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The incudo-malleolar joint and sound transmission losses

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Abstract

The question as to whether the incudo-malleolar joint (IMJ) is mobile or immobile at moderate sound pressure levels (SPLs) is addressed. Referring to the mechanical properties of elastic tissue, we suggest that the IMJ is mobile at any SPL. In order to test this hypothesis, we investigated the dynamics of the IMJ in nine temporal bones by means of laser scanning doppler vibrometry. The dynamic behavior of both ossicles is described by three degrees of freedom, and transfer functions (TFs) are shown for each of them. We show that there is indeed relative motion between the malleus and the incus. This transmission loss affects the middle ear TF and results in a frequency dependent sound transmission loss. Some characteristics of our results are in agreement with middle ear TFs described in the literature. The increasing transmission loss towards higher frequencies is caused by relative motion between malleus and incus at the IMJ. The concept that the IMJ is functionally mobile is consistent with the physical properties of elastic tissues which most likely define the mechanics of this joint. Since the IMJ is indeed mobile at moderate sound intensities and audible frequencies the theory of the lever ratio being responsible for the characteristics of the middle ear TF must be reconsidered.

Key words: Incudo-malleolar joint; Transfer function; Middle ear mechanics; Temporal bone; Human middle ear function

1. Introduction

The incudo-malleolar joint (IMJ) is an important and dominant structure in the ossicular chain and must therefore be carefully studied in order to understand the mechanism of sound transmission in the middle ear. Discussions about the structure and function of the middle ear joints go back as far as the 19th century. According to the P.N.A. (Nomina Anatomica, Paris 1955, revised New York 1960), the two middle ear joints are classified as synovial joints. Since then, they have been described as such by several authors (Kirikae, 1960; Harty, 1964; Belal, 1974; Etholm and Belal, 1974; Marquet, 1981; Hüttenbrink and Pfautsch, 1987). Although it has been anatomically classified, the function of the IMJ remains an open question. Hüttenbrink (1988) described the middle ear behavior quantitatively under static air pressure differences in fresh temporal bones. His results showed shearing between malleus and incus due to physiologically relevant static air pressure differences between the middle ear cavity (MEC) and the external ear canal. Hüttenbrink ascribes to the IMJ a protection mechanism for the inner ear.

In contrast to the middle ear function under static air pressure differences, there are opposing views about the dynamic behavior of the ossicular chain. In 1868, when Helmholz described the junction between the malleus and the incus, he assumed an asymmetric articulation that allows relative motion between the two ossicles. Mach and Kessel (1874) observed the middle ear dynamics under stroboscopic light and found relative motion between malleus and incus. In Frank's (1923) early mathematical model of the middle ear, the IMJ was represented by a spring and Frank ascribed to it a functional meaning. It was Dahmann (1930) who first experimentally described a transmission loss in the IMJ. He assumed that the lever ratio of the ossicular chain

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Abbreviations: AEEC, artificial external ear canal; I, incus; IMJ, incudo-malleolar joint; LPI, lenticular process of incus; LSDV, laser scanning doppler vibrometry; M, malleus; MEC, middle ear cavity; PH, phase of transfer function; *R*, amplitude of transfer function; SPL, sound pressure level; TF, transfer function; U-lat, laterally measured umbo displacement; U-med, medially measured umbo displacement; U-recon, reconstructed umbo displacement

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was compensating for the relative loss in the IMJ. Based on experiments with his carefully constructed oversized middle ear model, Stuhlman (1937) concluded 'that the malleus–incus joint is not rigidly locked'. Bárány (1938) and Békésy (1939), on the other hand, regarded the incudo-malleolar complex as a rigid body. Kobrak (1959) observed 'that during both the inward and outward motion the incus lags behind the malleus' and therefore inferred articulation in the IMJ from that. From his optical and electrical investigations, Kirikae (1960) concluded that below 140 dB sound pressure level (SPL), the 'malleus and incus… vibrate as a rigid body…'. Elpern et al. (1965) experimentally immobilized the IMJ, which did not affect the sound transmission up to 4 kHz. In 1967 Guinan and Peake observed a phase lag between malleus and incus in anesthetized cats at 'higher frequencies' and they consider the IMJ as the 'most attractive candidate' to allow relative motion between the two ossicles. An often cited study explicitly investigating the mechanics of the IMJ was conducted by Gundersen and Hogmoen in 1976. Using time-averaged holography in order to describe the motion pattern of the incudo-malleolar complex, they found a common rotational axis of incus and malleus and concluded that they vibrated as a rigid unit. In his detailed anatomical description of the IMJ, Marquet (1981) inferred that the 'dynamics of the incudo-malleolar articulation provide a three-dimensional buffered effect, maintaining the lenticular process and the stapes in a balanced vibrating position in relation to the oval window'. A study by Schön and Müller (1999) described a frequency dependent transfer function (TF) and a phase lag between the stapes and the umbo which they could neither ascribe to slippage in the incudo-stapedial joint nor to bending in the long process of the incus. By reconstructing the three-dimensional motion of the cat middle ear, Decraemer and Khanna (1999) found relative motion between malleus and incus. They carried out a similar experiment on human temporal bones (Decraemer and Khanna, 2001) and observed 'a substantial amount of slippage between malleus and incus even at low frequencies'.

This short retrospect on some important studies concerning the function of the IMJ illustrates the conflicting views despite being based on experimental data. The idea of incus and malleus vibrating as one rigid unit is widespread in the literature (Harty, 1964; Elpern et al., 1965; Cancura, 1980; Hüttenbrink and Pfautsch, 1987; Brenkman and Grote, 1987; Tay and Mills, 1996). The view that the IMJ is functionally fixed at moderate SPLs and mobile at very high SPLs or static air pressure differences is not consistent with the knowledge of the mechanical properties of elastic tissue. The IMJ is entirely composed of elastic tissue (Etholm and Belal, 1974; Harty, 1964). Since this capsule provides the articular cohesion, it is also responsible for the mechanical properties of the joint in the case of articular motion.

The articular cohesion implies that the enclosing elastic fibers are prestressed. A prestressed fiber responds with a change in length (usually in a linear way) to the slightest change of force. It is therefore reasonable that the joint capsule of the IMJ allows relative motion between malleus and incus even at low SPLs.

The frequency dependent TF between the umbo and the lenticular process of the incus (LPI) is often assigned to a frequency dependent position of the rotational axis and thus to the lever ratio of the incudo-malleolar complex (Gyo et al., 1987). A more straightforward explanation for that phenomenon would be articulation of the IMJ. The lever ratio certainly affects the middle ear TF, but in the case of a mobile IMJ, its significance must be reconsidered.

The goal of this study was to investigate the dynamics of this joint with the best possible present day technology available. We used a minimally invasive technique that allowed the dynamic behavior of the IMJ to be observed while preserving the entire inner ear and all the middle ear structures. The experiments were performed in very fresh temporal bones (within 24 h post mortem). By using a laser scanning doppler vibrometer (LSDV), many measurement points (>200) could be sampled within a short period of time before dehydration occurred. The sensitivity of the system permitted measurements on the ossicles at moderate SPLs (75–90 dB SPL).

2. Materials and methods

2.1. Measurement system

To investigate the dynamic behavior of the middle ear ossicles, a LSDV System PSV-200-1 (Polytec GmbH, Waldbronn, Germany) was at our disposal. The system consists of a sensor head (OFV 303), a vibrometer controller (OFV 3001-S), a scanning unit (OFV 040), a scanning controller (OFV 042) and a PC. Coaxial to the laser beam is a video camera (VCT 24) which captures an image of the scanning area. In the acquisition mode, the system software (PSV 6.14, Polytec) allows the user to calibrate and control the position of the laser beam, to generate the acoustic stimulus via a signal generator (33120-A, Hewlett and Packard), to acquire the velocity information from the sensor head and to monitor the SPL at the tympanic membrane via a microphone (ER-7C, Etymotic Research, Elk Grove Village, IL, USA). The software also offers a presentation mode for the evaluation and visualization of the measurement data.

2.2. Acoustic stimulus

The duration of an experiment is an important factor in temporal bone measurements because dehydration of small structures like ossicles and ligaments changes the mechanical properties of the system dramatically. In preliminary control experiments, 15 min without moisturization of the temporal bone was sufficient to cause obvious changes in the umbo admittance. Therefore individual measurements were kept under 10 min in duration and the temporal bones were remoisturized after each measurement. Two types of acoustic stimuli (a multi-sine signal and a periodic chirp), both limited to a frequency range of 0.5–10 kHz, were used. Within this bandwidth, the ER-7C microphone connected to the probe-tube has a relatively flat response curve (±1.5 dB). Due to its higher frequency resolution, the periodic chirp was generally preferred. The duration of a measurement is determined by the number of points, the number of averages per point and the type of signal used. Measurements on the umbo or the LPI require only about 15–20 points and the periodic chirp could be used without exceeding the time limit of 10 min. In contrast, measurements on the IMJ required more than 200 points and therefore a multi-sine stimulus was used in order to keep the duration of the measurement below 10 min.

At the beginning of each experiment, the output level of the signal generator was adjusted to compensate for the frequency characteristics of the artificial external ear canal (AEEC) and the receiver, such that the resulting signal at the tympanic membrane showed a flat (±3 dB) frequency spectrum. The remaining deviations of up to 3 dB were further taken into account when analyzing the data.

In a first measurement (base line measurement), the umbo velocity was acquired while stimulating with a flat multi-sine signal containing 41 frequency components each at 90 dB SPL. After the MEC was opened, the same measurement was repeated and the intensity of the sound stimulus was to obtain the same umbo velocity as in the closed MEC condition. Consequently, the vibrations of the ossicles correspond to those in the closed MEC with a flat multi-sine signal. The resulting multi-sine stimulus was used to measure velocities at the IMJ. An amplifier (A50, Revox AG, Regensdorf, Switzerland) was added between the signal generator and the loudspeaker (CI-2960, Knowles Elecronics, Itasca, IL, USA) to amplify the signal stepwise to 75, 80, 85 and 90 dB SPL.

A periodic chirp was used to measure the displacement of the umbo and the TF between the umbo and the LPI after perforation of the tympanic membrane (control experiment 3.3). The periodic chirp ranged from 0.5 to 10 kHz with a frequency resolution of 6.25 Hz. Over the frequencies tested, the SPL varied between 70 and 90 dB. The umbo displacements were compensated for the deviations in SPL.

2.3. Temporal bones

Most questions that arise in human middle ear mechanics must be addressed in temporal bones which were removed from human cadavers. It has been shown 'that the middle ears of extracted human temporal bones can be useful models for studies of middle ear function...' (Rosowski et al., 1990). Twelve fresh human temporal bones were used in this study. They were prepared immediately after removal from the cadaver and the experiments were performed within 24 h post mortem. Based on visual inspection and gentle mechanical testing of the mobility of the ossicular chain, the 12 specimens from five males and seven females ranging from 49 to 86 years were considered normal. Three of the 12 temporal bones were used for control experiments and the remaining nine specimens were used for the final experiments.

2.4. Temporal bone preparation

After connective tissues and muscles were removed from the temporal bone the cartilaginous and the bony wall of the external ear canal were removed or drilled down leaving a narrow bony rim (1–2 mm) around the tympanic annulus. The former external ear canal was replaced by a two-piece steel chamber (AEEC) of which the more proximal rim was mounted to the temporal bone by a general purpose acrylic resin (TRAD, Unifast, Leuven, Belgium). Fig. 1 shows a schematic drawing of the temporal bone after preparation. A glass cover slip terminated the distal part of the chamber and thereby sealed it acoustically while it's inclination to the tympanic rim (45°) reduced reflection of the laser beam from the glass cover slip towards the sensor head during umbo velocity measurements. The Knowles CI-2960 loudspeaker was attached to the distal segment of the AEEC. The SPL in the AEEC was recorded by an ER-7C tube microphone with its opening placed within a maximal distance of 3 mm from the tympanic membrane. A small opening in the MEC which was sealed immediately before the first umbo velocity measurement allowed equalization of possible static air pressure differences between the MEC and the environment. After the base line measurement (see Section 2.2) access to the IMJ was obtained by opening the MEC through the middle cranial fossa. The head of the malleus and the body of the incus were exposed as much as possible while preserving the inner ear and the ossicular ligaments. In order to keep the temporal bones moist during the preparation

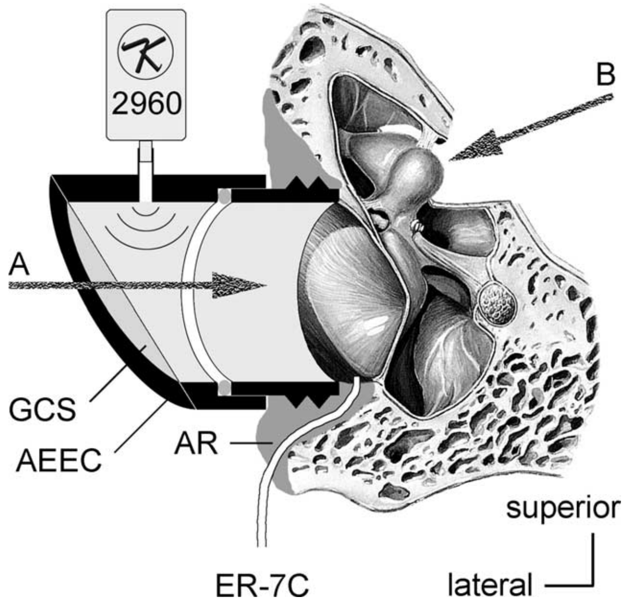

Fig. 1. Schematic drawing of the temporal bone after preparation. The AEEC is mounted to the temporal bone by an acrylic resin (AR). The AEEC is laterally terminated by a glass cover slip (GCS). The distal component of the two-piece steel chamber carries the loudspeaker (Knowles, CI-2960) and can be separated from the proximal component which is attached to the temporal bone. The microphone (ER-7C) records the SPL at the tympanic membrane. This setup allows umbo displacement measurements through the AEEC (A) and measurements on the IMJ through the middle cranial fossa (B). Drawing modified after Sobotta.

they were constantly sprinkled with physiological saline solution.

2.5. Data analysis

2.5.1. Three degrees of freedom

Since the ossicular motion at the IMJ was measured from a single direction, only three degrees of freedom comprising one translational and two rotational components could be evaluated (Fig. 2a). The decomposition of the motion was based on a two-dimensional coordinate system (x, y) and about 100 measurement points per ossicle. In order to obtain comparable results for right and left ears, the coordinate system was aligned with anatomical landmarks on the ossicles (Fig. 3a,b). The y-axis crossed the short process of the incus and the indentation at the IMJ edge of the incus. Orthogonally oriented to the y-axis, the x-axis needed one more landmark to define the coordinate system. This landmark was the superior edge of the IMJ of the incus. The polarities of the axes can be seen in Fig. 3b and were correlated to the same anatomical landmarks for right and left ears. The three-dimensional motion of a rigid body is completely described by the following equation:

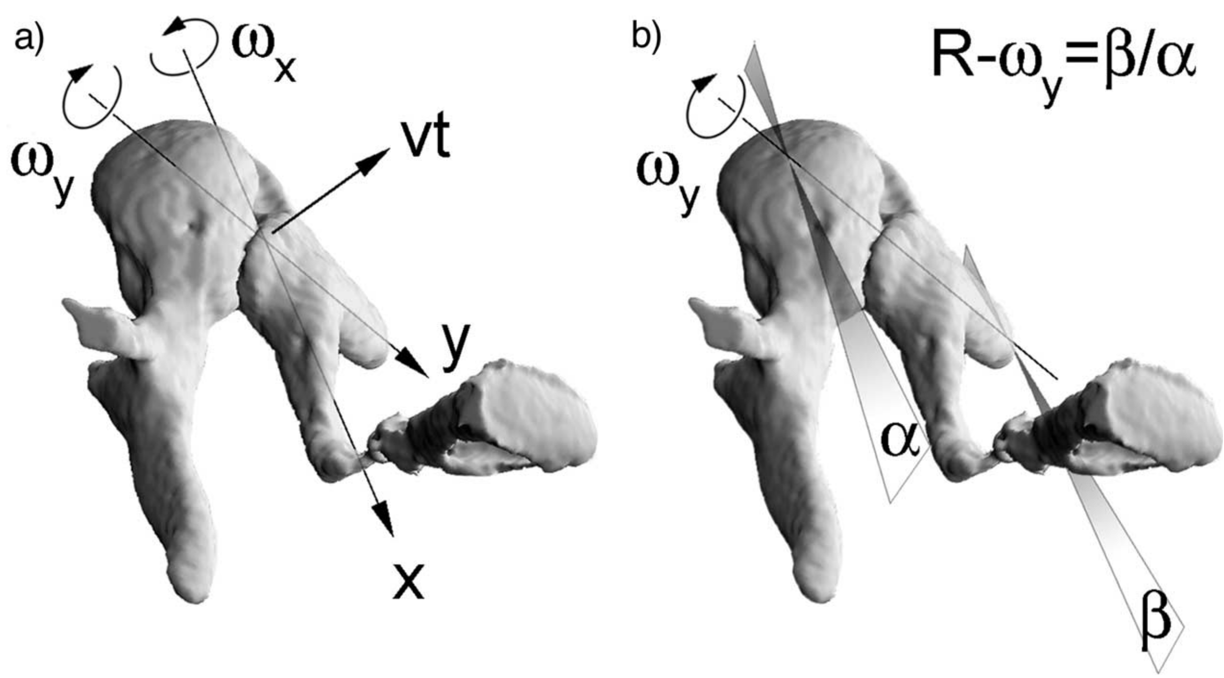

Fig. 2. (a) Due to the measurement technique the degrees of freedom for the ossicular motion at the IMJ were reduced to three, one translational (vt) and two rotational (ω_x, ω_y) components. The 'x–y'-plane is oriented orthogonal to the measuring axis of the laser beam. vt points towards the sensor head. The ossicular motion was described for both malleus and incus by calculating all three components for each of them. (b) The amplitude of the TF of the ω_y-component is illustrated. 'α' and 'β' stand for the maximal angular displacements of the ω_y-component for the malleus and the incus, respectively. R-ω_y is obtained by dividing the incus component (α) by the malleus component (β).

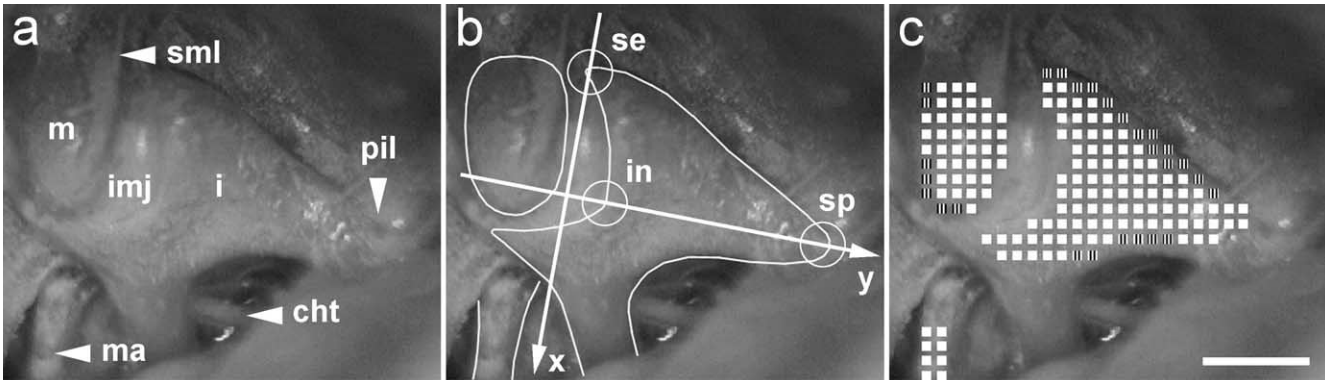

Fig. 3. View of the IMJ through the middle cranial fossa (for this illustration, parts of the semicircular canals were removed). (a) Some structures of the middle ear anatomy are pointed out and serve as an orientation guide. cht = chorda tympani; i = incus; imj = incudo-malleolar joint; m = malleus; ma = manubrium; pil = posterior incudal ligament; sml = superior malleolar ligament. (b) Three anatomical landmarks on the incus were used to align the two-dimensional coordinate system. in = indentation at the edge of the IMJ; se = superior edge of the IMJ; sp = tip of the short process. (c) Schematic illustration of the measurement points. The small group of eight points at the umbo was used in a control experiment (Section 3.2). The large group of points represent the measurements on the IMJ which were performed before removing parts of the inner ear. Measurement points near the edges of the ossicles were not considered (striped measurement points); bar = 2 mm.

$$\vec{v} = \vec{v}t + \vec{\omega} \times \vec{r} = \begin{bmatrix} v_x = v_x t + (\omega_y \times r_z - \omega_z \times r_y) \\ v_y = v_y t + (\omega_z \times r_x - \omega_x \times r_z) \\ v_z = v_z t + (\omega_x \times r_y - \omega_y \times r_x) \end{bmatrix} \tag{1}$$

Since the measurements on the IMJ could only be made from a single direction (along the z-axis), no information about motion along the x- and y-axes was available. Therefore these components (v_x and v_y) were omitted. In addition, the coordinate system was reduced to two dimensions (r_x, r_y) and the z-coordinate (r_z) was set to zero. Eq. 1 is thus reduced to:

$$v_z = v_z t + (\omega_x \times r_y - \omega_y \times r_x) \tag{2}$$

For each frequency, the three velocity components (one translational vt- and two rotational, ω_x- and ω_y-components) were calculated separately for both malleus and incus. The TF was calculated for each motion component (TF-vt, TF-ω_x and TF-ω_y, respectively) in order to characterize the transmission properties of the IMJ.

$$\mathrm{TF} = \frac{\underline{R}_\mathrm{I}}{\underline{R}_\mathrm{M}} = \frac{R_\mathrm{I}}{R_\mathrm{M}} \times \mathrm{e}^{j\omega(\varphi_\mathrm{I} - \varphi_\mathrm{M})} \tag{3}$$

The TF consists of an amplitude (R) representing the ratio at which each motion component is transferred from the malleus (M) to the incus (I), and a phase (PH).

$$2W\partial R = \frac{R_\mathrm{I}}{R_\mathrm{M}} \quad \mathrm{PH} = (\varphi_\mathrm{I} - \varphi_\mathrm{M}) \tag{4}$$

Since the TF of the ω_y-component (TF-ω_y) will be of major importance in this report it is visualized in Fig. 2b and the formula of the amplitude of this TF is described. If the IMJ is functionally fixed, the two ossicles move as one rigid complex and all three motion components must be equal. Therewith the amplitudes of the TFs become 1.0 and their phase becomes zero. If the IMJ is mobile, amplitudes below 1.0 indicate a transmission loss in a certain motion component, and a frequency dependent phase is expected.

2.5.2. Measurement point selection

The measurement points were assumed to lie in a plane. In order to prevent large deviations between the three-dimensional body and the abstracted two-dimensional body, measurement points at steep edges of the ossicles were not considered in the analysis (Fig. 3c). The remaining points were selected by their coherence. The coherence is the frequency domain 'correlation' between input and output signals of a system. It is defined as the ratio of the correlated cross power to the uncorrelated cross power, which includes noise. Only measurement points with coherence above 0.9 were used in the analysis, yielding a group of 20–25 points per ossicle. In order to evaluate the consistency of the measurement, the analysis procedure was executed 10 times each, considering a random choice of 15 points per ossicle. The standard deviation provides information about the consistency of a measurement.

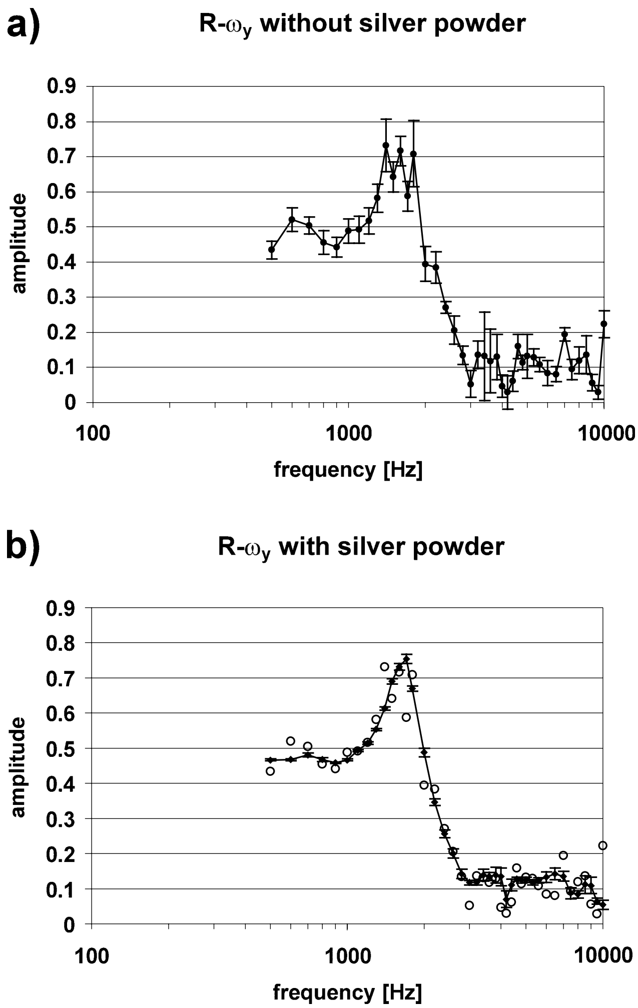

Fig. 4. The amplitude of the TF $R\text{-}\omega_y$ before (a) and after (b) treatment with silver powder. Both amplitudes are based on one measurement each analyzed 10 times with an arbitrary set of 15 points. At each frequency tested the TF amplitude $R\text{-}\omega_y$ is represented by a mean value (closed circle) and a standard deviation (bar). The open circles in the lower graph represent the mean amplitudes before treatment with silver powder (a).

3. Control experiments

3.1. Silver powder

The quality of the laser Doppler measurement depends on the intensity of the reflected signal and the signal to noise ratio. Since the ossicular chain constitutes a lever system with its rotational axis close to the IMJ, displacements in the joint area are much lower than at the umbo or the long process of the incus. Since we decided to measure at biologically reasonable SPLs (75–90 dB) we chose to enhance the reflected signal by covering the IMJ area with a thin layer of pure (99.9+%) silver powder (Sigma-Aldrich Chemie, Steinheim, Germany). The diameter of the silver particles ranged between 2 and 3.5 microns and the amount of silver used varied between 0.1 and 0.3 mg. Using this technique, the consistency of the measurements was improved and measurements became stable at SPLs down to 75 dB. In one temporal bone, the effect of using silver powder was tested at a SPL of 90 dB, calculating $R\text{-}\omega_y$ before and immediately after treatment with silver powder. Fig. 4 shows the two amplitudes ($R\text{-}\omega_y$) of the TF with (Fig. 4b) and without (Fig. 4a) silver powder. Both measurements were analyzed 10 times, each time using a different arbitrary set of 15 measurement points. The characteristics of the frequency response were maintained after treatment with silver powder but its consistency was improved (mean standard deviation without silver: 0.041 and with silver: 0.01).

3.2. How representative are IMJ measurements

Measuring the umbo velocity through the external ear canal is a generally used and broadly accepted technique to obtain a reference measurement. How well measurements on the IMJ correspond with umbo velocity measurements was evaluated in this control experiment. Parts of the semicircular canals and the cochlea were removed until visual access to the umbo and the LPI was achieved. This procedure also allowed one to note the x- and y-coordinates of the umbo and the LPI (also used in Section 3.3). The umbo velocity was laterally measured through the AEEC (U-lat). The IMJ measurement was performed from the same direction as the IMJ measurements in the main experiments with the inner ear intact. The medially measured umbo velocity (U-med) and the IMJ measurements were made from the same laser head position. Fig. 5 schematically illustrates the three types of measurements that were performed in this control experiment.

Firstly, the differences between the laterally (U-lat) and medially (U-med) measured umbo displacements indicate whether measurements performed from the medial side (U-med, IMJ-scan) correspond with a standard measurement from the lateral side (U-lat). Secondly, calculating the three velocity components at the IMJ and considering the umbo coordinates allows us to reconstruct the umbo displacement (U-recon). If the IMJ measurements and the analysis technique were accurate enough, the values for U-med and U-recon should overlap. Fig. 6 shows the laterally and medially measured and reconstructed umbo displacements. The differences in displacement between U-recon and U-med average at 1.4 dB (±1.6) and at 2.3 dB (±1.2) between the U-med and the U-lat. The mean difference between U-recon and the U-lat is 2.9 dB (±1.3) (all dB deviations are given with reference to U-med). The small differences between U-med and U-recon (especially below 6 kHz) demonstrate the accuracy of the

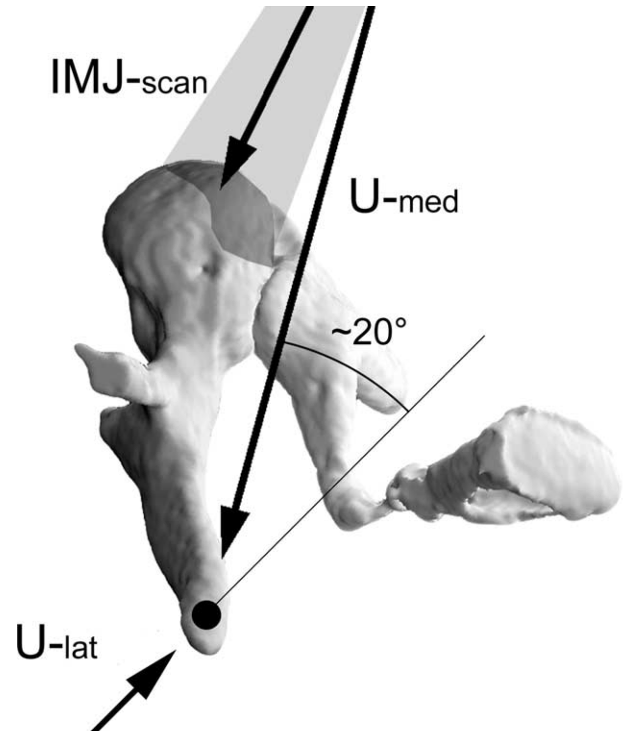

Fig. 5. Reconstruction of the umbo displacement. The arrows roughly indicate the orientation of the laser beam. The IMJ measurement was performed from the same direction as the IMJ measurements in the main experiments with the inner ear intact. Partially removing the inner ear gave medial access to the umbo and therewith allowed the U-med measurement. The U-med and the IMJ measurements were made from the same laser head position and only deviate about 1° from each other. The angle between the U-med and the U-lat measurement axes was approximately 20°.

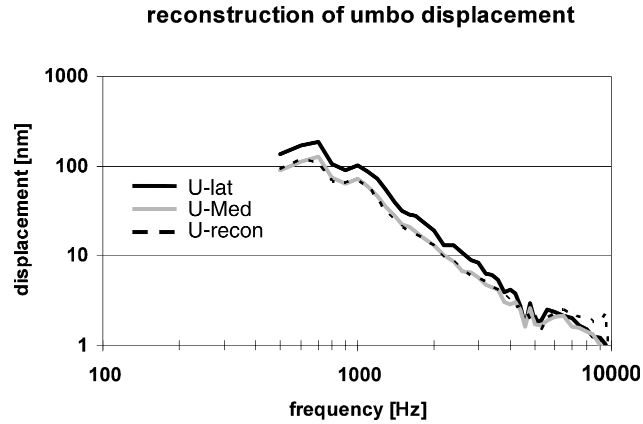

Fig. 6. Three umbo displacements (after removal of the inner ear) acquired with three different techniques all measured at 90 dB SPL: laterally measured (U-lat; solid black line); medially measured (U-med; solid gray line); reconstructed medial umbo displacement (U-recon; dashed line). U-recon was calculated from the three motion components of the malleus at the IMJ and the coordinates of the umbo position.

IMJ measurements and the analyzing technique. The U-lat and U-med measurements were not aligned in parallel (~20°), resulting in differences in the velocity portion captured by each measurement. In this case the difference between the captured portions of the two measurements decreased continuously toward higher frequencies. Below 4 kHz, the deviations averaged at 3.1 dB (±0.5 dB) while above 4 kHz, U-med and U-lat almost overlap and averaged at 1.0 dB (±0.6 dB).

3.3. IMJ-TFs

In control experiment 3.2 above, the use of IMJ measurements to describe ossicular motion was justified. The question whether a relationship between the TF amplitudes deduced from these descriptions above and the TF amplitudes of the middle ear exists is addressed next. To do this, the TF amplitude *R*-ui between the umbo and the LPI was evaluated. Lateral access to the LPI was attained through a small perforation (diameter <1 mm) in the tympanic membrane. A periodic chirp served as acoustic stimulus for these measurements on

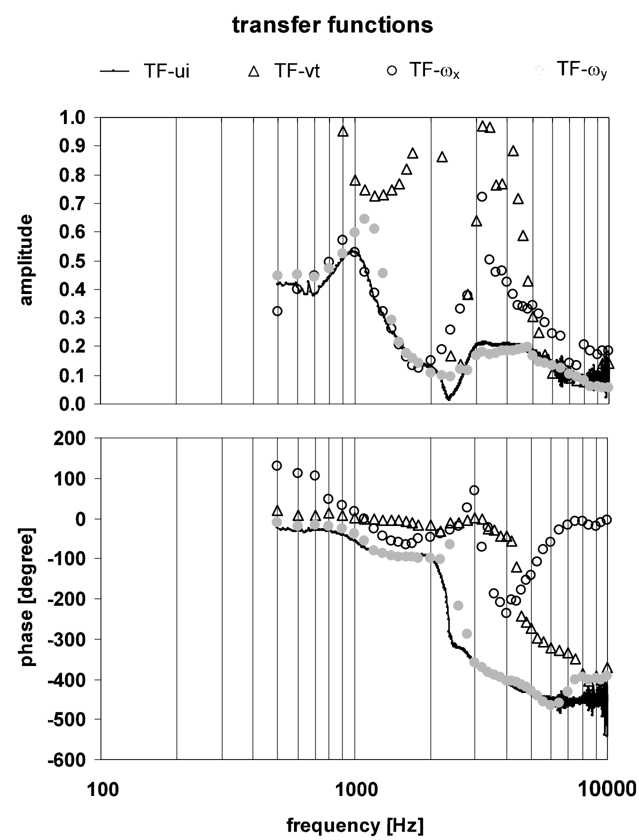

Fig. 7. (Upper graph) Mean amplitudes of TFs at the IMJ (*R*-*vt*, open triangles; *R*-ω_x, open circles; *R*-ω_y, gray circles) and between the umbo and LPI (*R*-ui, solid line) at 90 dB SPL. Below 2 kHz *R*-ui is best approximated by *R*-ω_x and *R*-ω_y. The dip in *R*-ui is only present in *R*-*vt*. The frequency response of *R*-ui was reproduced best by *R*-ω_y. (Lower graph) Phases of the TFs. The frequency response of the PH-ui (solid line) is only approximated by PH-ω_y (gray circles) (PH-*vt*, open triangles; PH-ω_x, open circles).

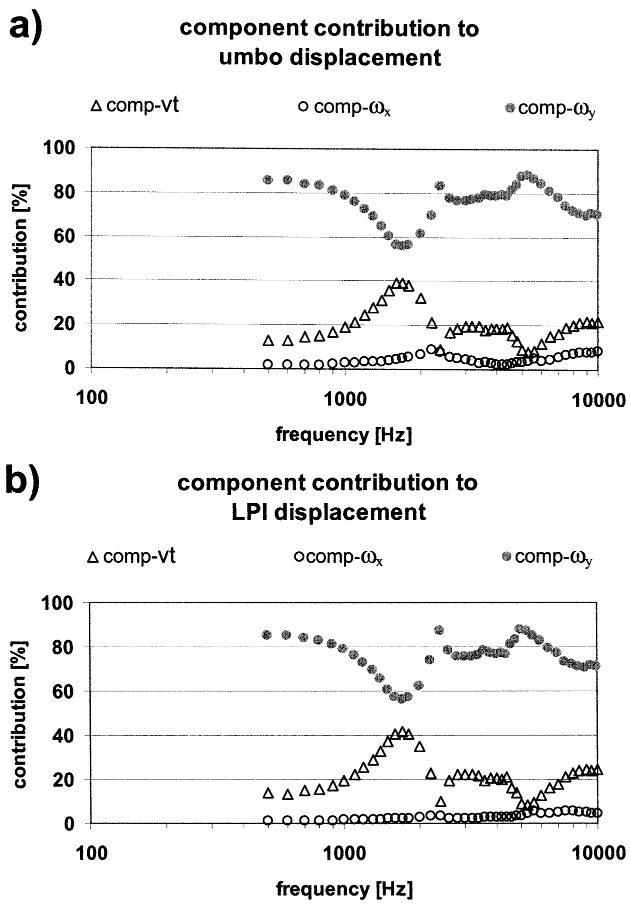

Fig. 8. (a) Contribution of each motion component (vt, ω_x, ω_y) of the malleus to the reconstructed umbo displacement. (b) Contribution of each motion component of the incus to the reconstructed displacement of the LPI. The reconstructed displacements were calculated from the three motion components at the IMJ and the coordinates of the umbo and the LPI position, respectively. For both malleus and incus, the ω_y-component contributes most. In both ossicles, the ω_y- and the vt-components are competing. A decrease of the ω_y-contribution is accompanied by a increase of the vt-contribution (vt-component, open triangles; ω_x-component, open circles; ω_y-component, gray circles).

the umbo and the LPI. The area of the IMJ was scanned using a flat multi-sine signal at 90 dB (SPL). The amplitude of the TF (R-vt, R-ω_x, R-ω_y) and its phase (PH-vt, PH-ω_x, PH-ω_y) were evaluated for each motion component at the IMJ. The TF between the umbo and the LPI (TF-ui) is given by the amplitude R-ui and its phase PH-ui. In Fig. 7 (upper graph), the R-ui is compared to the amplitudes of the three motion components R-vt, R-ω_x and R-ω_y. At frequencies below 2 kHz, R-ui is very well approximated by R-ω_x and R-ω_y. The dip of R-ui at 2.4 kHz is represented in R-vt but not in R-ω_x and R-ω_y. Above 2.6 kHz R-ω_y reproduces R-ui best. The phases of the TFs are depicted in Fig. 7 (lower graph). Except for the frequency range between 2.0 and 2.6 kHz and frequencies above 7 kHz, PH-ω_y is almost concurrent with PH-ui, whereas PH-ω_x and PH-ω_y deviate notably from PH-ui. The TF amplitudes contain only relative information and do not indicate how much a component is contributing to the ossicular motion. The phase of the overall TF should approximate the phase of the dominant component. Since the ω_y-component approximates the TF between the umbo and the LPI best by amplitude and phase we have a good indication that the ω_y-component is dominating the ossicular motion.

Fig. 8 strengthens that point. The x- and y-coordinates of the umbo and the LPI were used to reconstruct the umbo and the LPI displacement. The resulting displacement of the umbo and the LPI, which include all three components (vt, ω_x, ω_y) of the malleus and the incus, respectively, were set at 100%. The displacement of the umbo and the LPI were also reconstructed based on only one component (either vt, ω_x or ω_y). Fig. 8 shows the relative contribution of each motion component to the reconstructed displacement of the umbo (Fig. 8a) and the LPI (Fig. 8b) including all components. The results show that the amount to which a component contributes to the input (umbo) or the output (LPI) of the ossicular chain is frequency dependent. For both malleus and incus, the ω_y-component exceeds the two other components over all frequencies tested and therefore is the dominant motion component. The contribution of the ω_x-component is negligible small. Although the contribution of the vt-component is smaller compared to the ω_y-component, the two components seem to compete with each other (i.e. vt increases when ω_y decreases and vice versa).

4. Results

4.1. Umbo displacement

Before the umbo displacement measurement was performed, possible static air pressure differences between the MEC and the environment were equalized via a small opening to the MEC. A flat (±3 dB) multi-sine signal at 90 dB SPL was used and the umbo displacement was measured laterally through the AEEC. In Fig. 9 the umbo displacements of all nine temporal bones are displayed as a function of frequency. The displacements were compensated for the SPL deviations (±3 dB) and therefore illustrate the frequency response of the umbo to a flat multi-sine stimulus at 90 dB SPL. The peak displacement was between 0.6 and 1.1 kHz. Towards higher frequencies the displacements decreased continuously showing a second but lower peak between 2 and 4 kHz. The inter individual differences were larger at low than at high frequencies.

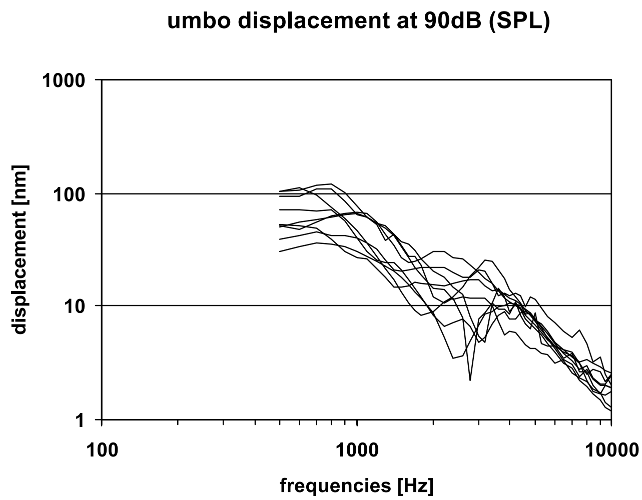

Fig. 9. Umbo displacements of all nine temporal bones under the closed MEC condition. The acoustic stimulus consisted of a flat multi-sine signal at 90 dB (±3 dB) SPL. The displacements were corrected for the small deviations (±3 dB) in SPL that were tolerated in the calibration procedure.

4.2. TF amplitudes at the IMJ

As for the TF amplitudes of the three velocity components, large differences were found between the various temporal bones. In Fig. 10a–c, the amplitudes of all nine temporal bones are shown. For R-ω_x and R-vt, the differences between the specimens were huge and no characteristics or comparable shapes of the curves could be found. Up to about 1.5 kHz, the R-vt showed relatively small deviations between specimens and the amplitudes seem to be reproducible. In contrast to R-vt and R-ω_x, R-ω_y never exceeded 1. Despite substantial differences between the specimens, R-ω_y showed characteristics which were present in all temporal bones. In Fig. 10c, R-ω_y of one temporal bone that typifies these characteristics is highlighted. Starting at 0.5 kHz, the amplitudes varied between 0.45 and 0.8 and stayed almost flat for several 100 Hz until they rose to reach their peak typically between 1 and 2 kHz. Towards higher frequencies, the peak was followed by a steep downward slope which bottoms out at about 3 kHz. The amplitudes then either remained flat or increased slightly towards 10 kHz. R-ω_y was reproducible and the same characteristics could be observed in all nine temporal bones.

4.3. Linearity

The temporal bones were stimulated stepwise at 75, 80, 85 and 90 dB SPL. The TF-ω_y amplitude R-ω_y evaluated at different SPLs did not show any systematic changes with increasing sound intensity (Fig. 11, upper graph) and this applied to all temporal bones which were investigated in this study. The lower graph of

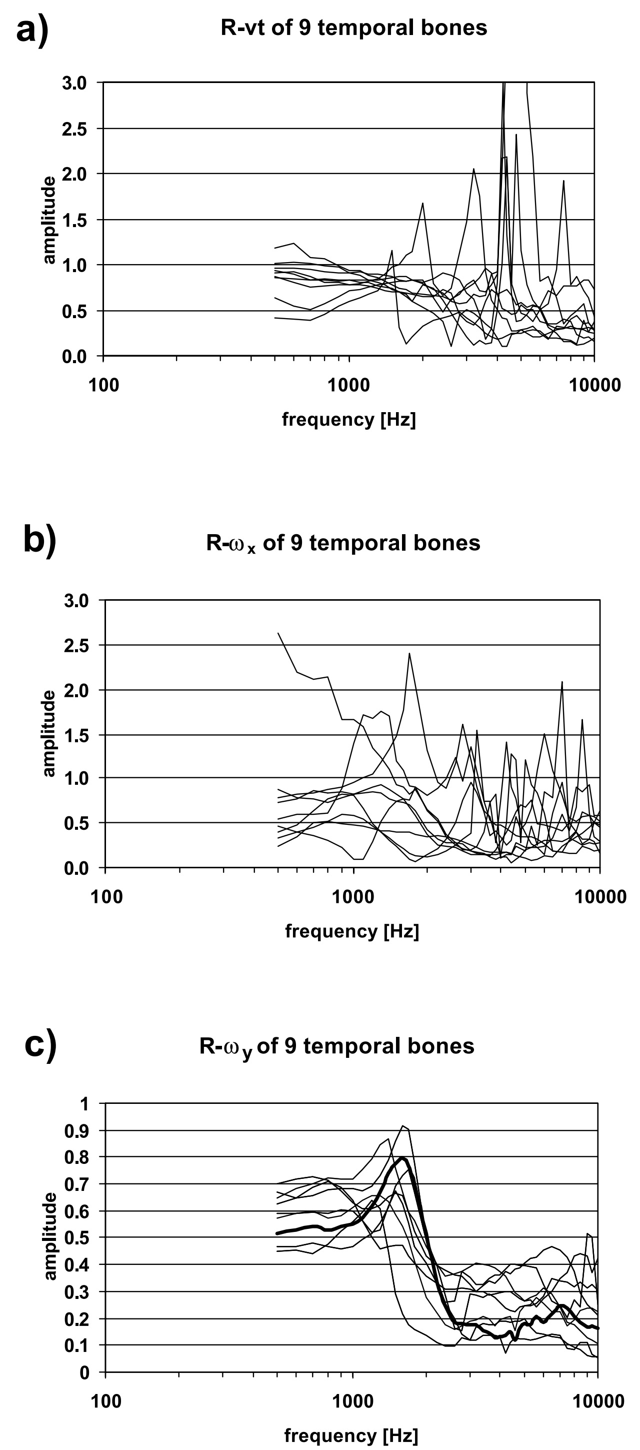

Fig. 10. TF amplitudes of the three motion components, one translational, R-vt (a), and two rotational, R-ω_x (b) and R-ω_y (c). There is little consistency in the vt- and ω_x-component. In contrast, the ω_y-component shows a reproducible and characteristic frequency response. The R-ω_y of one temporal bone that typifies these characteristics is emphasized by a solid line (c).

Fig. 11 shows the phase of the TF-ω_y (PH-ω_y). Although the results became a bit noisy at higher frequencies, the overall frequency response was still consistent over all intensities tested. We therefore conclude

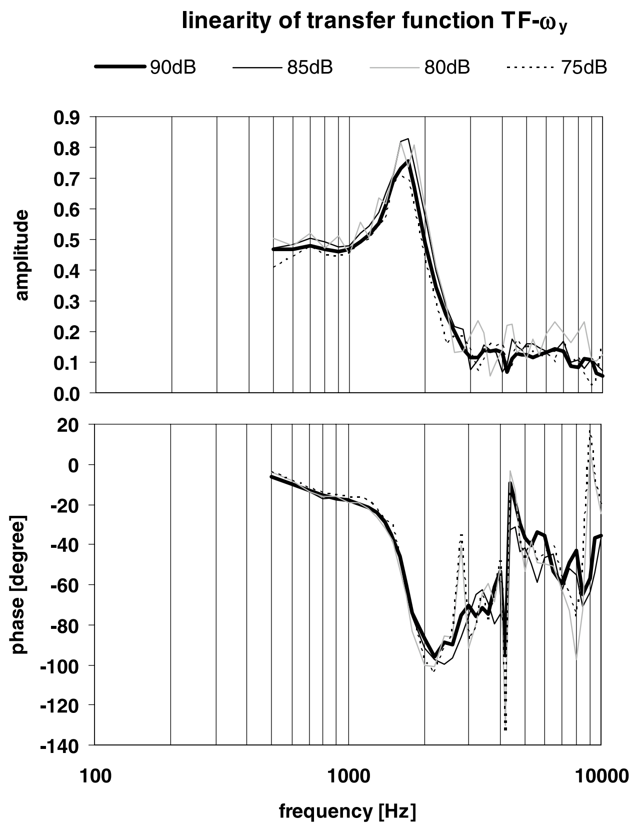

Fig. 11. The TF amplitude R-ω_y is given for SPLs at 75 dB (dashed line), 80 dB (gray line), 85 dB (thin black line), 90 dB (thick black line) in one temporal bone. The frequency response does not show a systematic change with increasing intensity of the acoustic stimulus. The largest deviations are found at the resonance frequency (1.7 kHz) but these deviations were not systematic either. At higher frequencies (> 3 kHz) the amplitudes become unstable at lower intensities (80, 75 dB SPL).

that the IMJ functions within its linear range between 75 and 90 dB SPL.

5. Discussion

5.1. Control experiments

In the first control experiment, we legitimated the use of silver powder. Except for some deviations around the resonance frequency (1.7 kHz), the shape of the two curves (with and without silver) coincided well. The epithelium which covers the ossicles does not diffusely reflect light. Since we measured close to the rotation axis on the IMJ, the intensity of the reflected signal is affected by the angle between the surface and the laser beam. Therefore it is possible for the sensor head to receive a weak or no signal at certain rotational displacements, which would be a reasonable source of error. If the surface is covered with silver powder, the reflection of the laser beam is more intense and more diffuse, making it less sensitive to angular variations between the laser beam and the surface. As shown in Fig. 4, the use of silver powder does not affect the dynamics of the ossicular chain but rather increases the consistency of the measurement.

By comparing the displacement of a measurement point outside of the IMJ (U-med) with its projection from data based on measurements on the IMJ (U-recon), we demonstrated the accuracy of the IMJ measurements and the analysis technique. Up to 6 kHz, the reconstructed (U-recon) and the medially measured umbo displacement (U-med) almost overlap. Above 6 kHz, U-recon slightly deviates from the measured U-med. These findings further indicate that bending of the ossicles does not occur or is negligibly small. If bending of the neck of the malleus or the manubrium occurred, U-recon would exceed U-med. This was not the case.

Laterally measured umbo displacements are often described in the literature and therefore we used it as a reference for our measurements. Since U-lat and U-med were measured from slightly different angles, differences between the two measurements are expected. The motion of the umbo is known to be complex and includes several degrees of freedom (Decraemer et al., 1991; Decraemer and Khanna, 1994). The differences in the registered portions of the umbo motion between U-lat and U-med continuously decreased towards higher frequencies. This is due to the fact that the ossicular chain changes its pattern of motion (modes) with frequency. However, the differences between U-lat and U-med are relatively small (2–3 dB), which supports the assumption that IMJ measurements truly correspond to umbo measurements.

5.2. Our findings

We regard the rotation around the y-axis (ω_y) as the most important motion component because the amplitude and phase of its TF approximate very well those of the TF between the umbo and the LPI. The anatomy of the ossicular chain, the position of its ligaments and its geometry support this rotational degree of freedom. The input (umbo) as well as the output (LPI) of the ossicular lever arm are dominated by this rotational ω_y-component. The portions to which each motion component at the head of the malleus and incus contributes to the motion of the umbo and the LPI, respectively, are very similar (Fig. 7a,b). In other words, the motion components of the malleus are transferred to the incus. Reproducible transmission losses were only found for the rotational ω_y-component.

It is furthermore not surprising that losses in the dominant ω_y-component became prominent in the middle ear TF. Our results coincide with the description of

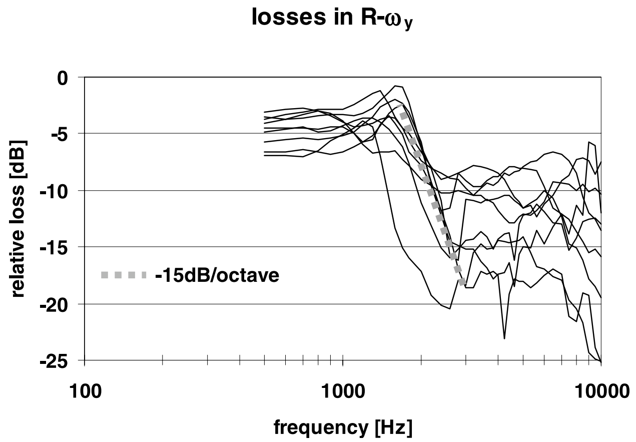

Fig. 12. The TF amplitudes R-ω_y (Fig. 10c) are given as relative transmission losses (dB). The steep slope (−15 dB/octave) of the middle ear TF as described by Goode (1989) is depicted by the superimposed dashed line. This slope coincides very well with the slope of the TF amplitude R-ω_y.

the human middle ear TF by Goode et al. (1994). He found a decrease of 12–15 dB/octave in the middle ear TF between 1 and 3 kHz, which is exactly what we saw in the TF amplitude R-ω_y. In Fig. 12, the TF amplitudes of the ω_y-component (R-ω_y) are shown for the nine temporal bones and the slope described by Goode is indicated by a straight dashed line. A slope value of −15 dB/octave above 1 kHz in the volume displacement at the round window membrane was also published by Kringlebotn and Gundersen (1985).

Gyo et al. (1987) reported on displacement measurements on the umbo, the head of the stapes and the LPI. They mentioned the possibility that the frequency dependent middle ear TF they found could be explained by 'a loosening of the malleo-incudal joint'. However, they overruled this possibility, referring to the findings of Kirikae (1960), Gundersen and Hogmoen (1976) and Elpern et al. (1965) and concluded that a frequency dependent orientation of the rotation axis of the incudo-malleolar complex (its lever ratio) produced the frequency response of the middle ear TF. Since articulation indeed occurs in the IMJ, the significance of the lever ratio determining the TF of the middle ear must be reconsidered.

5.3. Disagreements in the literature

As mentioned in Section 1, the list of authors who have regarded the IMJ as functionally fixed is quite long (Bárány, 1938; Békésy, 1939; Harty, 1964; Elpern et al., 1965; Gundersen and Hogmoen, 1976; Cancura, 1980; Brenkman and Grote, 1987; Gyo et al., 1987; Hüttenbrink, 1988).

We comment on some important and often cited studies next. From their holographic experiments Gundersen and Hogmoen (1976) concluded that (without the contribution of the middle ear muscles) 'malleus and incus... rotate like one stiff body around the axis'. In most temporal bones measured, we observed a common rotational axis of malleus and incus at about 1 kHz which matches the findings of Gundersen and Hogmoen. A common rotational axis is not necessarily accompanied by a zero phase shift. In contrast to the time-averaged holography, laser Doppler velocimetry provides information about the phase of the ossicular motion. Our data show phase differences and also transmission losses at the afore-mentioned frequency (∼1 kHz). Since Gundersen and Hogmoen used time-averaged holography and therefore did not have the phase information to take into account, their conclusion that the two ossicles rotated like one stiff body is not necessarily correct.

Kirikae (1960) took phase into account in his inductive measurements and he found no phase differences between malleus and incus. Kirikae does not mention the precise post mortem time within which he performed his experiments. He removed the m. tensor tympani and the superior malleal ligament which probably changed the mechanical properties of the ossicular chain. The experiments were performed at very high SPLs (110–140 dB), restricted to a small band of frequencies and results were only given for 400 and 800 Hz.

Elpern et al. (1965) measured the differences in volume displacement of the round window membrane due to mechanical fixation of several middle ear structures like the IMJ. They found no changes due to the fixation of the IMJ and therefore concluded that the joint was functionally fixed, but they did not check whether the fixation of the IMJ was successful or not. No measurements were made on the ossicles close to the IMJ. The fact that other fixations showed a decreasing effect with increasing frequency indicates that firm fixation of the structures was probably not achieved. Experimental fixation of the IMJ might be very difficult and therefore the findings of Elpern et al. could be explained by inadequate fixation of the IMJ. Another explanation for the findings described by Elpern et al. is as follows: In their study, the TF of the middle ear refers to the SPL at the tympanic membrane and the volume velocity of the round window membrane. This TF includes the admittance of the umbo, the TF of the ossicular chain and the inner ear. These first two components strongly depend on each other. It is reasonable to suggest that an increase of the ossicular TF by fixation of the IMJ is accompanied by a decrease of the umbo admittance. This was experimentally shown by Dahmann (1930) and demonstrated in a three-dimensional circuit model by Weistenhöfer and Hudde (2000). Therefore the method used by Elpern at al. did not allow any conclusions to be drawn about the function of the IMJ.

The three afore-mentioned papers are often cited as evidence that the IMJ is functionally fixed. We have good reason to question the conclusions of these papers. However, articulation in the IMJ has been observed by several researchers more than 100 years ago. Mach and Kessel (1874) saw the relative motion between malleus and incus under stroboscopic light and Dahmann (1930) quantitatively described the loss of transmission in this joint. The techniques they used are nowadays considered primitive but nevertheless allowed these researchers a minimally invasive insight into the middle ear mechanics. There has been a continuous list of researchers who described, cited or measured articulation in the IMJ (Mach and Kessel, 1874; Helmholz, 1868; Frank, 1923; Dahmann, 1930; Stuhlman, 1937; Kobrak, 1959; Harty, 1964; Etholm and Belal, 1974; Marquet, 1981; Schön and Müller, 1999; Decraemer and Khanna, 1999, 2001). The laser scanning technique provides us with an instrument which facilitates the description and quantitative analysis of small systems like the middle ear with high precision. With this fast, accurate and non-invasive technique we can now confirm what researchers qualitatively and quantitatively observed over more than a century.

6. Conclusions

The high sensitivity and accuracy of our measuring system (LSDV) enabled us to investigate the dynamic behavior of the IMJ at moderate (physiologically relevant) SPLs for the first time. From our results, we can draw the following conclusions:

1. The use of silver powder (in the amounts we used) does not affect the dynamics of the ossicular chain but improves the consistency of the measurements.
2. Reducing the vibration of the ossicular chain to three degrees of freedom still leads to representative results for the entire ossicular chain.
3. The rotation around the axis through the short process of the incus and the head of the malleus (y-axis) constitutes the most important vibrational component of the ossicular chain and determines the middle ear TF in a crucial way.
4. The IMJ is mobile at moderate SPLs (75–90 dB) and operates within its linear range. The mobile IMJ affects the middle ear TF as demonstrated by the transmission losses of the ω_y-component. Relative motions between the malleus and the incus contribute to the steep slope in the middle ear TF between 1 and 3 kHz.

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