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Research paper

Contribution of the incudo-malleolar joint to middle-ear sound transmission

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ABSTRACT

The malleus and incus in the human middle ear are linked by the incudo-malleolar joint (IMJ). The mobility of the human IMJ under physiologically relevant acoustic stimulation and its functional role in middle-ear sound transmission are still debated. In this study, spatial stapes motions were measured during acoustic stimulation (0.25–8 kHz) in six fresh human temporal bones for two conditions of the IMJ: (1) normal IMJ and (2) IMJ with experimentally-reduced mobility. Stapes velocity was measured at multiple points on the footplate using a scanning laser Doppler vibrometry (SLDV) system, and the 3D motion components were calculated under both conditions of the IMJ. The artificial reduction of the IMJ mobility was confirmed by measuring the relative motion between the malleus and the incus. The magnitudes of the piston-like motion of the stapes increased with the reduced IMJ mobility above 2 kHz. The increase was frequency dependent and was prominent from 2 to 4 kHz and at 5.5 kHz. The magnitude ratios of the rocking-like motions to the piston-like motion were similar for both IMJ conditions. The frequency-dependent change of the piston-like motion after the reduction of the IMJ mobility suggests that the IMJ is mobile under physiologically relevant levels of acoustic stimulation, especially at frequencies above 2 kHz.

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1. Introduction

The ossicular chain in the human middle ear transmits sound-induced mechanical vibrations of the tympanic membrane (TM) to the inner ear. The middle-ear ossicular chain comprises three bones – the malleus, incus, and stapes, which are connected via the incudo-malleolar joint (IMJ) and incudo-stapedial joint (ISJ).

The IMJ connects the articular surfaces of the malleus and incus and has a twisted saddle shape (Helmholtz, 1863; Etholm and Belal, 1974; Sim and Puria, 2008). It has previously been described in the literature as a synovial joint (diarthrodial joint/diarthrosis) (Politzer, 1884; Harty, 1953, 1964; Etholm and Belal, 1974; Schuknecht, 1974; Marquet, 1981; Hüttenbrink and Pfautsch, 1987; FICAT, 1998; Sim and Puria, 2008). According to the literature, the IMJ is encapsulated by fibrous structures along its borders and contains synovial fluid inside the capsule, without the muscular components that are present in skeletal joints. The thickness of the IMJ tissue structures between the articular surfaces of the malleus and the incus varies from 0.04 mm to 0.32 mm along the intra-articular space, with maximal thickness on the medial and lateral aspects (Sim and Puria, 2008). The anatomical features of the IMJ may allow it to be deformed, resulting in relative motions between the malleus and incus.

The role of the IMJ as a protection mechanism against large static pressure changes has been proposed. For example, Kirikae (1960) argued that the IMJ is immobile up to 140 dB SPL, after

Abbreviations: 3D, three dimensional; AEC, artificial ear canal; IMJ, incudo-malleolar joint; ISJ, incudo-stapedial joint; LDV, laser Doppler vibrometry; Micro-CT, micro–computed tomography; SLDV, scanning laser Doppler vibrometry; TB, temporal bone; TM, tympanic membrane

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which relative motion between the malleus and the incus could occur. Hüttenbrink (1988a) found that the IMJ is mobile under static pressure change. Such relative shear motions between the malleus and incus in human temporal bones (TBs) has been found in other studies as well (Kobrak, 1959; Cancura, 1980; Hüttenbrink, 1988b; Dahmann, 1929; Politzer, 1873; Mach and Kessel, 1874).

While relative displacement between the malleus and the incus under static pressure change of large magnitudes is generally accepted, flexibility of the human IMJ under acoustic stimulation at physiologically-relevant levels and its functional role in middle-ear sound transmission are still under debate.

Several previous works have proposed frequency-dependent behavior of the IMJ, which allows considerable relative motion between the malleus and incus only for the high frequencies. Elpern et al. (1965) observed relative motion above 4 kHz in human TBs, Guinan and Peake (1967) more relative motions at "higher frequencies" in cats and Willi et al. (2002) above 2 kHz in human TBs. Such high-frequency dominant slippage was also observed in three-dimensional measurements of ossicular motion in one human TB (Decraemer and Khanna, 2004). "Slippage" of the IMJ was observed in a study with two human TBs even for the low frequencies (Decraemer and Khanna, 2001), but in their study, the slippage was dominant at the high frequencies.

While some previous studies have argued that the IMJ is functionally immobilized during middle-ear sound transmission under physiological acoustic stimulation, the methods used in these studies did not account for factors that we realize today can influence the results resulting in potential inaccuracies. Harty (1964) made predictions based solely on morphological examination. Békésy (1960) used TBs with a drained cochlea in his measurements. It is known that absence of impedance of the cochlear fluid with a drained cochlea results in an increase of the middle-ear transfer function, especially above 0.5 kHz (Gyo et al., 1987). Some measurement systems were in contact with the middle-ear ossicles, which may change the natural motions of the ossicles. One example is a capacitive probe (Békésy, 1941), where a piece of metal foil is attached to measure the vibration of the surface of interest. Gundersen and Hogmoen (1976) performed their measurements only at frequencies below 2 kHz with time-averaged holographic methods. The measurement with an electromagnetic probe in a study reported by Cancura (1980) was only static and not dynamic. In Elpern et al. (1965), the immobilization of the IMJ was not verified; thus the information of the degree of immobilization was missing.

Willi (2003) and Offergeld et al. (2007) have reported that relative motion between the malleus and the incus caused by the mobility of the IMJ resulted in frequency-dependent transmission loss in the middle-ear transfer function. Willi (2003) observed that immobilizing the IMJ resulted in less transmission loss between the malleus and incus. In this study, after the immobilization of the IMJ, almost no change in transmission was observed below 1.5 kHz, and the transmission increased with frequency above 3 kHz, reaching a 10-dB increase at 10 kHz. Similarly, an increase (less than 10 dB) of stapes motion amplitude occurred in the high frequencies (from 1.2 kHz to 5 kHz) after immobilization of the IMJ, as reported by Offergeld et al. (2007). However, the work by Willi explored transmission loss between the malleus and incus rather than transmission loss through the entire middle ear, which is defined as motion of the stapes with respect to ear-canal pressure. Further, the measurements and analysis were two-dimensional. In the work by Offergeld et al., motions of the stapes were measured one-dimensionally, and immobilization of the IMJ was not quantitatively examined.

In our study, it is hypothesized based on previous studies that the IMJ is mobile under physiological relevant acoustic stimulation, and the mobility of the IMJ results in transmission loss in the middle-ear transfer function, especially at higher frequencies. Our aim is to assess the contribution of the IMJ to middle-ear sound transmission accurately by using current methodologies that include quantification of artificial immobilization of the IMJ and three-dimensional measurement of stapes motion.

2. Material and methods

Fresh TBs from human cadavers were used in this study, and approval was obtained by the Ethical Committee of Zurich (KEK-ZH-Nr. 2012-0007).

To assess the contribution of the IMJ to middle-ear sound transmission in human ears, spatial motions of the stapes, which were measured using a laser Doppler vibrometry (LDV) system, were compared under two different conditions of the IMJ: (1) normal IMJ and (2) IMJ with experimentally reduced mobility. To reduce the mobility of the IMJ, the articular capsule of the IMJ was opened with a surgical hook on the superior side, and removal of the synovial liquid was facilitated by capillary flow to an absorbent tissue. Then, the cavity was filled with glue (Denseal Superior, Prevest Denpro GmbH, Germany) such that the glue replaced the synovial fluid and connected the articular surfaces of the malleus and the incus. For purposes of the study, we refer to the unmodified IMJ as "mobile IMJ," and the IMJ with reduced mobility following insertion of the glue (reduced by 15–18 dB, see Fig. 3) as "immobilized IMJ."

The effectiveness of the immobilization of the IMJ was quantified based on the relative motions between the malleus and incus, measured on an area covering the superior parts of the malleus head and the incus body around the IMJ using the LDV system. Once the immobilization was confirmed, spatial motions of the stapes were re-measured and compared to corresponding data with the mobile IMJ. To avoid bias due to physiological changes of middle-ear tissues caused by drying (Rosowski et al., 1990; Voss et al., 2000; Sim et al., 2004), the samples were placed in saline solution for 30 min prior to the second stage of the measurement, which was with the immobilized IMJ. The time interval between removing the TBs from the saline solution and the measurements was kept constant at approximately 20 min for both stages of the measurement.

2.1. Temporal bone preparation

The fresh TBs were harvested within 24 h after death and were preserved in thiomersal 0.1% (thimerosal, $C_9H_9HgNaO_2S$) solution at 4 °C. Subsequent measurements were done within 7 days after the TBs were harvested (except for TB 2, which was done at 13 days). One TB, which did not conform with the American Society for Testing and Materials (ASTM) standard (F2504-05, Philadelphia, 2005), was excluded during the first stage of the measurements, resulting in a total of six TBs. The six fresh TBs were from four males and two females, with an average age of 68.2 years (ranging from 48 to 83 years).

Exposure of the middle-ear ossicular chain, which included a near-perpendicular view of the stapes footplate and a superior-medial view of the malleus–incus complex, was made by a mastoidectomy with posterior tympanotomy. The TM, middle-ear ossicles, ligaments, and tendon were left intact. The external ear canal was removed and was replaced by an artificial ear canal (AEC) of about 0.5-ml volume (diameter of 9.65 mm and length of 6–8 mm) (Sim et al., 2010, 2012; Lauxmann et al., 2012).

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