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Research Paper

Estimation of the ear canal displacement field due to in-ear device insertion using a registration method on a human-like artificial ear

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A B S T R A C T

Passive and active in-ear devices (IED) occluding the ear canal are commonly used to (i) protect people from high noise levels (earplugs), (ii) assist people suffering from hearing impairment (hearing aids) or (iii) help people in listening from their sound systems (earbuds). However, the usability and/or efficiency of IEDs can be greatly affected by several discomfort components (physical, acoustical and functional). The mechanical pressure exerted by the IED onto the ear canal walls is greatly suspected to affect the aforementioned comfort components. This physical characteristic is closely related to the displacement field induced by the IED insertion, which has to be known for a better understanding of perceived discomfort. Thus, this paper proposes to validate a method based on medical images to estimate the displacement field of the ear canal walls due to the insertion of an IED. The approach is validated on a human-like artificial ear with canal geometry deformed using two custom molded IEDs with controlled shapes. These geometries are obtained using computed tomography imaging and the displacement field is computed using a registration method. The errors due to the ear canal segmentation and to the registration steps are small enough to compute a relevant estimation of the expected displacement field. Results show that the amplitude of the displacement and its location into the ear canal can be evaluated with an accuracy of $\pm$ 0.2 mm and $\pm$ 0.4 mm respectively. Preliminary results on images with a degraded resolution indicate that the proposed approach used to assess the displacement field of the ear canal walls using computed tomography images could be applied on magnetic resonance images, which is a preferred method to image human subject ear canals for future investigations.

1. Introduction

Passive and active intra-auricular devices occluding the ear canal, referred to as in-ear devices (IED) in this paper, are commonly used to protect people from high noise levels (earplugs), assist people suffering from hearing impairment (hearing aids) or help people in listening from their sound systems (earbuds). A common specification for all of these IEDs is related to the quality of the mechanical seal at the ear canal/IED interface that should ensure a good positioning of the IED with time. Another important specification shared by most of the IEDs is related to the quality of the acoustic seal at the ear canal/IED interface that should insulate adequately the eardrum from external noise. However, the usability and/or the efficiency of such devices can be limited by three major discomfort components also related to the quality of the mechanical and acoustic seals: (i) the physical comfort component characterized by attributes such as friction, irritation or the mechanical pressure exerted by the device on the body, (ii) the acoustical comfort component characterized by attributes such as over- or under-attenuation of external noise, difficulty in communication, occlusion effect or acoustical feedback and (iii) the functional comfort component characterized by attributes such as the ease of insertion or the looseness of the fit (French-Saint and Barr-Hamilton, 1978; Casali et al., 1987; MacKenzie et al., 1989; Park

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and Casali, 1991; Harrison, 1993; Arezes et al., 2008; Kochkin, 2000; Pirzanski and Berge, 2004; Davis, 2008; Conrad and Rout, 2013; Davis and Shaw, 2016; Doutres et al., 2017).

A factor that is greatly suspected to affect all three aforementioned comfort components is the deformation applied by the IED on the ear canal walls (Darkner et al., 2007; Darkner et al., 2008; Baker et al., 2010; Norris et al., 2012). However, the investigation of this deformation is not trivial. Direct measurement techniques are unpractical since they would require miniature displacement sensors onto the ear canal walls. Moreover, these sensors should deliver the 3D deformation field without affecting the mechanical coupling at the ear canal/IED interface. Indirect techniques based on the analysis of the shape modifications of a deformable solid due to an external load seem more appropriate to investigate ear canal deformations. In the specific application of an occluded ear canal, the initial shape corresponds to the geometry of the open ear canal and the modified shape, the one of the occluded ear canal. According to the authors' knowledge, the determination of the ear canal displacement field due to IED insertion has never been proposed in the past. A couple of studies have used indirect techniques to evaluate the ear canal deformation due to the jaw motion from two different perspectives: comfort (Grenness et al., 2001; Darkner et al., 2007) and energy harvesting (Delnavaz and Voix, 2013; Delnavaz and Voix, 2014; Carioli et al., 2016). In these studies, the regions of maximum displacement between the open and closed mouth were evaluated using 3D scans of ear impressions obtained for both jaw positions and analyzed to get geometrical parameters of the ear canal (e.g., diameter, curvature, torsion and aspect ratio) (Delnavaz and Voix, 2013; Delnavaz and Voix, 2014; Carioli et al., 2016) or to get 3D displacement field using a non-rigid registration technique (Darkner et al., 2007).

The approach proposed by Darkner et al. (Darkner et al., 2007) can be applied to the open/occluded ear canal if both geometries are captured from medical images. Indeed, ear impression cannot be used to evaluate ear canal deformation due to IED insertion since (i) it will deform the ear canal (even slightly) and thus prevent the acquisition of the open ear canal geometry and (ii) it will prevent the acquisition of the ear canal geometry for an occlusion by any type of IED. Furthermore, acquiring the shape of the ear canal from medical images in place of using a 3D scan of an ear impression allow (i) avoiding any bias associated with non-uniform contact between the ear canal and the ear impression, (ii) imaging of the entire ear canal from its entrance to its tip and not only to the tip of the ear impression (Egolf et al., 1993; Oliveira, 1997; Yu et al., 2015; Darkner et al., 2017) and (iii) observing the position of the IEDs inside the ear canal (Inoue et al., 2011). A registration method can be used for assessing the 3D displacement field of the ear canal due to IED insertion using the open and occluded ear canal images as the source and target images respectively (Zitova and Flusser, 2003; Klein et al., 2009, Avants et al., 2011). However, before to be applied on real subjects, this approach must be validated by controlling the deformation applied into the ear canal and evaluating its accuracy and precision.

In this work, the proposed approach was applied to an artificial ear mimicking a real human ear. To precisely control the displacement applied to the ear canal, the artificial ear was successively occluded using two non-deformable acrylic custom molded IEDs. The first one was a custom molded earplug made up from an ear impression of the artificial ear. The second IED was identical to the first earplug but its geometry was modified by gluing small beads with a controlled diameter (1.9 mm) on it. Computed tomography (CT) images of the artificial ear occluded by the two aforementioned IEDs were performed. A registration method was used to obtain the displacement field between these two occlusion cases in order to observe the geometry modification of the ear canal due to the presence of the beads. The use of two occlusion conditions instead of an open and occluded ear canal was preferred because it was easier to locally control the dimensions of two beads rather than the geometry of a whole IED. To evaluate the accuracy of the method, the computed displacement was compared to the known diameter and position of the beads and similarity indices were used to evaluate the precision of the approach.

This paper is organized as follows. The design of the artificial ear and of the IEDs is detailed in the first section. Then, CT measurements and the obtained images are presented. The segmentation and registration steps applied to the obtained images to assess the displacement field due to the presence of the beads are detailed. The accuracy and the precision of these two steps are defined and the tools used to evaluate them are presented. Then, the resolution of images is degraded to mimic images obtained using magnetic resonance imaging (MRI). In the second section, computed results using the proposed approach are compared to the measured diameters of the beads and similarity indices are used to evaluate the accuracy and the precision of the method. The segmentation process is performed by different operators in order to evaluate the variability of the method. The proposed approach is also applied to images with MR-like resolution. In the end, these results are discussed in the third section.

2. Materials and method

2.1. Controlled environment

2.1.1. The artificial ear

To finely control the deformation induced by the IEDs, the proposed method was validated on an artificial human ear. Measurements on an artificial ear are easier to perform than on a human subject. For example, an artificial ear is smaller than a human head and can easily be imaged using a small imaging apparatus (Micro-CT or MRI with a reduced size of the antenna). Another advantage to use an artificial ear is that the image noise due to human subject movements during imaging is eliminated. As the artificial ear remains static, there is no such movement during acquisition. The anatomical structure of the ear can also be simplified using an artificial ear in order to make the image post-processing easier. However, the artificial ear must still closely mimic a real ear in order to be able to easily transfer the proposed approach on human subjects after validation. To obtain a realistic ear canal and surrounding tissue geometries, the artificial ear was reconstructed using magnetic resonance images acquired on a 28 years old male subject. The characteristics of the sequence used to image the ear canal of the subject are given in Table 1.

The left ear canal of the subject was inspected by an otolaryngologist to ensure there was no outer ear pathology. Then, the tissues surrounding the left canal of the subject were segmented on MR images using the software *MIMICS, Materialise (Leuven, Belgium)*. Three masks were used to differentiate the soft tissues

Table 1
Parameters of the MRI sequence used to develop the human-like artificial ear.

MR system	Siemens 3T (Verio)
Radiofrequency (RF) coil	Head 32 channels
Sequence	Space 3D
Weighting	T1
Plane	Axial
Slices	128
Resolution [mm]	0.6 isotropic
Acquisition time [min]	9