# Predicting the acoustics of individual ears for hearing aid and audio applications - model framework and future work

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## Motivation

The sound pressure at the ear drum is considered *the* reference quantity for virtually all applications involving sound delivery to the ear, such as hearing aids, mobile phones, ear- and headphones. Traditionally, so-called couplers (i.e., small cavities) are used to mimick the acoustics of the residual ear canal. However, it is known that on the one hand, couplers do not correctly represent the average human ear [1]. Even if, on the other hand, artificial ears do a better job in representing the *average* ear, there is still the problem of *interindividual* differences in ear canal acoustics, which may result in ear drum sound pressure levels varying by as much as 20 dB in the frequency range up to 10 kHz, see fig. 1.

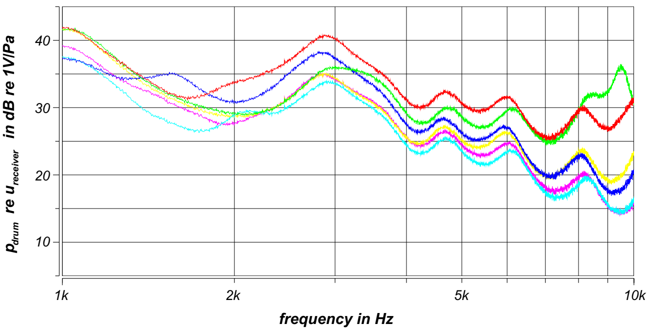


**Figure 1:** Measured transfer functions of the sound pressure at the ear drum relative to the voltage at the source (hearing aid receiver + 60 mm tubing + individual closed ear shell) in 6 human temporal bones.

In order to better predict the sound pressure at the ear drum for individual subjects, yet another modeling attempt [1] is made – this paper gives the model framework and names some open questions, while the companion papers [7, 8] look at specific aspects.

## Model Framework

The model framework is shown in fig. 2. It applies to the situation of an individual subject fitted with a vented hearing aid in a sound field created by an electrically driven sound source (such as a loudspeaker). As stated earlier, this model is largely inherited from references [2, 3, 4], with the exception that those do not include the interaction with the sound field in the manner shown here. The key feature of the model framework is that it is essentially one-dimensional. This was considered necessary to ensure practical applicability, although 1D approches to ear canal acoustics have been questioned lately [5, 6]. A closer look at these references shows that errors due to violations of 1D assumptions occur mainly in cases not or rarely relevant within the present context, such as at higher frequencies or in the vicinity of the ear canal entrance or around the first ear canal bend. Therefore, a 1D approach is maintained.

[1] interestingly, such attempts appear to occur roughly every 10 years [2, 3, 4]

## Individual Ear Canals

Individual ear canals can be modeled as a chain of lossy tubes of varying cross-section. The cross-section function of individual ear canals can be estimated on the basis of measured acoustic impedances at the entrance of the residual ear canals, see the companion paper by Sankowsky et al. [7]. Also, the rather complex vibration pattern of the ear drum appears to be of no great importance to the sound field in front of it, see the companion paper by Roeske et al. [8].

## Vented, Open and Leaky Fittings

In a recent study [9] it was shown that the largest interindividual variability for real-ear-to-coupler-differences (RECDs) occurs at low frequencies, due to leaks in supposedly tight (but non-individual) fittings (so-called closed domes), with interindividual standard errors of up to 10 dB. In contrast, individual closed ear shells lead to an interindividual standard error of only about 3 dB. The residual standard error for the closed domes could be somewhat lowered by considering a very simple classification of ear canal cross section, to about 7 dB. Although we are far from defining a (perceptually relevant) error threshold (see below), this seems to be too high. Thus, one option of improving individual predictions of sound transfer to the ear drum would be to work on a better prediction of leaks.

A second issue arising within the residual ear canal is the presence of strong near fields at the inner face of the ear shell. It was shown in [10] that in the plane at the interface between the ear shell and the residual ear canal, level differences could reach 25 dB at 8 kHz. On the other hand, if one moves away from the discontinuity one has one-dimensional fields again, meaning that one could use 1D models and perhaps apply some correction. Thus ist would be interesting to investigate the needed correction in terms of simply accessible parameters.

## Interaction with Room Acoustics

The interaction with room acoustics can, within the proposed model framework, be described by head-related transfer function (HRTFs), radiation impedances and

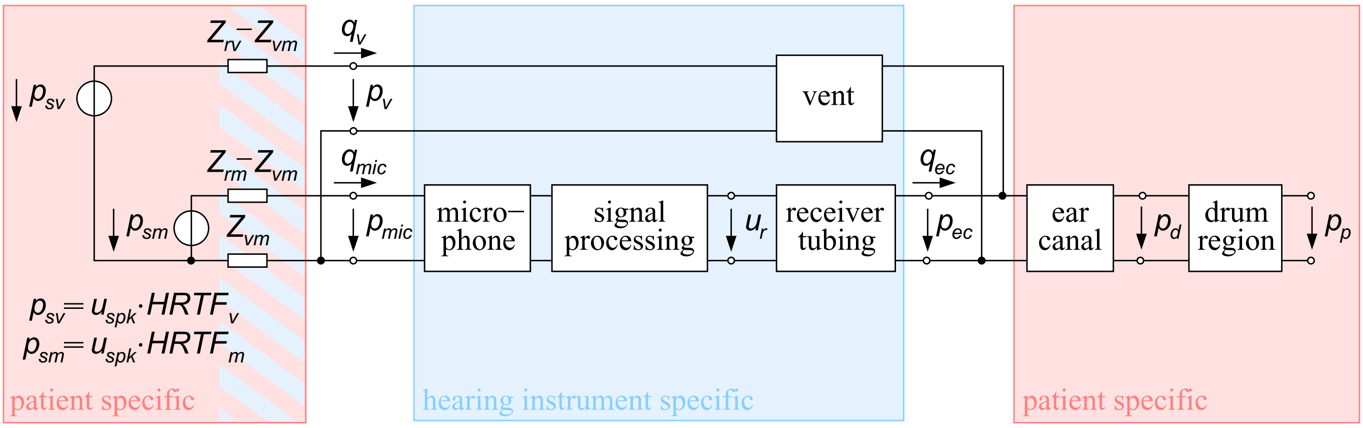


**Figure 2:** Proposed one-dimensional model of a vented hearing aid worn by an individual subject in a sound field generated by a loudspeaker. $p_{\mathrm{sv}}$, $p_{\mathrm{sm}}$ - blocked pressure at the vent opening and the microphone, $u_{\mathrm{spk}}$ - speaker voltage, $HRTF_{\mathrm{v}}$, $HRTF_{\mathrm{m}}$ - head related transfer functions to the vent opening and the microphone, $Z_{\mathrm{rv}}$, $Z_{\mathrm{rm}}$ - radiation impedances of the vent opening and the microphone, $Z_{\mathrm{vm}}$ - transfer impedance from vent to microphone, $p_{\mathrm{v}}$, $q_{\mathrm{v}}$ - pressure and volume velocity at/into the vent opening, $p_{\mathrm{m}}$, $q_{\mathrm{m}}$ - pressure and volume velocity at/into the microphone, $u_{\mathrm{r}}$ - receiver voltage, $p_{\mathrm{ec}}$, $q_{\mathrm{ec}}$ - pressure and volume velocity in the ear canal (at some distance from the inner face of the ear shell), $p_{\mathrm{d}}$ - pressure at the ear drum, $p_{\mathrm{p}}$ - perceptually relevant pressure.

feedback transfer impedances, see the left part of the model shown in fig. 2. Whereas it appears that the details of the radiation impedances don't influence RECD nor the feedback path too much [3], there *is* an increased interindividual standard error of the feedback path compared to RECD [9], indicating that feedback transfer impedances might contain significant individual information.

Whereas most publications on feedback consider a free sound field only, Stinson and Daigle (2003) [11] and Schmidt and Hudde (2008) [12] showed that the presence of a reflecting surface near the ear (such as a mobile phone) will influence feedback in in-the-ear (ITE) hearing instruments only if the reflecting surface is rather close to the ear (less than 15 mm), whereas this was not confirmed for behind-the-ear (BTE) instruments.

Thus it appears to be worthwhile, in order to improve feedback models, to look further into incorporating these and similar types of sound fields into the analysis.

## Real Time Simulation of Hearing Instruments

One application in which it seems sufficient (at least to begin with) to consider average and/or simplified models is the real-time simulation of a vented hearing instrument, which could then be used to test new signal processing algorithms for hearing instruments. The problem here is to couple a topologically complex (including feeback paths) but linear system to the signal processing device which is single-input-single-output but may contain nonlinear operations such as compression or noise reduction.

This was handled by cutting off the signal processing device, and computing the transfer functions of the input to the signal processing device, with respect to the three sources present in the model (receiver voltage, and the two sound pressure sources), and representing them as FIR filters, see fig. 3. A first implementation in a Matlab-based simulation software resulted in processing times of about 10 seconds for a 6 second signal. In order to actually achieve real time, future implementations are planned in a C++ based environment.

## Perceptual Relevance

In every modeling effort, one should have an idea of the desired accuracy. In the present context, the desired accuracy should be given on the basis of perceptual tests and/or user benefit tests. It appears now that such data does not exist in the published literature, perhaps with the exception of (Ludvigsen and Tøpholm, 1997) [13] who showed that using in-situ-audiometry greatly decreased the time to find an acceptable set of fitting parameters, compared to a standard fitting procedure.

Because of the lack of better data, we chose the desired accuracy to be ±5 dB. Further investigations into better founded values appear to be necessary.

## Summary and Conclusion

In this work, a one-dimensional model framework of a vented hearing aid worn by an individual subject in an arbitrary soundfield generated by one source (e.g., a loudspeaker) is proposed. This model was used to set up a time-domain simulation of a vented hearing aid at near real time.

Some open issues concerning the acoustics of individual ear canals and the influence of ear drum vibrations on it are discussed in the companion papers [7, 8].

In addition, there appears to be a need of future work to improve individual models of vented and open fittings, of the interaction with room acoustics and of the perceptual relevance of interindividual differences in the acoustic transfer functions in question.

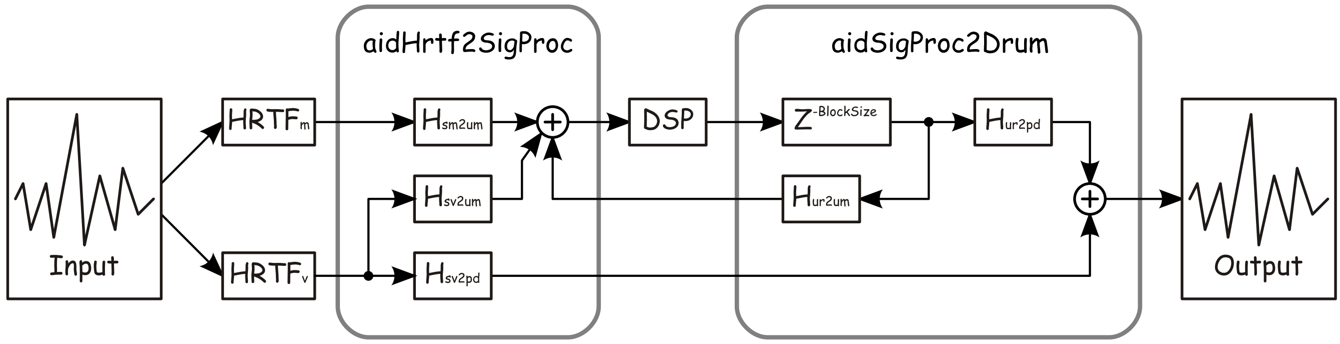


**Figure 3:** Block diagram of the (time-domain) implementation of a simulation of a vented hearing instrument.

## Acknowledgement

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