring the response of an insert earphone in a 2-cc coupler (left) and in the real ear (right), from Moodie et al. (1994).

The 2-cc coupler which is shown in the above figure is defined in the IEC 60318-5
standard. Besides the 2-cc cavity it also features an earmold adapter which is a cylinder that is 18 mm long and has an inner diameter of 3 mm. This configuration is called a HA2 2cc coupler and it is used for hearing aids that goes behind the ear (BTE). Another type is the HA1 2cc coupler, which has no earmold adapter. It is designed for hearing aids that are positioned in the ear (ITE) or completely in the canal (CIC). These hearing aids are connected directly to the coupler via putty.

2.3 Previous studies

Previous studies have shown that there is a large variability in the RECD across individuals. Saunders & Morgan (2003) measured RECD on 1814 ears of 910 subjects with normal ear canals and no conductive pathology. Figure 2.3 show results from their study. The mean RECD is plotted together with the maximum and minimum RECD’s that where measured. The huge difference between minimum and maximum values illustrate that the RECD can vary significantly between subjects. The main reason for this variance, is differences in volume of the residual ear canal and middle ear input impedance. The authors state that very negative RECD’s at low frequencies are probably due to poor sealing between ear canal and transducer, which results in leakages. The very negative and highly positive RECD’s at high frequencies may have been influenced by the probe tube having been inserted at an insufficient depth.

At mid frequencies, which are especially important to understand speech, the RECD values up to 30 dB from the mean value. This means, that if a mean value is used to predict the eardrum SPL, the prediction might be off by 30 dB. This will substantially affect the understanding of speech if this deviation is not accounted for.

---

1 The problematics regarding leakages and probe tube insertion depth will be discussed later in the report.
Bagatto et al. (2002) investigated the RECD as a function of age. They measured on 392 subjects, with an age range from 1 month to 16 years, divided into two categories. RECDs were obtained from 141 ears with immitance tips and from 251 ears using the individuals’ custom earmolds. Figure 2.4 show the RECD as a function of age (months) at 500, 1000, 2000 and 4000 Hz. Each dot in the figure represents one measurement. The authors found substantial variability between subjects at all ages. However, they determined that the RECD is related to age, especially at 4 kHz.
Figure 2.4: RECD data plotted as a function of age (months). Each pane show data for a single frequency. Measured with custom earmolds [Taken from Bagatto et al. (2002)].

In figure 2.5, average RECD values from 5 different studies are presented. There is a large variation between the studies, even though the studies are based on a large number of test subjects. The studies are made using different measuring equipments. For example, Saunders & Morgan (2003) used Etymotic ER-3A insert phones with foam tips. Bagatto et al. (2002) used the same insert earphone with immitance tips or custom earmolds. Especially at very low and high frequencies there is a fairly big difference between the mean values. But there are also other remarkable characteristics among the studies. For example the results from Saunders & Morgan (2003) show a dip around 4 kHz, where the results from the other studies show tendencies for an increase in RECD or a flattening.
The clinical protocol described in the previous section, assumes that the RECD values obtained with the insert earphone can be used when fitting and verifying a hearing aid’s performance in the 2cc coupler. But studies have shown that different transducers can lead to different RECD values.

Munro & Salisbury (2002) made a comparison between two measurement earphones commonly used for RECD measurements. They compared two lengths of tubing between the earphones and medial end of the earmold. Their results showed a 3 dB difference in RECD at 1.5 kHz between the earphones with 25 mm of tubing, however, this magnitude difference increased to 9 dB when the tubing was increased to around 40 mm. A study by Munro & Toal (2005) have compared RECD measurements made with an ER-3A insert earphone and two different models of hearing aids. To measure the RECD with a hearing aid they presented stimulus via a loudspeaker with the subject wearing the hearing aid. The REAR was measured using the so-called pressure comparison method. Coupler responses were measured in both HA1 and HA2 2cc couplers. They found mean differences in RECD values of up to 11 dB between one of the hearing aids and the ER-3A insert earphones, when the coupler response was measured in a
HA2 2cc coupler. This means that even though the RECD was measured on the same subject, large differences did occur, due to different transducers. A similar study by Munro & Millward (2006), with four different models of hearing aids, revealed a mean difference between 5 and 10 dB at mid frequencies. These studies show that the RECD depends on the transducer used for measuring the response.

Ricketts & Bentler (1995) investigated the difference between the HA1 and the HA2 coupler configuration for measuring the coupler response in an RECD measurement. In other words, they examined the influence of the earmold attached to the 2cc coupler. Custom made acrylic shell earmolds were used in connection with the HA1 coupler, and the standard earmold adapter specified in the IEC standard (a 18 mm long cylindrical tube, with an inner diameter of 3 mm) were used in connection with the HA2 coupler. They found significant discrepancies above 2 kHz between the two methods.

Hoover et al. (2000) have investigated the validity of the RECD procedure, in a situation where the SPL in the ear canal is dominated by the sound entering via a vent in the earmold rather than via the hearing aid, and the RECD values are negative. The situation can occur if the hearing aid provides very little gain at low frequencies, and the RECD is negative due to vent/leakage effects. In this case, the predicted ear canal SPL may underestimate the actual ear canal SPL. They determined that if the RECD values was in the -10 to -22 dB range, the predicted values could underestimate the real ear SPL as much as 14 dB, when the gain is close to 0 dB.

This report will not address the problem regarding direct transmitted sound, but it is be kept in mind that one would have to be cautious in the specific scenario. The above mentioned studies have shown that the RECD depends the individuals ear characteristics. But the equipment that is used to obtain the RECD will also affect the result. The fact that the RECD depends on the measurement equipment means that the predicted REAR will depend on it as well. It is therefore of big interest to study the effect of the variables that might be different from one measurement equipment to another.

To gain better understanding of how each of these variables can affect the RECD, a systematic computer simulation study will be conducted in this work. A computer model makes it easy to change parameters and get fast predictions on the outcome. In order to verify that, the computer model works as intended, verification of the model needs to be conducted by means of measurements.
The purpose of this study is to perform a systematic study to identify how an RECD measurement is affected by changes in the variables that exist in a RECD measurement system. A computer model is ideal for this sort of analysis, since it can make fast predictions on what implications a change in the acoustic system has on the RECD response, without putting demands on fabrication facilities.

Egolf et al. (1988) have demonstrated a method to model hearing aid acoustics by means of transmission line theory. The transmission line is built up by a cascade of subsystems, so-called two-ports. Two-port models consists of four frequency dependent parameters in the form of a transmission matrix, and can be put together by use of matrix multiplication. The entire system can then be represented by a single transmission matrix, which makes it easy to calculate the transfer function of the acoustic system.

This work is based on existing two-port models developed by Widex. They are intended to simulate the acoustics of a hearing aid in situ. These two-port models have been used to build up a acoustics circuits that reflects a real ear -and coupler measurements. In the following, descriptions of the two port models of each component in the model for simulating RECD are presented. First, some basic equations will be presented, since they are needed in order to derive an acoustic two port model for a tube without losses, which is the first component that will be described.

### 3.1 Theory

The acoustic circuits which are considered in this work are restricted to a frequency range where only plane waves propagates. The acoustical wave equation can be developed from three physical formulas.

- Conservation of mass
  \[ \nabla \cdot (\rho_{\text{tot}} \mathbf{u}) + \frac{\partial \rho_{\text{tot}}}{\partial t} = 0 \]  

\hspace{1cm} (3.1)
where $\mathbf{u}$ is the particle velocity (a vector), and

$$\rho_{\text{tot}} = \rho_0 + \rho$$  \hspace{1cm} (3.2)

is the density of the medium, which is a sum of the density at equilibrium value $\rho_0$ and the small time-varying change in density $\rho$.

- The condition for an adiabatic process, (no local heat exchange),

$$p_{\text{tot}} = K\rho_{\text{tot}}^\gamma$$  \hspace{1cm} (3.3)

where

$$p_{\text{tot}} = p_0 + p$$  \hspace{1cm} (3.4)

is the total pressure which is a sum of the static pressure $p_0$ and the time-varying change in pressure (the sound pressure), $K$ is a constant, and $\gamma$ is the ratio of the specific heats $c_p/c_v$ of the fluid medium.

- Euler's equation of motion,

$$\nabla p + \rho_0 \frac{\partial \mathbf{u}}{\partial t} = 0$$  \hspace{1cm} (3.5)

where $p$ is the change in pressure.

Together they form the wave equation:

$$\nabla^2 p - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0$$  \hspace{1cm} (3.6)

where $c$ is sonic velocity in the fluid medium, and the Laplacian, $\nabla^2$ has the form,

$$\nabla^2 = \frac{\partial^2}{\partial x^2} + \frac{\partial^2}{\partial y^2} + \frac{\partial^2}{\partial z^2}$$  \hspace{1cm} (3.7)

In cylindrical tubes where the diameter is sufficiently small, with respect to frequency of the propagating sound, the sound field can be considered plane. The criteria for this is (Jacobsen 2006),

$$ka < 1.84$$  \hspace{1cm} (3.8)

where,

$$k = \frac{\omega}{c}$$  \hspace{1cm} (3.9)

is the wavenumber, and $\omega$ is the radian frequency $2\pi f$, and $a$ is the radius of the cylindrical tube.

The frequency range that is considered is in this project goes up to 10 kHz. This
3.2 Transmission line for tubes without losses

means, that it is a good approximation to assume plane waves in all tubes that
has a smaller inner diameter than 20.1 mm\(^1\). The largest tube diameter in the
systems investigated in this work will be the one in the 2-cc coupler, which measures
18.92 mm in diameter.

At plane waves, the sound only propagates in one direction, the axial coordinate, z.
The wave equation simplifies to,

\[
\frac{\partial^2 p}{\partial z^2} - \frac{1}{c^2} \frac{\partial^2 p}{\partial t^2} = 0
\]  \hspace{1cm} (3.10)

If the sound pressure is described as a harmonic motion, equation 3.10 can be written
with complex notation, and becomes the Helmholtz equation.

\[
\frac{\partial^2 \hat{p}}{\partial z^2} + k^2 \hat{p} = 0.
\]  \hspace{1cm} (3.11)

The general solution to equation 3.11 is,

\[
\hat{p} = p_+ e^{j(\omega t - kz)} + p_- e^{j(\omega t + kz)}
\]  \hspace{1cm} (3.12)

The particle velocity can be derived from the Euler’s equation of motion (equation
3.5). In case of a plane progressive wave it is given by,

\[
\hat{u}_z = -\frac{1}{j\omega \rho} \frac{\partial \hat{p}}{\partial z} = \frac{1}{\rho c} \left( p_+ e^{j(\omega t - kz)} p_- e^{j(\omega t + kz)} \right)
\]  \hspace{1cm} (3.13)

where \(\rho c\) is the characteristic impedance of the medium. The volume velocity, which
is the cross sectional integral of the particle velocity is defined as

\[
\hat{q} = \int_S \hat{u}_z dS = S \hat{u}_z = \frac{S}{\rho c} \left( p_+ e^{j(\omega t - kz)} - p_- e^{j(\omega t + kz)} \right)
\]  \hspace{1cm} (3.14)

where, \(\rho c\) is the characteristic impedance of the medium, and \(S\) the cross section of
the tube.

3.2 Transmission line for tubes without losses

As an introduction to explaining the theory of sound propagation in tubes, the case
where losses are neglected is described first. A cylindrical tube as shown in figure
3.1 can be considered as an acoustic two-port (or four-pole) system, when the sound
propagates as plane waves (Jacobsen 2006).

\(^1\)At transitions between to tube diameters, there will occur some higher order modes. However,
these modes will die out exponentially, and it is reasonable to neglect these (Jacobsen 2006).
Figure 3.1: A cylindrical tube with a plane sound field. $p_{\text{in}}$, $p_{\text{out}}$, $q_{\text{in}}$ and $q_{\text{out}}$ are input and output sound pressure, and input and output volume velocity, respectively.

This system can be described by its transmission matrix,

$$
\begin{pmatrix}
\hat{p}_{\text{in}} \\
\hat{q}_{\text{in}} \\
\end{pmatrix}
= \begin{pmatrix} A & B \\ C & D \end{pmatrix}
\begin{pmatrix}
\hat{p}_{\text{out}} \\
\hat{q}_{\text{out}} \\
\end{pmatrix}
$$

(3.15)

where $\hat{p}_{\text{in}}$, $\hat{p}_{\text{out}}$, $\hat{q}_{\text{in}}$ and $\hat{q}_{\text{out}}$ are the sound pressures and volume velocities at the input and output. From the transmission matrix the following expressions for the frequency dependent four pole parameters can be found.

$$
A = \frac{\hat{p}_{\text{in}}}{\hat{p}_{\text{out}}} \bigg|_{\hat{q}_{\text{out}}=0}, \quad B = \frac{\hat{p}_{\text{in}}}{\hat{q}_{\text{out}}} \bigg|_{\hat{p}_{\text{out}}=0}, \quad C = \frac{\hat{q}_{\text{in}}}{\hat{p}_{\text{out}}} \bigg|_{\hat{q}_{\text{out}}=0}, \quad D = \frac{\hat{q}_{\text{in}}}{\hat{u}_{\text{out}}} \bigg|_{\hat{p}_{\text{out}}=0}.
$$

(3.16)

To find the four pole parameters of a tube with length $l$ and cross section $S$ it is necessary to find the input and output sound pressure and volume velocity for the tube. This can be done by defining the $z$-coordinates as in figure 3.1, where the inlet is at $z = -l$ and the outlet $z = 0$. The input sound pressure is,

$$
\hat{p}_{\text{in}} = p_+ e^{j(\omega t + kl)} + p_- e^{j(\omega t - kl)}.
$$

(3.17)

and the input volume velocity is,

$$
\hat{q}_{\text{in}} = \frac{S}{\rho c} \left( p_+ e^{j(\omega t + kl)} - p_- e^{j(\omega t - kl)} \right).
$$

(3.18)

The output sound pressure is given by,

$$
\hat{p}_{\text{out}} = (p_+ + p_-) e^{j\omega t}.
$$

(3.19)

and output volume velocity is,

$$
\hat{q}_{\text{out}} = \frac{S}{\rho c} (p_+ - p_-) e^{j\omega t}.
$$

(3.20)

The four pole parameters can now be found by the equations in (3.16) and equations 3.17 to 3.20.
For example, the parameter $A$ is found setting volume velocity, $q_{out}$ (equation 3.20) equal 0, which means that $P_+ = P_-$. 

$$A = \left| \frac{\hat{p}_{in}}{\hat{p}_{out}} \right| = \frac{p_+ (e^{j(\omega t + kl)} + e^{j(\omega t - kl)})}{2p_+ e^{j(\omega t)}} = \frac{e^{jkl} + e^{-jkl}}{2} = \cos kl$$ (3.21)

By doing the same for the other parameters, one will get the transmission matrix,

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \begin{pmatrix} \cos kl & jZ_c \sin kl \\ jZ_c^{-1} & \cos kl \end{pmatrix}$$ (3.22)

### 3.3 Tubes with losses

In the previous section losses the tube were not taken into consideration. However, when a tube is narrow, losses at the wall of the tube will have a significant influence on the sound propagation, and must be considered. As mentioned earlier, acoustical elements such as tubes can be equated in terms of electrical analogues when the sound propagates as plane waves, and the transmission of sound can be considered as a transmission line with two inputs and two outputs.

The sound pressure across the terminals of the transmission line is analogue to voltage and the volume velocity is analogue to current. Figure 3.2 shows a circuit diagram of a transmission line. It consist of a series impedance $Z$,

$$Z = (R + j\omega L)$$ (3.23)

and a shunt admittance $Y$,

$$Y = (G + j\omega C)$$ (3.24)

The R component is the acoustical resistance that describes the viscous losses, L is the acoustical mass of the air, G is acoustical conductance that reflects thermal losses and C is the compliance of the air in the tube.

![Transmission line](image)

Figure 3.2: Transmission line

The transmission line can be defined in terms of its characteristic impedance $Z_c$,

$$Z_c = \sqrt{Z/Y}$$ (3.25)
and its propagation wavenumber,
\[ \Gamma = \sqrt{ZY} \]  
(3.26)

which is defined to be the phase change per unit length at an arbitrary time. The transmission matrix for a length \( L \) of transmission line for tube with losses are given by (Egolf et al. 1988),
\[
\begin{pmatrix}
a & b \\
c & d \\
\end{pmatrix} = 
\begin{pmatrix}
cosh \Gamma L & Z_c sinh \Gamma L \\
Z_c^{-1} sinh \Gamma L & cosh \Gamma L \\
\end{pmatrix}
\]  
(3.27)

where,
\[ \Gamma = j \frac{\omega}{c} \sqrt{1 + 2(\gamma - 1) \frac{J_1(\alpha a)}{\alpha a J_0(\alpha a)}} \]  
(3.28)

The characteristic impedance \( Z_c \) is defined as,
\[
Z_c = \frac{\rho_0 c }{\pi a^2} \sqrt{\frac{1}{1 - \frac{2J_1(\beta a)}{\beta a J_0(\beta a)}} \frac{1}{1 + 2(\gamma - 1) \frac{J_1(\alpha a)}{\alpha a J_0(\alpha a)}}} 
\]  
(3.29)

where
\[
\alpha = \sqrt{-j \omega \rho / \mu}, \quad \beta = \sqrt{-j \omega \sigma / \mu},
\]  
(3.30)

and \( J_0 \) and \( J_1 \) are cylindrical Bessel functions of the first kind of orders zero and one. \( \sigma \) is Prandtl number and \( \mu \) is the absolute viscosity of the fluid medium.

The use of equations 3.28 and 3.29 are based on several criteria which are specified in Egolf & Leonard (1977). These criteria are:

1. Damping is a wall-dependent phenomenon due to viscous friction along the tube wall and heat loss to the tube wall.
2. The tube wall is rigid.
3. The tube wall is isothermal (equal temperature at any place).
4. The tube is long enough so that radial effects are negligible \( (l >> a) \).
5. The fluid medium in the tube is continuous.
6. The fluid medium in the tube is excited by small-amplitude perturbations.
7. The fluid medium in the tube is such that $\frac{\eta}{\rho c a} << 1$.

8. The excitation frequency $\omega$ is such that $\frac{\eta \omega}{\rho c} << 1$ and $\frac{\omega a}{c} << 1$

9. The acoustic pressure is uniform over the tube cross section (plane wave).

### 3.3.1 Losses in boundary layer

Kirchoff derived in 1868 the theory for sound propagation in narrow tubes. He included two kinds of losses in a boundary layer along the walls of the tube, viscous and thermal losses Nordahn (2007). These losses are much greater than the losses in the main current in the middle of the tube.

It is beyond the scope of this work to go into details with these losses. However, this section will shed some light on the issue, since it is interesting with regards to positioning of the probe tube in the ear canal.

**The viscous boundary layer**

At surfaces where the particles of air are forced to stand still, a viscous boundary layer will exist. The volume velocity decreases exponentially due to friction, when approaching the wall. This friction will result in losses in the sound wave. The layer is given by,

$$\delta_v = \sqrt{\frac{\eta}{\omega \rho}}$$  \hspace{1cm} (3.31)

where $\eta$ is the absolute viscosity of air, and $\rho$ is the density of air.

At a temperature of $20^\circ C$ and a frequency of $100 \text{ Hz}$ the layer is approx. $0.15 \text{ mm}$.

The probe tube that has been used in this project had a tube wall thickness of $0.25 \text{ mm}$. It is therefore assumed that the position of the probe tube inlet will be in the main current.

**The thermal boundary layer**

The propagation of sound is an adiabatic process, that means that no exchange of heat exist, even though, there will be local temperature differences due to compression and expansion of the air. However, close to the wall the process will be isothermal, which means the temperature is constant. This results in heat exchange with the environment through the wall, which leads to a loss in energy of the sound. The thermal boundary layer is given by,

$$\delta_v = \sqrt{\frac{\eta}{\omega \rho \sigma}}$$  \hspace{1cm} (3.32)
where \( \sigma \) is the Prandtl number. The layer denotes the transition region where the process is changing from adiabatic to isothermal. At a temperature of 20\(^\circ\)C and a frequency of 100 Hz the layer is approx. 0.18 mm. So, the probe tube walls are thicker than the thermal boundary layer as well.

### 3.4 Leaks

A leakage between the earmold and the ear canal wall, will result in an extra path for the sound to propagate, into - or out of the residual ear canal. Such a leakage is more likely to exist when a probe tube is inserted between the earmold and the ear canal wall, since it might work as a spacer between the two. Figure 3.3 (upper) shows a sketch of the problem. The dimensions, and shapes in sketch are somewhat hypothetical, and will always be a rough estimation. It is assumed in this work, that the leak/leakages around the probe tube can be approximated as a narrow rectangular slit as shown in the lower part of the figure.

The dimensions of the leak are based on the assumption that an average ear canal is circular and has a diameter of 7.5 mm. The width of the leak (a) is set to half a circumference of this average ear canal \( (\pi \times d)/2 \).

The height (b) of leak is set to a tenth of the outer diameter of the probe tube, which has an outer diameter of 1 mm. The length of the leak will be equal to the insertion depth of the earmold, which has been estimated to be 9 mm, based on insertion depth of the earmolds that has been used for the real ear measurements in this study.

![Figure 3.3: Sketch of a slit leak.](image)

The propagation wavenumber (equation 3.28) for this rectangular duct, is calculated
in the same way as for the narrow tubes, but the diameter is found by using the hydraulic diameter $D_h$ of the duct, which is four times its cross-sectional area, $A$, divided by its circumference, $C$.

$$D_h = 4 \frac{A}{C}$$  \hspace{1cm} (3.33)

The four pole parameters of the this rectangular duct can the be calculated by equation 3.27, where the length is equal to the insertion depth.

### 3.5 Radiation impedance

#### 3.5.1 Vents

The radiation impedance of an open ended tube, like a vent in an earmold, may be approximated by that of a piston of the same diameter set in an infinite baffle, and is given by (Egolf et al. 1988),

$$Z_{rad} = \frac{\rho c}{\pi a^2} \left(1 - \frac{J_1(2ka)}{ka} j \frac{H_1(2ka)}{2(ka)^2}\right)$$  \hspace{1cm} (3.34)

Where $J_1$ is the bessel function of the first kind and $H_1$ is the Struve function of first order.

#### 3.5.2 Slit leaks

The calculation of the radiation impedance of a rectangular opening such as a slit leakage is given in (Kemp 2002). It is a very complicated expression and it is therefore considered beyond the scope of this work to go into details of how to calculate this frequency dependent impedance.

### 3.6 Receivers

In order to implement the receivers into the model, their electro-acoustic two-ports are needed. Knowles electronics (LoPresti 2000) has made electric analogs for some of their receiver models. A generic circuit is shown in figure 3.4.
Figure 3.4: Schematic of a Knowles receiver analog, from LoPresti, 2003

The transmission matrix of such a circuit is defined as

\[
\begin{pmatrix}
V_{in} \\
I_{in}
\end{pmatrix} = \begin{pmatrix}
A & B \\
C & D
\end{pmatrix}\begin{pmatrix}
V_{out} \\
I_{out}
\end{pmatrix}
\]  

(3.35)

The four pole parameters can be found by considering the two cases where the load impedance is infinite (open circuit, \(I_{out} = 0\)) and 0 (short circuit, \(V_{out} = 0\)), as shown in figure 3.5, and are given in equation 3.36.

Figure 3.5: Electric two-port open and closed for determination of four pole parameters.

\[
T = \begin{pmatrix}
A & B \\
C & D
\end{pmatrix} = \begin{pmatrix}
\frac{V_{in,open}}{I_{in,open}} & \frac{V_{in,closed}}{I_{in,closed}} \\
\frac{V_{out}}{I_{out}} & \frac{V_{out}}{I_{out}}
\end{pmatrix}
\]  

(3.36)

The electric analog has been loaded into PSpice and the procedure shown in figure 3.5 has been applied to obtain the four pole parameters in the frequency range 0.1-10 kHz. Further details regarding the procedure can be found in LoPresti (2000).

An alternative experimentally method for determining the four pole parameters of a receiver is the so-called 'two-load method' demonstrated by Egolf & Leonard (1977). This method has been used to develop a two-port model for a
3.7 Ear simulator

Brüel & Kjær’s has made an electrical equivalent circuit for their ear simulator (711 coupler), type 4195. The circuit is displayed in figure 3.6. This model meets the requirements of IEC 60711:1981, and it is therefore expected that the equivalent for this coupler is a valid representation for the 711 coupler that has been used in the verification measurements.

The four pole parameters are derived by analyzing the circuit when the output is open and when it is closed (equation 3.36). This is can be done analytically by the use of Kirchhoff’s circuit laws.

![Electric equivalent for a standard 711 coupler from Brüel & Kjær (ear simulator, type 4195).](image)

3.8 Building the model

Now that all the two-port models are described, their application for modeling RECD will be described here.

The idea is to build up two models, one representing the 2cc coupler component
and the other representing the real ear component, and then subtract their transfer functions (in dB) from each other.

Figure 3.7 show a typical acoustic circuit that is considered in this work. It consist of a transducer (receiver) connected to a coupler’s earmold adapter via tubing. In some cases there will be a vent and/or a leak included as a branch in the circuit as well.

The coupler can either be a 2cc coupler, or an ear simulator (711 coupler) that represents the real ear. The system is split up into subsystems which can be described by their respective two-port models as shown in figure 3.8.

The entire system can then be represented by one single matrix, by use of matrix
3.8 Building the model

multiplication,

\[
\begin{pmatrix}
A_T & B_T \\
C_T & D_T
\end{pmatrix}
= \begin{pmatrix}
A_{rec} & B_{rec} \\
C_{rec} & D_{rec}
\end{pmatrix}
\begin{pmatrix}
A_{tube} & B_{tube} \\
C_{tube} & D_{tube}
\end{pmatrix}
\ldots
\]

\[
\begin{pmatrix}
A_{SB} & B_{SB} \\
C_{SB} & D_{SB}
\end{pmatrix}
\begin{pmatrix}
A_{ventbranch} & B_{ventbranch} \\
C_{ventbranch} & D_{ventbranch}
\end{pmatrix}
\begin{pmatrix}
A_{coupler} & B_{coupler} \\
C_{coupler} & D_{coupler}
\end{pmatrix}
\]

(3.37)

where the indices refer to each subsystem in figure 3.7. The rules of calculations for these operations are described in appendix D. The entire system can then be represented by a single transmission frequency dependent matrix,

\[
\begin{pmatrix}
V_{in}(f) \\
I_{in}(f)
\end{pmatrix}
= \begin{pmatrix}
A_T(f) & B_T(f) \\
C_T(f) & D_T(f)
\end{pmatrix}
\begin{pmatrix}
p_{out}(f) \\
q_{out}(f)
\end{pmatrix}
\]

(3.38)

The transfer function of the acoustic system, from the input terminals of the receiver to the microphone in the coupler, can now be calculated by,

\[
H(f) = \frac{1}{A_T(f) + B_T(f)/Z_{mic}}
\]

(3.39)

In order to simulate an RECD response, two transfer functions, need to be calculated. One that represents the real ear response and another that represents the 2cc coupler response. By converting the transfer functions into dB and subtracting them, a simulated RECD response can be derived:

\[
RECD_{sim}(f) = H_{realEar}(f) - H_{2cc}(f)
\]

(3.40)
4.1 Coupler measurements for model verification

Couplers are in contradiction to individual ears well defined in terms of physical dimensions, and impedance properties. Furthermore, it is a lot easier to reproduce a frequency response measurement in a coupler than in a real ear due to the fact that coupler measurements can be conducted in a highly controlled environment. This makes them suitable for verification measurements.

In this work two types of couplers are used for verification measurements. An IEC 711 coupler, also known as an ear simulator, and a HA2-cc coupler. By measuring the frequency response in each coupler attached to a sound generator via tubing, and subtract the 2-cc coupler response from the 711 coupler response, an artificial ‘real ear to coupler difference’ can be obtained. It is used to verify the computer model which is described in chapter 3. This chapter contains a description of the measurement procedure for both the verification measurements and the RECD measurements, which will be described in the next section.

4.1.1 Measurement setup

Figure 4.1 shows a sketch of the measurement setup. A Brüel & Kjær PULSE analyzing system is used for data acquisition. An amplifier is connected between the output of PULSE and an electro acoustic transducer, which is attached to the coupler’s earmold substitute via a tygon tube. The 1/2 inch pressure microphone which usually is positioned at the bottom of the coupler is substituted with a probe tube adapter as described in Moodie et al. (1994). A probe tube microphone is connected to a microphone preamplifier. The output of the preamplifier is connected to an input terminal on PULSE. The terminals of the electro acoustic transducer are connected to another input terminal on PULSE to monitor its input voltage.

The PULSE analyzing system is set to generate a stepped sinusoidal signal from
0.1 to 10 kHz, with an output voltage of 10 mV RMS. The gain of the power amplifier is 13.79 dB, which results in a voltage across the transducer terminals of 48.9 mV RMS. The power amplifier had no adjustment option, and was fixed at this odd gain, which explains the odd amount of gain. The output signal from the microphone preamplifier is analyzed by PULSE’s steady state response (SSR) analyzer in 1/24 octave bands, giving a total of 161 measurement points.

![Figure 4.1: Setup for coupler measurements.](image)

### 4.1.1.1 List of apparatus

- **Analyzer:** Brüel & Kjær Pulse
- **Electroacoustic transducers:** Knowles, ED 7398
  - Knowles, EF6665
  - Etymotic, ER-3A insert earphones
- **Microphone:** Knowles, FG 3629
- **Microphone preamplifier:** T&W 474824
- **Amplifier:** T&W 474820
- **2-cc coupler:** Brüel & Kjær DB0138
- **711 coupler:** Brüel & Kjær 4157
- **Tygon tubes:** Inner diameter, 2 ± 0.05 mm.
  - Length, 15, 25 and 35 mm (± 1 mm).
- **Probe tubes:** Inner diameter, 0.5 ± 0.05 mm.
  - Lengths, 100, 150 and 200 mm (± 2 mm).

### 4.1.2 Procedure

The verification measurements in the 711 coupler have been conducted with different transducer types, tygon tube lengths, earmold substitute dimensions, vent diameters and probe tube lengths.
The verification measurements in the 2-cc coupler measurements have been conducted with the same transducer and probe tube length as the 711 coupler measurements, but the tygon tubing between the transducer tube and the earmold substitute had a fixed length of 25 mm, and the earmold substitute were 18 mm long and had an inner diameter of 3 mm.

Figure 4.2 show the acoustic circuit with the variables that has been changed. Retest measurements has been performed to ensure that the measurements are accurate.

Figure 4.2: Measured variables for model verification.

### 4.1.3 Transducers

Three different transducers have been used for the measurements. An ER-3A insert earphone, and two hearing aid receivers (Knowles ED7398 and Knowles EF6665). The ED7398 and EF6665 receivers are typically used for behind the ear (BTE) hearing aids.

The two types of receivers were attached to the same type of hearing aid hook, ensuring the same tube dimension from receiver outlet to hook tip, indicated as 'transducer tube' in figure 4.2. The ER-3A insert ear phone consist of a housing with a receiver, and an electric and an acoustical equalization network, and a 278 mm long tube attached to the housing. The 278 mm tube is also referred to as transducer tube in the following.

A more detailed description of the ER-3A is given in appendix B.

The rest of the system consisted of, a 25 mm long tygon tube, a 3 × 18 mm earmold substitute, a 711 coupler and a 100 mm long probe tube.

### 4.1.4 Tube lengths

The tygon tube between transducer tube and earmold substitute was measured for lengths of 15, 25 and 35 mm. The rest of the system consisted of a Knowles ED7398 receiver, a 3 × 18 mm earmold substitute, a 711 coupler and a 100 mm long probe tube.
4.1.5 Earmold dimensions

Besides the normal earmold adapter which has a length of 18 mm and a diameter of 3 mm, a modified one with a length of 12 mm and a diameter of 2.2 mm was measured as well.

4.1.6 Vent diameters

Three personal earmolds have been used to measure the vent effect. One without a vent and two vented with diameters of 1 and 2 mm. All of the earmolds were made from the same imprint to have approximately the same dimensions in sound bore and vent length. The earmolds were attached to a 711 coupler as illustrated in figure 4.3. The mold is attached to a tapered insert via putty.

![Figure 4.3: Schematics of a personal mold attached to a 711 coupler.](image)

4.1.7 Probe tube lengths

Three probe tube lengths have been measured to see if the length of the tube has an influence on the RECD. The lengths of the probe tubes were: 100, 150 and 200 mm.

4.1.8 Calibration of probe microphone

In order to investigate the SPL produced by the transducer in the coupler, or in the real ear, it is necessary to calibrate the probe microphone. It is then possible to subtract the effects the probe microphone has on the measured response, assuming that the probe microphone does not influence the acoustics in the either measurement. The probe tube microphone is placed in a sound isolated test box (interacoustics TBS25 External Test Chamber). The tube was placed sideways to the loudspeaker in the test box (see figure 4.4). A flat 70 dB SPL frequency sweep is presented through the loudspeaker in the test box, and the output voltage of the microphone
4.2 Real ear measurements

4.2.1 Subjects

Six subjects, 3 men and 3 women (Age range 26-49 years, with a mean age of 37 years) with normal hearing, participated in the experiment. Each participant had three personal acrylic shell earmolds, one unvented, and two vented. The earmolds which were used in the experiment had a sound bore diameter and length of individual size, ranging from 1.6 to 2.0 mm and 10 to 15.1 mm respectively. See appendix A for specific measures. All measurements were conducted on the participants right ear.

4.2.2 Probe tube positioning

Moodie et al. (1994) suggests a constant probe tube insertion depth from the intertragal notch of 31 mm for male subjects and 28 mm for female subjects. This insertion depth means that the tip of the probe tube is likely to be within 5 to 6 mm of the tympanic membrane. Figure 4.5 shows how the SPL measured in the ear canal varies with the distance between the probe tube tip and the tympanic membrane. Each curve shows the SPL at a different frequency as the distance from the eardrum changes. The dip in each curve is caused by sound reflecting off the eardrum. It is therefore important to position the probe tube as close to the tympanic mem-

Figure 4.4: Position of probe tube microphone during calibration.
brane as possible (without hurting the subject) if this attenuation in SPL should be minimized.

Figure 4.5: Effect of the probe tube distance from the tympanic membrane, from Gilman and Dirks (1986)

To get a more precise response at high frequencies, it was decided to position the probe tube closer to the tympanic membrane, than suggested by Moodie et al. (1994).

It was inserted to a constant depth from the intertragal notch of 35 mm for male subjects and 30 mm for female subjects in the present study. To ensure that the probe tube would not touch the tympanic membrane at these insertion depths, an otoscope was used for visual inspection the first time the probe tube was inserted for each subject. The probe tube that was used for the real ear measurements was another type than the ones used for the verification measurements. It was the type that is usually used in connection with an Audioscan RM500 hearing aid analyzer. It has a smaller outer diameter of 1 mm, where the other type had an outer diameter of 1.3 mm. The smaller outer diameter was expected to minimize potential leakages and was therefore chosen in favor of the other type. The inner diameter for both types were 0.5 mm.

4.2.3 Measuring real ear response

All measurement were made in a sound insulated room. The background noise was measured prior to each real ear measurement session, to determine the signal to noise ratio (SNR) across frequencies.

All transducers were supplied with a constant voltage of 14.7 mV RMS. The specific value was based on measurements made with a 2cc coupler, where the SPL was measured for each transducer at different receiver input voltages. The output voltage was set to 3 mV in PULSE, the signal was amplified by the power amplifier and
resulted in a voltage across the transducer terminals. The probe tube and earmold were completely removed and re-inserted, and the measurements were repeated twice to investigate test-retest reliability. Figure 4.6 schematize the experimental setup. A reference configuration was chosen consisting of the following:

- Receiver: ED7398
- Tube length: 30.8 mm
- Probe tube length: 77 mm
- Unvented earmold

### 4.2.4 Procedure

A protocol was designed for the measurements. The following list of variables were measured.

- Transducer type.
- Length of tube between hook and earmold.
- Vent diameter.
- Length of probe tube.

![Figure 4.6: Schematic of experimental setup for real ear measurements.](image)

### 4.2.5 Transducer type

Four transducers were used for the measurements. The three that were used for the verification measurement: Knowles ED7398, Knowles EF6665, and the ER-3A insert earphone. The fourth transducer was the Knowles HiFi FK, which also has been used in the simulations.
4.2.6 Vent

Two vented and one unvented custom earmolds were used for each participant. The diameter of the vents were ordered as 1 and 2 mm, but they had small deviations up to 0.2 mm. See appendix [A] for individual measures of the earmolds used the present study.

4.2.7 Tube length

The tube length In addition to the tube length of 30.8 mm between the hook tip and the earmold sound bore, two other length of 20.8 and 40.8 mm where measured as well.

Figure 4.7: Sketch of the earmold type that was used for the real ear measurements.

4.2.8 Probe tube dimensions

Three other probe tube lengths of 100, 150 and 200 mm where also measured. They had an outer diameter of 1.3 mm, in contradiction to the standard probe tube with an outer diameter of 1 mm.

4.2.9 2cc coupler responses

A HA/2 2-cc coupler was used for measuring the 2cc coupler responses. The silicone tube attached between transducer tube and the earmold substitute had a length of
4.2 Real ear measurements

25 mm, as specified in the IEC standard. Since four different transducers have been used, with a 77 mm probe tube, seven responses were measured before the real ear measurements were conducted.
Experimental methods
This chapter presents the results that has been obtained from the measurements and simulations. First the validation of the computer model will be presented. Second, the model will be used to perform parameter studies, where the effect of different variables that are subject to changes in an RECD measurement will be investigated. These findings will be hold up against the RECD measurements that have been conducted with six particants.

In the following, an ear simulator (711 coupler) is used to reflect the real ear, in the verification of the model, and in the simulations studies as well. When the response of a 2cc coupler is subtracted from the 711 coupler response it is referred to as ‘$RECD_c$’ (ear simulator to coupler difference).

### 5.1 Verification of computer model

The measurements described in chapter 4.1 are compared to simulations of a model with the same parameters, to confirm the validity of the model.

#### 5.1.1 Electroacoustic transducers

Measured and simulated frequency responses with the three different transducers connected to the 2-cc and 711 couplers are shown in figures 5.1 and 5.2 respectively. The data is adjusted in order to represent the responses in dB SPL. Measurements and simulations for the ED7398 and EF6665 receivers have a good match, for both coupler circuits. There are minor differences in location of resonance peaks and in magnitude, but the trends in measurements and simulations agree very well.

The electric equivalent circuits that the two-port model for the receivers are based on, are only approximations, so minor deviations must be expected. Additionally, one of the criteria for the two-port model of the tubes, is that the tube walls
are rigid. Since the tubes are made of silicone, the tube walls will have some compliance, and the assumption is not entirely satisfied. This means that the real system possibly has some damping that is not considered in the model.

Comparison of measured and simulated data for the ER-3A insert earphones, show good agreement in the frequency range 0.7 - 7 kHz. Below that frequency range the simulated data has greater magnitude (up to 14 dB at 100 Hz), but the trend is similar to the measured data. The deviation at low frequencies is possibly related to the impedance of the electrical equalization network in the ER3A insert earphone. There may be an inaccuracy in the two-port model for the insert earphone, but due to lack of time this issue has not been resolved.

The difference is seen in the spectra for the system with the 711 coupler and the system with the 2-cc coupler.

![Comparison of measured and simulated transfer functions for different electro acoustic transducers, 2-cc coupler.](image-url)
Figure 5.2: Comparison of measured and simulated transfer functions for different electro acoustic transducers, 711 coupler.

Figure 5.3 shows measured and simulated coupler differences, $RECD_c$, for each transducer. The low frequency effect in the simulation for the ER-3A has been cancelled out. The model for the earphones may therefore be considered valid when the two responses are subtracted, but with the differences kept in mind. For all three transducers, an excellent match is seen up to 5 kHz, with a difference less than 2 dB between measurements and simulations. In the frequency range 5 to 8 kHz the simulated data has a smaller magnitude on average, which is best seen on the derived response for the ER-3A insert earphones.
Figure 5.3: Comparison of measured and simulated difference between the electroacoustic transducer attached to a 711 coupler and a 2-cc coupler.

### 5.1.2 Tube length

The silicone tube between the transducer and the earmold is also a parameter that is subject to changes. If the real ear component measurement of the RECD is conducted with the subjects personal earmold, the tygon tube between the transducer and the earmold will vary in length, because it is individually fitted. In the coupler component measurement the tygon tube has a fixed length of 25 mm according to the IEC 60318-5 standard. Three lengths of tygon tubing which connects the receiver to the 711 coupler has been measured and simulated to verify the computer model. Figure 5.4 shows the derived responses when subtracting the 2-cc coupler response from the 711 coupler response. The computer simulations match the measured data very good up to 10 kHz. A change in the tube length will alter the resonance of the tube, and eventually affect the other resonance peaks in the response. The systems with tube lengths of 15 and 35 mm will therefore have peaks further away in frequency from the 2-cc coupler response compared to the system with a 25 mm tube. This results in greater excursions which is seen in the figure.
5.1 Verification of computer model

The reason for this is, that the spectra are measured with a stepped sine signal, where one frequency is measured at a time. By using this narrow bandwidth all these dips and peaks that are seen in the response are revealed.

The responses have the same shape with peaks located at the same frequencies, but the simulated responses are more pronounced, which probably relates to the fact that the model does not consider the additional damping introduced by the compliant tube walls. Figure 5.5 reveals that in the measured responses, the peaks to some extent are smoothened, because of the damping.

The good match demonstrates, that the model accurately shows the trends in the RECD when the tube length is being changed.

![Comparison of measured and simulated difference between the 711 coupler and a 2-cc coupler for different tube lengths attached between hook and couplers.](image)

Figure 5.4: Comparison of measured and simulated difference between the 711 coupler and a 2-cc coupler for different tube lengths attached between hook and couplers.
40 Results

Figure 5.5: Comparison of measured and simulated transfer functions for three different tube lengths between hook and the 711 coupler. The bottom panel shows the response measured in the 2-cc coupler.

5.1.3 Earmold dimensions

A modified earmold adapter with other dimensions has been attached to the 711 coupler to verify that the simulations are consistent with the measurements. This modified earmold adapter is 12 mm long and have an inner diameter of 2.2 mm. Figure 5.6 show that simulations and measurements fit well together.

Figure 5.6: Comparison of measured and simulated difference between the ear simulator and a 2-cc coupler, for different earmold adapters attached to the 711 coupler.
5.1 Verification of computer model

5.1.4 Vent dimensions

A vent acts, together with the residual ear canal, as a Helmholtz resonator, and it works as a high pass filter with a cut-off frequency defined by the Helmholtz resonance frequency given by,

\[ f = \frac{c}{2\pi} \sqrt{\frac{S}{V l_{eff}}} \]  

(5.1)

where \( c \) is the velocity of sound, \( S \) is the cross sectional areas of the vent, \( V \) is the volume of the cavity and \( l_{eff} \) is the effective length of the tube, (here \( l + 0.82 \cdot a \)), \( a \) is the radius of the vent and \( l \) is the length of the vent.

Figure 5.7 shows a comparison of measurements and simulations with vented custom earmolds attached to a 711 coupler with putty. The effect of the vent is clearly seen in both measurements and simulations. The larger the vent diameter is, the more negative is the RECD at low frequencies. The Helmholz resonances are also clearly seen at 250 Hz and 470 Hz for the 1 and 1.9 mm vents respectively. The earmolds that has been used in these verification measurements are the ones that are listed as 'MAN V0', 'MAN V1' and 'MAN V2' in appendix A. They all have a sound bore that is 1.9 × 15.1 mm (ø × l) and the vents dimensions were 1.05 × 22.1 mm and 1.9 × 23.5 mm. By using these dimensions in the equation 5.1 together with the equivalent volume of the 711 coupler (1.6 cm\(^2\)), the two Helmholtz resonance frequencies are found to be: 269 Hz and 469 Hz for the 1.05 mm and the 1.9 mm vents respectively. These results are in good agreement with the resonance frequencies that have been found in the responses. Data is only shown up to 6 kHz because data on retest deviated substantially above that frequency. This was due to the probe tube microphone, which caused some sharp strange dips in the response at 6.5 kHz. Ideally the vent verification measurements should have been measured again with the same microphone that was used for the other measurements. But due to lack of time these measurements were not conducted.

It has not been possible to achieve the same accuracy as the previous verification measurements.

At low frequencies, there are deviations of around 2 dB between measurements and simulations for the earmolds with no vent and 1 mm vent. At the peak frequencies the simulations reveals that the model has too little damping. The less accuracy is a consequence of using acrylic earmolds which had to be attached to the coupler via putty. This makes it difficult to avoid leakages, and the positioning of the sound bore outlet is also uncertain.

Another uncertainty is the dimension of the vent canal. The diameter of the vent was measured with a sliding gauge, but details such as rounded edges makes it difficult to obtain a precise measure. The radiation impedance is also difficult to model. This may affect the accuracy of the model as well. A suggestion to improve
this measurement would be to create special earmold substitutes with an extra drilled cylindrical hole acting as a vent, to have well defined vent dimensions.

Figure 5.7: Comparison of $RECD_c$ with different vent diameters.

5.1.5 Probe tube length

Three different lengths of probe tubes has been measured to see if the length of the probe tube has an impact on the RECD. The same length of probe tube is used for the ear simulator measurement and for the 2-cc coupler measurement. The measured differences are compared to a computer simulation with the same change in probe length and is shown in figure 5.8.
5.1 Verification of computer model

Figure 5.8: 711-2cc difference is measured and simulated with probe tube lengths of 100, 150 and 200 mm. The three simulated responses lie exactly on top of each other.

The measurements and the simulations show no difference in the RECD when changing the probe tube length. The influence a longer probe tube has on the transfer function seems to be the same, regardless of whether the coupler is a 2-cc type or a 711 type.

This indicates that the presence of the probe tube does not influence the measurements.

An increase in probe tube length will not only change the tube resonances, but also lower the amplitude of the response due to a longer signal path. To see the magnitude of the damping, the measurements and simulations with probe tube lengths of 150 and 200 mm are normalized to 100 mm and shown in figure 5.9. The graphs show that the increase from 100 to 150 mm results in a damping up to 5-6 dB at 10 kHz and an increase from 100 to 200 mm up results in a damping up to 11-12 dB, and a corresponding lower signal to noise ratio.
5.1.6 Conclusions on verification measurements

The verification measurements and simulations are generally in good agreement. The match in absolute values is not perfect, but it is applicable. The results show that the model is ideal to describe trends following relative changes in the dimensions of an in situ hearing aid, and insert earphones. The model is therefore considered valid as a tool for investigating RECD responses, where variables have changing parameters.

5.2 Simulations

This chapter present simulations that investigate how changes in different parameters will affect the RECD.

The simulations are made with MATLAB, in 1/24 octave bands. The simulations are based on a ‘reference model’ which act as a starting point for individual parameter studies.

The reference model is schematized in figure 5.10 and consist of an Knowles ED7398 receiver, transducer tubing consisting of the receiver tube \((l = 5 \text{ mm}, \Theta = 1.1 \text{ mm})\) and ear hook \((l = 19.88 \text{ mm}, \Theta = 1.6 \text{ mm})\), tygon tube \((l = 33 \text{ mm}, \Theta = 2 \text{ mm})\), earmold sound bore \((l = 12 \text{ mm}, \Theta = 2.2 \text{ mm})\), and the 711 coupler which represents the real ear. The circuit is terminated at the bottom of the coupler, since
the verification measurements and simulations showed that the probe tube has no influence on the RECD. A vent and a leakage are not included in the reference model, but the effect of these parameters will be examined. A two-port representation of the model is shown in figure 5.11 including the vent and leakage, which are coupled in parallel, as a side branch.

![Diagram of a two-port model for simulations](image)

**Figure 5.10:** Standard circuit for simulations.

![Diagram of a two-port model that represents the model used for simulations](image)

**Figure 5.11:** Two port model that represents the model used for simulations.

The dimensions for the tygon tube and the earmold are based on a collection of 50 earmolds taken from a test subject database provided by Widex. The values for tube length, vent length and sound bore length and diameter are shown in a histogram in figure 5.12.
The histogram reveals some interesting information. The sound bore and tube lengths have huge differences, which indicates that these parameters can change quite a lot from subject to subject.

The manufacturer told that the sound bore diameter is usually 2 mm if there is enough space. But after having polished the earmold, the diameter is increased a bit. The sound bore diameter seems to be normal distributed around 2.2 mm which is in good agreement with the information from the manufacturer.

5.2.1 Effect of the transducer

Four different sound sources are compared to see what effect they have on the RECD. The transducers are three receivers from Knowles, ED7398, EF6665 and HiFiFK, and the insert earphones ER3A from etymotic.

The HiFi FK receiver is a so called wide band receiver. This is a new type of receiver, where two receivers have been joined by a simple cross-over filter.
5.2 Simulations

Figure 5.14 show the derived $RECD_e$ responses. The simulations show that in the frequency range from around 1 to 6 kHz the transducer has an influence on the RECD. The differences between responses are up to 10 dB at 1.3 kHz between the EF6665 and the HiFiFK, and up to 9-10 dB between the ER3A and either the ED7398 or the HiFiFK at 1.5 kHz. This is in good agreement with Munro & Toal (2005), who found similar differences in RECD responses between the ER3A insert earphone and an undamped hearing aid (Widex Senso Diva SD-19).

An RECD that is 10 dB higher at 1.6 kHz, than the actual case, means that the predicted ear drum SPL is overestimated by 10 dB at that frequency. If that value is used to match a prescription target for the hearing aid it would result in substantially lower gain (and output) than the real ear target at 1.6 kHz. This again can affect the audibility in speech and other sounds at that frequency.

An explanation for the different RECD’s due to differences in the impedances of the sound sources has been given by Munro & Toal (2005). If the impedance of the sound source and the coupling system grouped together as $Z_s$ and the impedance of the ear and coupler are taken as $Z_e$ and $Z_c$ respectively, then

$$RECD = \frac{Z_e}{Z_c} \cdot \frac{Z_s + Z_c}{Z_s + Z_e}$$  \hspace{1cm} (5.2)

If the impedance of the sound source and the coupled system is much larger than the input impedance of either the ear or the coupler, equation 5.2 would be simplified.
to,

\[ \text{RECD} = \frac{Z_s}{Z_c} \]  \hspace{1cm} (5.3)

If equation (5.3) applies, the RECD would be independent of the sound source impedance \( Z_s \).

A receiver is changing its impedance rapidly at resonance, and receivers that normally have a high impedance, may approach the impedance of the ear / coupler, and equation then (5.2) applies. A system will resonate when its reactance is zero. For a single component like a receiver diaphragm, this happens at its natural frequency, determined by its own inertance and compliance.

When the receiver is connected to a load (tubes and coupler) that has an impedance that vary with frequency, the reactance of the diaphragm and the reactance of the load may be equal and opposite at frequencies different from the natural frequency of the diaphragm. If that happens at a frequency close to the natural frequency of the diaphragm, the resonance of the diaphragm will be shifted to the frequency where the total reactance equals zero (Gilman, Dirks & Stern 1981).

To illustrate this, the reactance components of the ED7398 receiver and the systems that are coupled to the receiver in the simulations are shown figure (5.15), lower panel. The vertical lines indicate where the reactance of the receiver and the coupled system is equal but has opposite signs.
5.2 Simulations

Figure 5.15: The upper show the resistance characteristics of the coupled system with either the 2cc or the 711 coupler attached. The lower panel show reactance characteristics of the coupled system with either the 2cc or the 711 coupler attached, and the values for the ED7398 receiver. The vertical lines indicate where the reactance of the receiver and the coupled system is equal but has opposite signs.

In figure 5.16 the first resonance peaks for ED7398 are shown together with the vertical lines that indicates the frequencies where the reactance of the receiver and the coupled system is equal but has opposite signs.
5.2.2 Tube length

The histogram in figure 5.12 showed that the length of the tygon tube between the hook of the hearing aid and the earmold can vary significantly. Based on the distribution of the tube lengths in the histogram, simulations have been made with tube lengths from 23 to 43 mm in steps of 10 mm. The tubing for the 2cc coupler component simulation is kept fixed at 25 mm as specified in the IEC standard. The influence the tube length has on the $RECD_c$ is shown in figure 5.18. The reference system is shown in the upper left panel. In this plot the following can be observed. The responses starts to deviate by more than 3 dB from around 800
Hz, and the tube length is seen to have an influence up to 10 kHz. This is because an alteration of the tube length will result in shifts in peak frequencies, in the ear simulator response. When subtracting the 2cc coupler response from the real ear response, there will occur excursions if there is a peak mismatch.

The difference between the $RECD_c$ for the configuration with a 23 mm tubing and the configuration with a 43 mm tubing is 9 dB at 1.5 kHz. However, if the $RECD_c$ response is obtained with an ER3A insert earphone (lower left panel), the difference is -4 dB, which demonstrates that there is an interaction with tube length and transducer.

As an example; at 1.5 kHz the difference in the $RECD_c$ for the ED7398 and the ER3A transducers both attached with 23 mm of tubing is 3 dB. However, with a tubing of 43 mm the difference is 16 dB, a difference that is even higher than what was found in the previous section between these two receivers. The $RECD_c$ with changing tube lengths has also been simulated for all four transducer types that are considered in this work. The results are presented in figure 5.18.

![Figure 5.18: $RECD_c$ simulated with changing tubes lengths. Each subplot shows different transducer types.](image-url)
5.2.3 Earmold dimensions

The histogram in figure 5.12 showed that the length of the sound bore in the earmolds varied quite a lot (8 to 15 mm). To find out if this variation in length will significantly affect the RECD, simulations have been conducted to investigate this. Figure 5.20 show the effect of different lengths ranging from 9 to 15 mm in steps of 3 mm. The change in length of the sound bore, with a diameter of 2.2 mm, is seen to have a small effect on the RECD above 4 kHz, (mainly at the resonance frequencies). The diameter of the sound bore is close to the diameter of the tygon tube. The result is that the sound bore acts as an extension of the tygon tube, and the total difference in the length of the tubing is not large, from one simulation to another (41 to 48 mm). As a consequence of this, the differences in the RECD are not large either.

Figure 5.20: Effect of changing the length of the earmold from 9 to 15 mm. The diameter of the sound bore was fixed at 2.2 mm.
5.2 Simulations

Figure 5.21: Acoustic circuit for parameter study of change in sound bore diameter.

The diameter of the earmold is on average 2.2 mm. To investigate the effect when this is changed, simulation with changes from 2 to 3 mm in steps of 0.5 mm have been made. The result is shown in figure 5.22. The change in diameter is seen to influence the RECD from around 1 kHz, with differences between RECD responses up to 3 dB. Again, this is due to shifts in the frequency where the first resonance occur in the 711 response.

From around 4 kHz the differences between the RECD responses are increasing (up to 6 dB). The reason for this, is that the increasing sound bore diameter starts to act as a horn. The so-called horn effect will increase the high frequency 711 coupler response, which then affects the RECD response, by increasing the RECD correspondingly. The conclusion is, that it is important to use the subject’s own earmold when measuring an RECD, so these effects are included in the RECD response.

Figure 5.22: Effect of changing the diameter of the earmold from 2.0 to 3 mm. The length of the sound bore had a fixed length of 12 mm.
5.2.4 Vents and leakages

Simulations with changing vent diameters is shown in figure 5.24. In the right panel there is a slit leakage in parallel with the vent. In the left panel the slit is neglected to show what influence the vent has without any leakage being present.

To get a better image of the influence of the vent, the $RECD_c$ responses with vent have been normalized to the $RECD_c$ response without a vent (the vent effect), and these are shown in figure 5.25. The figure show what an audiologist can expect when conducting an RECD measurement on a subject with a vented earmold compared to a measurement with an unvented earmold.

The effect of the vent is a high pass filter with 2nd order cut-off in the low frequencies. The cut-off frequency is determined by the Helmholtz resonance as discussed previously. The effect of increasing the vent diameter is seen to reduce the bass and boost the sound at the Helmholtz resonance by 8-10 dB, in the ear simulator, thereby affecting the RECD.

The deviations at high frequencies are due to the influence of the vent’s halfwave resonance ($f = c/(2l)$). However, in this region the transducers have very little output power, so this effect is negligible.

At mid frequencies the vent has no effect on the RECD.

When introducing a leakage in parallel with the vent the peaks at the Helmholtz resonances are reduced in magnitude. This scenario is possibly more likely in a clinical RECD measurement, since leakages are almost unavoidable in a practical measurement.
5.2 Simulations

Figure 5.24: The upper panel show the effect of changing the diameter of the vent from no vent to 3 mm. In the the lower panel there is no leakage.

Figure 5.25: The effect of the vent is seen to mainly influence the low frequencies. However the vent has also an effect at high frequencies. This is due to its halfwave resonance.

5.2.5 Summary and conclusions of the simulation study

Based on the simulation study, the following conclusions can be made:

- The transducers that is used for the measurement, might have an influence on the RECD in the frequency range from 1 to 6 kHz. With largest discrepancies between the RECD’s in the frequency range 1 to 2 kHz.
Changes in the length of the silicone tube between the transducer and the earmold sound bore has an influence on the RECD, by more than 3 dB, from around 800 kHz and up to 10 kHz. The simulations also showed that there is an interaction between the silicone tube length and the transducer.

The length of the earmold that is used in the real ear measurement does not affect the RECD significantly, however, if the diameter of the sound bore is increased from 2 to 3 mm, an increase in the RECD of up to 6 dB was seen from 4 kHz to 8.5 kHz, in connection with an ED7398 receiver as sound source.

A vent in the earmold will affect the RECD at low frequencies, and result in negative RECD values, below the Helmholtz frequency. But at the Helmholtz resonance frequency there will be a boost in the RECD.

A leakage will also have an effect in low frequencies. The simulations show, that if the leakage is combined with a vent in the earmold, the distinct peak at the Helmholtz resonance will be lowered.

A probe tube microphone, with an inner tube diameter of 0.5 mm has no effect on the RECD measurement when the length of the tubing is in the range from 100 to 200 mm, as long as the same tube is used for both the 2cc coupler measurement, and the ear simulator measurement.

### 5.3 RECD measurements

The results from the RECD measurements with six subjects are presented in this section. Four different variables were investigated: (1) transducer type, (2) tube length between transducer and earmold, (3) Vent diameter and (4) different lengths of probe tube. The mean RECD responses for each variable are plotted in separate graphs in the following subsections. Variances across subjects were averaged, and the square root was used to derive mean intra-subject deviations. The test retest reproducibility of the measurements are shown in a panel below the figures by means of standard deviations (SD). The same colour code is used for the standard deviation curves and the parameter they relate to. The separate RECD measurements and standard deviations for each test subject are included in appendix C.

#### 5.3.1 Transducer type

The mean RECD responses for the transducers ED7398 and ER3A are shown in figure 5.26. Due to problems with the measurement equipment, data for the receivers
Knowles HiFiFK and Knowles EF6665 are unfortunately only available for two test subjects. It is therefore only possible to compare the ED7398 and ER3A transducers for all six subjects.

The trends that were seen in the simulations are also present in the measurements. There are substantial differences in the frequency range from 1 to 5 kHz, which confirms that the transducer has an effect on the RECD.

The differences below 1 kHz are possibly related to a more shallow insertion depth of the earmold when measuring with the ER3A insert ear phones. The housing of the ER3A was attached to the collar on the test subject’s blouse or shirt, to make sure it would not pull in the earmold. But the long tube had bend slightly, in order to be connected to the earmold. Maybe this influenced the position of the earmold. The SDs are increasing at high frequencies, which relates to the positioning of the probetube microphone. The insertion depth of the probe tube microphone, from the inter tragal notch, was 35 mm for male subjects, and 30 mm for female subjects, in order to place the probe tube as close to the tympanic membrane as possible. However, even though great care was taken when inserting the probe tube, deviations of a couple of mm was not unusual. The SDs show that this affects the measurements at high frequencies.

![Graph of Mean RECD for the ER3A insert earphone and the ED7398 hearing aid receiver.](image)

Figure 5.26: Mean RECD for the ER3A insert earphone and the ED7398 hearing aid receiver.

The measurements that were possible to conduct with the HiFiFK and EF6665 receivers are shown in figure C.3 in appendix C for test subjects BBE and UFO. These measurements show that the RECDs obtained with the EF6665 has a different
pattern than the RECDs obtained with the ED7398 due to different impedances, as mentioned earlier.

5.3.2 Tube length

The tygon tube between the earmold and the hearing aid hook, was measured for three different tube lengths attached to the earmold. These were 15, 25 and 35 mm. Including the internal tubing in the earmold these lengths were: 20.8, 30.8, and 40.8 mm. Figure 5.27 show the mean RECD responses for all test subjects. The same trends that was seen in the simulations are seen in these measurements.

![Mean RECD for three different tube lengths.](image)

5.3.3 Vent diameter

Figure 5.28 shows the mean data for the effect for all 6 subjects. At low frequencies the RECD is decreasing with increasing size of the diameter of the vent, and the result is similar to the simulation where a leakage was included. However, if we take a look at the individual subject’s RECD responses for different vent configurations in figure C.5 (appendix C), it can be seen that the Helmholtz frequency is not located at the same frequency across test subjects, for the same vent diameter. For the 1 mm vents the frequency range among subjects are from around 250 Hz for BBE and MAN to around 450 Hz for HCO and CPM. This means that the slopes at low frequencies in the RECD is shifted correspondingly.
This is mainly because of differences in the residual ear canal volumes among subjects. As mentioned earlier, the Helmholtz resonance depends on the cross sectional area of the vent (and thereby the diameter), the length of the vent, and the residual ear canal volume. Since the diameter is the same, and the lengths are almost constant, the residual ear canal volume has to be different. Visual inspection of the test subjects CPM’s and HCO’s earmolds did also indicate that their ear canals had a smaller diameter.

![Graph showing mean RECD for unvented earmolds and two vent diameters of 1 and 2 mm.](image)

**Figure 5.28:** Mean RECD for unvented earmolds, and two vent diameters of 1 and 2 mm.

### 5.3.4 Probe tube length

Figure 5.29 shows the mean RECD responses measured with probe tube lengths of 77, 100, 150 and 200 mm. Where the 77 mm long probe tube is the ‘reference tube’ that has been used in the other measurements. The shortest tube had an outer diameter, Ø_outer, of 1 mm, compared to the other three where Ø_outer was 1.3 mm. The are differences at low frequencies due to leakage between the earmold and the ear canal wall. It can be seen that the shortest tube with a thinner outer diameter results in approximately 5 dB higher RECD at low frequencies due to less leakage.
5.4 Summary of results

The mean RECD measurements showed good agreement, in terms of signatures and trends, compared to the results from the simulations presented in the previous section. It is therefore assumed, that conclusions made regarding trends in the simulations will fit on the mean RECD responses of this group of subjects.
The goal of this project was to investigate variables that affect the real ear to coupler difference.
There is no formal definition of how to measure this difference, which means that there are numerous variables that can be considered. This project concentrated on variables in the measurement equipment that can be used, to obtain the RECD response. The analysis where made using plane wave transmission line models implemented in Matlab and measurements in real ears and couplers.
The model was validated by verification measurements in a 2cc coupler, and in an ear simulator, and proved its ability to accurately describe trends in RECD responses, where variables have changing parameters.

In the simulation study a comparison where made of three different hearing aid receivers connected to a hearing aid hook, to represent the acoustics in undamped hearing aids, with different receivers, and an Etymotic ER3A insert earphone and found differences up to 10 dB in RECD. This suggests, that if an undamped hearing aid is fitted to a subject using RECD data obtained with an ER3A insert earphone, the predicted REAR might be up to 10 dB off.

The simulation study revealed that the there is an interaction between the transducer and the hearing aid tubing. This was also shown by Munro & Salisbury (2002), who found similar interactions when they measured the RECD with two different earphones (Audioscan RE770 and ER3A). Their results showed a 3 dB difference in RECD at 1.5 kHz, between the earphones with 25 mm of tubing, where the RE770 earphone had the highest value. However, this magnitude difference increased to 9 dB when the tubing was increased to around 40 mm. In the present study, simulations with a total tube length (silicone tube + sound bore) of 45 mm, revealed a difference of 9 dB between the ER3A insert earphone and the ED7398 receiver at 1.5 kHz. But in this case the RECD for the ER3A had the highest value. This suggests that the magnitude difference between the RECD obtained with an
RE770 earphone and an ED7398 receiver may differ even more than any of the two compared to an ER3A insert earphone. However, this has not been investigated further.

Figure 2.5 in chapter 2 shows different trends in mean RECD’s. At low frequencies the different studies had a relatively large variation. This is likely to be due to leakage effects. The present study showed that the outer diameter of the probe tube can affect the size of leakage between the earmold and the ear canal wall, which affects the RECD at low frequencies significantly. This could be one explanation for the large variation among studies at these frequencies. Feigin et al. (1989) used immitance probe tips in their real ear measurements, which are likely to have poorer sealing than foam tips or custom earmolds. The mean RECD from this study has also the lowest RECD at low frequencies compared to the other studies.

The mean RECD measurements that were conducted in the present study, showed good agreement with the simulations, in terms of signatures and trends. However, at high frequencies the results showed increased standard deviations due to the positioning of the probe tube since the decrease in wavelength of sound with increasing frequency, will increase the influence of standing waves on probe tube measurements remote from the tympanic membrane (Gilman & Dirks 1986). Figure 2.5 revealed also relatively large variations at high frequencies. These variabilities are possibly related to the insertion depth of the probe tube.

In the same figure it was noticed that the mean RECD results from Saunders & Morgan (2003) had a dip at 4 kHz where the other studies showed a tendency for an increase in RECD or a flattening. Saunders & Morgan (2003) used foam tips that have a sound bore diameter of 2 mm. The other studies used either custom earmolds or immitance tip which are likely to have a larger diameter. In the simulations where the sound bore diameter was increased (figure 5.22) the so-called horn effect resulted in a boost in the RECD, with increasing diameter, in the frequency range above 4 kHz. This lack of this horn can be an explanation for this dip.

The findings of this work demonstrate that the RECD response is affected by the entire acoustic system from the transducer to the medial end of the earmold’s sound bore. This is in agreement with previous published studies. A difference in the RECD response means that the predicted real ear aided response will differ by the same amount and this will affect the fitting targets and eventually the SPL the hearing aid will produce at the eardrum.
This knowledge is important to consider in the development of hearing aid fitting procedures and in regard to clinical practice.

A simulation study of real ear acoustics would have been interesting to conduct in relation to the present study. That would give the option to investigate variables like: impedance properties of the tympanic membrane, the shape of the ear, residual ear canal volume with the earmold in place, insertion depth of the earmold and positioning of the probe tube microphone in the ear canal. All these factors are not possible to investigate when using an ear simulator as a representation of the real ear in the RECD simulations. However, it was beyond the scope of this project to perform such an analysis, and is a proposal for future work ideas.
The dimensions of the custom earmolds used for the real ear measurements are listed below.

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<th>SB dia.</th>
<th>Vent length</th>
<th>Vent dia.</th>
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Table A.1: Dimensions of the custom earmolds for all test subjects. (SB = Sound Bore) All dimensions are in mm.
Model for ER-3A insert earphones

The Etymotic ER-3A insert earphones consist of a receiver, an electrical equalization network, an acoustical equalization network and a main tubing between the receiver and the foam tip or ear mold as shown in B.1. The information about the receiver, the equalization networks and the tubing was found in US patent #4,763,753 (confirmed by email correspondence with Russ Thoma, Etymotic Research Inc.). There are three versions available with different nominal impedances. The 10 Ohm version was used in this project.

Figure B.1: Diagram of the ER-3A insert earphones. The receiver is part 18 with the electrical equalization network attached to its input terminals. At the outlet of the receiver the acoustical equalization is located to the left and the main tubing to the right.

The list of components are:

Receiver:

- Knowles CI1955

Acoustical equalization network:

- Component 37: Resistor, 0 Ω
• Component 38: Resistor, 27 Ω
• Component 40: Capacitor, 3 μF
• Component 41: Resistor, 13 Ω

Acoustical equalization network:

• Tube 29, Length: 22 mm, Inner diameter: 0.56 mm
• Tube 30, Length: 7 mm, Inner diameter: 3.8 mm
• Tube 31, Length: 43 mm, Inner diameter: 0.56 mm
• Tube 32, Length: 14 mm, Inner diameter: 3.8 mm

Tubing from receiver outlet to foam tip:

• Tube 26 + 16, Length: 290 mm, Inner diameter: 1.35 mm

The insert earphone has been modeled as a two-port by calculating the total transmission matrix by matrix multiplication of all the transmission matrices for each subsystem in the earphones. The transmission matrix for the receiver was found by simulating the electrical equivalent circuit for the receiver in PSpice.

The four pole parameters for the two-port model are calculated by the Matlab function er3a2p.m
Appendix C

Individual RECD measurements
C.1 Tube lengths

Figure C.1: Individual RECD for different tube lengths.
C.1 Tube lengths

Figure C.2: Standard deviations for different tube lengths.
C.2 Transducer type

Figure C.3: Individual RECD for different transducers.
Figure C.4: Standard deviations for different transducers.
C.3 Vent diameter

Figure C.5: Individual RECD for different vent diameters.
C.3 Vent diameter

Figure C.6: Standard deviations for different vent diameters.
C.4 Probe tube length

Figure C.7: Individual RECD for different probe tube lengths.
Figure C.8: Standard deviations for different probe tube lengths.
The transmission matrices that describes the components in the acoustical circuits are put together as building blocks to build up the plane wave transmission model. To do so, the following calculation rules for matrices apply (Lampton 1978).

## D.1 Serial connection of two-ports

Two-ports in serial connection as shown in figure [D.1] are cascaded by simple matrix multiplication (equation [D.1]).

$$T_{ser} = T_1 T_2 = \begin{pmatrix} A_1 A_2 + B_1 C_2 & A_1 B_2 + B_1 D_2 \\ C_1 A_2 + D_1 C_2 & C_1 B_2 + D_1 D_2 \end{pmatrix}$$ (D.1)
D.2 Branch.

A branch, like a vent or a leakage, is included using the following matrix,

\[ T_{\text{branch}} = \begin{pmatrix} 1 & 0 \\ C/A & 1 \end{pmatrix} \]  \hspace{1cm} (D.2)

D.3 Termination impedance as a two-port.

To terminate the end of the circuit or a branch with an impedance, \( Z \), the following matrix is used,

\[ T_Z = \begin{pmatrix} 1 & 0 \\ 1/Z & 0 \end{pmatrix} \]  \hspace{1cm} (D.3)

When terminating the circuit with a load impedance, it is not possible to cascade additional elements to the system.
D.4 Transfer function of the system.

After the two-port models representing the entire system, have been reduced to one single matrix by the above mentioned calculation rules as shown in figure D.4.

$$v_i = A_T p_o + B_T u_o$$  \hfill (D.4)

$$I_i = C_T p_o + D u_o$$  \hfill (D.5)

$$p_o = u_o Z_L$$  \hfill (D.6)

The transfer function, $p_o/v_i$ of the system is found by deriving $u_o$ from equation (D.5) and inserting it into equation (D.4).

$$v_i = A_T p_o + B_T \frac{p_o}{Z_L}$$  \hfill (D.7)

$$\frac{p_o}{v_i} = \frac{Z_L}{A_T Z_L + B_T}$$  \hfill (D.8)

D.5 Input impedance

The input impedance of a two-port is found by considering it with its output terminals left open ($u_0 = 0$).

$$\frac{p_o}{v_i} = \frac{Z_L}{A_T Z_L + B_T}$$  \hfill (D.8)
The input impedance of a two-port can be calculated as follows,

\[ Z_{in} = \frac{A}{C} \]  \hspace{1cm} (D.9)
The following settings were used in the measurements. The output voltage depends on type of microphone and whether the measurements were performed for verification measurements or RECD measurements.

Analyzer: SSR

- Average mode: Complex adaptive.
- Accuracy: 0.01 dB
- Delay: 50 ms
- Max time: 800 ms
- Stimuli: 1/24 octave logarithmic sweep from 100 - 10 kHz.

An accuracy setting of 0.01 dB means that a repeated measurement has to differ less than 0.01 dB from the first measurement, before the next frequency is measured.

Generator:

- Output voltage: 10 mV RMS, when using the Knowles FG3629 microphone, 100 mV RMS in connection with Sonion 8008 probe microphone.
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