The PIRATE: an anthropometric earPlug with exchangeable microphones for Individual Reliable Acquisition of Transfer functions at the Ear canal entrance

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Introduction

Measurements of individual Head-Related Transfer Functions and Headphone Transfer Functions require positioning a microphone at the blocked ear canal entrance. The common approach is to modify foam earplugs or silicone domes that are easily inserted into different ears to accommodate a microphone [1]. However, the soft material results in a poorly defined fit in the individual ear, as well as a poor stability and repeatability between insertions. The best option would be individually made earplugs [2], which are, however, expensive and tedious to make.

We present the open design of the PIRATE, an anthropometric earPlug for Individual Reliable Acquisition of Transfer functions at the Ear canal entrance. Its outer shape is available in 5 sizes and provides a deep, tight and reproducible fit in virtually all human ears. It was designed based on the statistical analysis of several hundred ear canal scans, as first presented in [3]. The design includes a recess to accommodate a MEMS microphone. Thus, the same microphone can be conveniently used in different earplugs without losing accuracy, and the microphone can be removed for calibration. The PIRATE or previous versions of it have been utilized in several studies with more than 200 subjects, including publicly available datasets [3, 4]. We believe that it would be helpful also for other researchers, therefore the 3D models are made available to the public under a Creative Commons license at Zenodo (http://doi.org/10.5281/zenodo.2574395). From these, the earplugs can be 3D printed in silicone with only minor manual working steps necessary.

We here describe the design of the PIRATE and show the achievable reproducibility of measurements in an individual human ear. Also, this document includes the technical documentation necessary to make the PIRATE from the published 3D models.

Earplug Design

A CAD model of the PIRATE as well as an image of the assembled version is shown in Figure 1. The outer form of the earplug is described in detail in the following section. The complete device consists out of the main earplug, a MEMS microphone, and a holder for the microphone (visible at the upper left). The main earplug is made out of 3D printed silicone with Shore 65 hardness, the holder was 3D printed in a standard PA plastic.

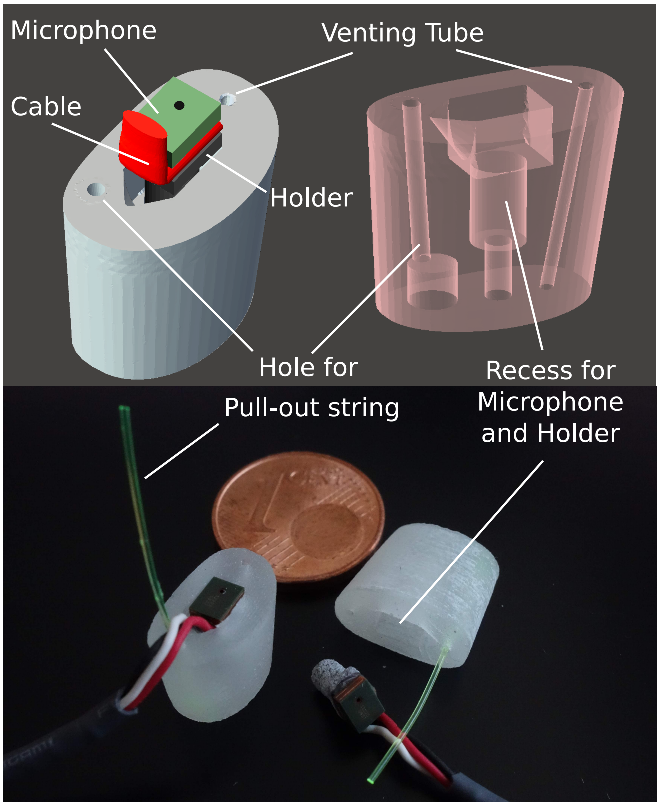

Figure 1: CAD model (top) and photograph (bottom) of the assembled PIRATE. See text for further details. All images show right-ear, medium-sized earplugs.

In the main earplug, several holes and recesses are included, best seen at top right of Figure 1. The largest hole (in the middle) is a matched recess for the microphone attached to a holder. The holder is a rod (Ø = 2.4 mm) with a plate on top that matches the size of the utilized microphone (2.65 x 3.5 mm). We here utilized a MEMS microphone with a top port location, specifically a Knowles SPH1642-HT5H. Several other microphones are available with the same size and port location. MEMS were chosen over electret condenser microphones due to the superior ratio of SNR to size, better temperature stability and smaller variation between devices [5]. Also, they are a factor of about 20 cheaper than electret condenser microphones with a comparable size. See the

Technical Documentation for more details on the microphone.

The recess is designed such that the microphone port is flush with the outer surface of the earplug when inserted. Also, the microphone sits very tight. A small tube connects the bottom of the recess to the inner surface of the earplug (see Figure 1, top right). This allows to push the microphone out of the earplug without any stress on the wiring. At the bottom side of the outer face of the recess, space for the cables is provided. The design makes it very convenient to use the same microphones with different earplugs, and to take out the microphone for calibration purposes.

Also, a small venting tube (Ø = 0.7 mm) located above the microphone is included to avoid an over-pressure in the ear canal after insertion of the earplug. Due to the tight sealing, this issue had turned out to be a problem with previous versions. The diameter was chosen as small as possible and does not influence the ear acoustics.

Furthermore, the earplug features a tube where a string for pulling the earplug out of the ear can be mounted. Attempts to have such a string 3D printed with the earplug were not successful due to poor stability within acceptable diameters. Instead, a nylon string can easily be glued into the provided tube. At the inner end, the tube is broadened such that the inner end of the string can be knotted. Detailed instructions on this are given in the Technical Documentation.

Anthropometric Shape

To provide a good fit across a large variety of ear canals, the earplugs were designed in five different sizes (XS, S, M, L, XL) and in a shape inspired by the anthropometry of the human ear canal. As seen in Figure 1, the basic form consists of two ellipsoid-like faces that form the the top and bottom of a conical body. The major and minor diameter of the ellipsoid-like faces were designed based on the major and minor diameter of the ear canal entrance at the position of the first bend, and inside the ear canal at the position of the second bend (cf. Figure 2). For the size M earplug, the mean values extracted from 999 laser scans of human ear canals were used. The remaining sizes were designed under the assumption of normally distributed measures by calculating selected percentile values based on the mean and corresponding standard deviation (cf. Table 1). The exact form and relative position of the faces was designed after an inspection of individual ear canal impressions. The depth of earplugs was set to 9.2 mm in all cases, because the initially favored distance between the first and second bend was too short to provide a stable microphone mount and fit of the earplug in the ear canal. This, however, was considered a negligible drawback as the outer part of the ear canal is somewhat elastic due to a layer of cartilage.

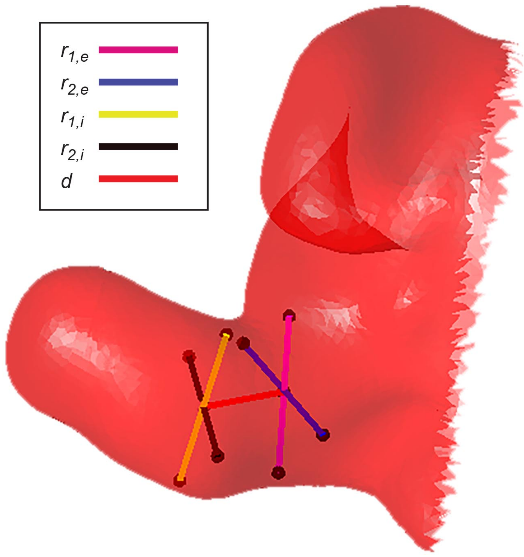

Figure 2: Example of an ear canal scan and extracted measures. The major and minor radii at the ear canal entrance at the position of the first bend are given by $r_{1,e}$ and $r_{2,e}$; radii inside the ear canal at the position of the second bend are given by $r_{1,i}$ and $r_{2,i}$; the distance between the first and second bend is given by d.

$\mathbf{P_i}$ size	$\mathbf{P_{15}}$ XS	$\mathbf{P_{25}}$ S	$\mathbf{P_{50}}$ M	$\mathbf{P_{75}}$ L	$\mathbf{P_{85}}$ XL	$\boldsymbol{\sigma}$
$r_{1,e}$	12.61	13.28	14.50	15.74	16.39	1.82
$r_{2,e}$	6.30	6.82	7.75	8.69	9.19	1.39
$r_{1,i}$	9.99	10.63	11.79	12.98	13.60	1.74
$r_{2,i}$	5.83	6.35	7.29	8.24	8.75	1.40
d	3.20	3.72	4.65	5.59	6.10	1.39

Table 1: Selected percentile values $\mathbf{P_i}$ of ear canal measures in mm (calculated under the assumption of a normal distribution with the mean $\mathbf{P_{50}}$ and the standard deviation $\boldsymbol{\sigma}$).

Reproducibility Measurements

To assess the reinsertion accuracy in measurements with the PIRATE, we conducted repeated measurements of the diffuse-field response at the blocked ear canal entrance of an individual subject. To this end, the subject was sitting in an anechoic chamber with a multichannel 3D loudspeaker setup. Uncorrelated white noise was played from 47 uniformly distributed loudspeakers at the same time, thus generating an approximated diffuse field [4]. The PIRATE was re-inserted into the subject's ear five times, and each time 10 s of the diffuse noise recorded. The paradigm was chosen over direction-resolved measurements to rule out head movements as a source of variation [6]. The fit of the earplug in this subject's ear is shown in Figure 3. We want to note that this measurement was attempted only once, and the subject was by no means selected, e.g., for their ear.

Figure 4 shows the diffuse-field response at the ear canal entrance of the subject, with each line showing one repetition. The reproducibility of the measurement is excellent. Noticeable differences of a few dB only occur between 4 kHz and 10 kHz. On a closer inspection, it be-

Figure 3: Photograph of the PIRATE inserted into a subject's ear.

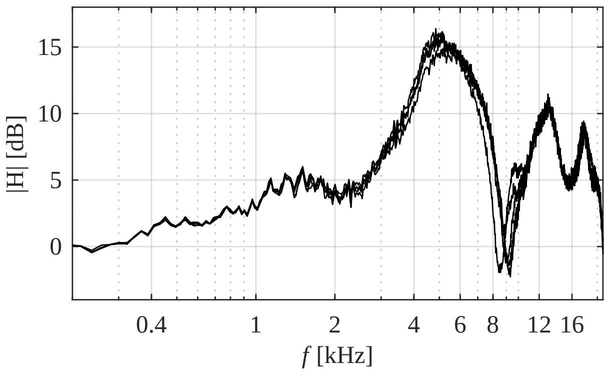

Figure 4: Diffuse-field response of an individual subject's ear; each line represents a measurement with the earplug newly inserted.

comes apparent that only one measurement differs from the other four. Apart from that, no considerable differences are observed, which holds even for the high frequency range above 10 kHz. The results also demonstrate that the microphone blocks the ear canal very well and sits very deep. That is, the resonance of the cavum conchae is captured with a peak amplitude of 16 dB, which verifies that the cavum conchae is not obstructed at all [4]. The results agree with previous measurements where a plastic ear was used to avoid variance due to positional changes of the subject [3].

Availability

The 3D models are available at Zenodo (http://doi.org/10.5281/zenodo.2574395) under the Creative Commons 4.0 CC-BY-SA license. They can be freely used, modified and redistributed, provided that the original source is attributed and modifications are published under a similar license.

The models can be directly 3D printed and only some manual steps are required before using the earplugs, which are documented below.

Technical Documentation

3D Printing

Both the earplugs and the holder are designed for 3D printing. By the time this documentation was written, several 3D print shops offered the suitable technology at comparable prizes (roughly: earplug 15 €, holder: 3 €). The key aspect is 3D printing of flexible silicone with a suitable hardness. While the optimum would be at around Shore 50-55, we only found possibilities to print silicone (specifically, silicone G1H) with a hardness of either Shore 35 oder Shore 65. The hardness should not be below Shore 50, or the earplug will be too soft to provide the defined, reproducible fit that is intended by design. We made good experiences with the Shore 65 silicone. For the holder, any rigid plastic material can be used. However, the resolution should be at least 200 μm.

Preparing the Earplug

Three manual steps are required before the earplug can be used.
First, clean the earplug from residual dust-like material that may stick to the surface after 3D printing.
Second, rework the venting tube and the hole for the pull-out string. Especially the venting tube may be non-permeable after 3D printing, although it should be well-defined. Stick something with suitable diameter ($<$ 1 mm) through it to fix this. Any tiny drill or a stiff piece of wire with a flat end does the job, needles are not recommended.
Third, insert the pull-out string for safely removing the earplug from the subjects' ears. We recommend a monofilament fishing line with a diameter of 0.4 mm or more. Cut a piece of about 10 cm and stick it through the appropriate hole (the one that ends in a larger cavity at the inner end, see also Figure 1). Then, make a knot into the inner end, and make sure this knot fits into the cavity. Push back the knot from the cavity by the length of the earplug, apply glue into the knot cavity (as shown in Figure 5) and pull the knot into its cavity. The glue should stay flexible after it dried – we recommend silicone sealant. Finally, cut the pull-out string to length. We recommend to shorten it to about 1 cm and use tweezers to remove the earplug.

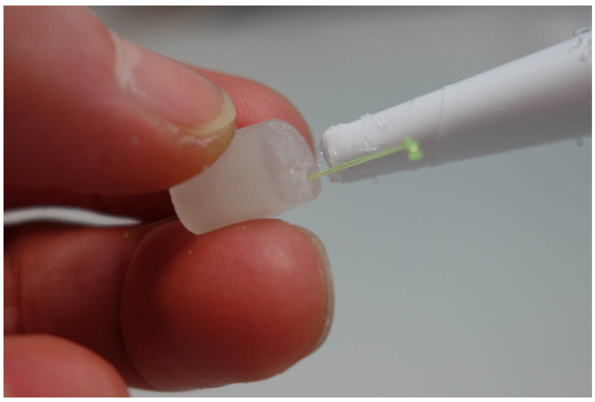

Figure 5: Image of the pull-out string (yellow) being glued into the earplug.

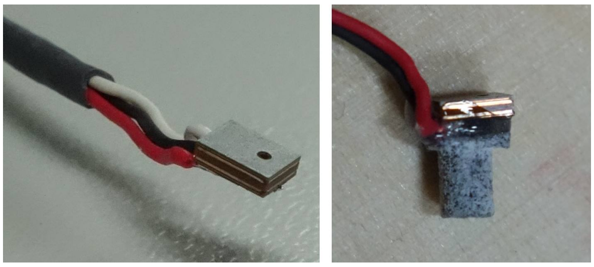

Figure 6: Microphone, with wires attached (left) and glued onto the holder (right).

Microphone Assembly
MEMS microphones are usually only available without cables attached. The wires should be soldered as flat as possible on their pads, and guided away at one of the short sides (see Figure 6). Since the port location is asymmetric, make sure to do this consistently in all your microphones. In the models, 0.9 mm are accounted for the wiring and glue layer between the holder and the microphone. If you need more or less space, you are advised to modify the 3D model of the holder instead of grinding away material or attaching extra glue.

To glue the microphone to the holder, we recommend fast-drying epoxy raisin. Make sure that the microphone is level with the holder. Avoid accumulations of glue at the sides of the microphone, or it may not fit into the recess. Also, guide the cables towards the top surface of the microphone using some glue. A good example how it should look like at the end is shown at the right side of Figure 6.

Microphone and Power Supply
The microphone we utilized (Knowles SPH1642-HT5H) provides an SNR of 65 dB, has a sensitivity of -38 dB V/Pa and cost less than 1.5 € by the time this documentation was written. It requires a power supply between 1.5 and 3.5 V, and we highly recommend to utilize an amplifier between the microphone and the AD converter. Generally, the necessary circuitry is identical to electret condenser microphones.

Practical Tips
Finally, here are some practical tips for using the PIRATE based on our experience:

- Make sure to insert the correct earplug side with the right orientation. The cable guide of the recess always points downwards. For distinguishing left and right earplugs: The more rounded side of the earplug goes to the front, the straight one to the back. The pull-out string is located more towards the concha, not to the front (see also Figure 3).
- Check the ear for large accumulations of cerumen before inserting the earplugs. Cerumen will be pushed deep into the ear canal, which might occasionally clog the ear.
- Choose the earplug size before you put in the microphones by test-inserting them into the ear. If an earplug sits loosely, try a larger size.
- The earplug should sit tight and firmly, with its outer surface flush with the ear canal entrance. This position is the easiest to reproduce, and the reference position for most measurements.
- The inner end usually sits at the second bend of the ear canal, therefore be gentle when pushing it in or you might hurt your subjects. In some ear canals, this will result in the earplug being tilted against the ear canal entrance plane. In this case, try to make the rear edge of the earplug (sticks out further) flush with the ear canal entrance.
- Do not pull at the microphone cable, use the pull-out string. To relief stress on the cable, it is a good idea to tape the cable to the cheek or neck of your subject using medical tape.

Last but not least: we are happy about feedback on any experiences with the earplugs, positive or negative!

Acknowledgement

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