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Methodological paper

Errors in measurement of three-dimensional motions of the stapes using a Laser Doppler Vibrometer system

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ABSTRACT

Previous studies have suggested complex modes of physiological stapes motions based upon various measurements. The goal of this study was to analyze the detailed errors in measurement of the complex stapes motions using Laser Doppler Vibrometer (LDV) systems, which are highly sensitive to the stimulation intensity and the exact angulations of the stapes. Stapes motions were measured with acoustic stimuli as well as mechanical stimuli using a custom-made three-axis piezoelectric actuator, and errors in the motion components were analyzed. The ratio of error in each motion component was reduced by increasing the magnitude of the stimuli, but the improvement was limited when the motion component was small relative to other components. This problem was solved with an improved reflectivity on the measurement surface. Errors in estimating the position of the stapes also caused errors on the coordinates of the measurement points and the laser beam direction relative to the stapes footplate, thus producing errors in the 3-D motion components. This effect was small when the position error of the stapes footplate did not exceed 5 degrees.

1. Introduction

It has been revealed by previous works that motions of the stapes involve piston-like motions as well as other components such as rotational motions of the stapes footplate in human and mammals. However, the precise components of stapes motion patterns and the relative sizes and the significance of the non piston-like motions are still unclear. Vlaming and Feenstra (1986) measured motions of four points on the stapes footplate in human temporal bones and observed no significant differences between motions at the four points. They concluded that the motion of the stapes is piston-like. Similar observations and conclusions were also made in animal measurements by Guinan and Peake (1967) and Dankbaar (1970). By contrast, Békésy (1960), based on his anatomical observation on the annular ligament of the stapes, noted that the anterior portion of the footplate had larger displacement than did the posterior part in human. He also predicted that the modes of stapes motion would differ with sound pressure level in the ear canal. Kirikae (1960) measured stapes motion with a drained cochlea and observed rotational motions of the footplate as well as the piston-like motion. It is now generally accepted that the stapes motions are piston-like at low frequencies and include rotational motions at high frequencies in human (Heiland et al., 1999; Voss et al., 2000; Huber et al., 2001; Hato et al., 2003) as well as experimental animals, such as cat (Decraemer et al., 2000) and gerbil (Decraemer et al., 2007; Ravicz et al., 2008).

Various techniques have been developed to measure the dynamic motions of the stapes and other middle-ear structures. Békésy (1960) used capacitive probes, and Gilad et al. (1967) applied the Mossbauer method to measure motions of the ear structures. Optical methods using imaging such as holography (Tonndorf and Khanna, 1968; Gundersen and Hogmoen, 1976; Bally, 1978), video stroboscopy (Helms, 1974; Gyo et al., 1987), and electronic speckle pattern interferometry (Lokberg et al., 1980) have also been used to measure dynamic motions as well as static motions of the middle-ear structures. Merchant et al. (1996) used

Abbreviations: LDV, Laser Doppler Vibrometer; SLDV, Scanning Laser Doppler Vibrometer; *MPE, maximum possible error*; *ER, error ratio*; EC, ear canal; GP, guinea pig.

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an optical motion sensor to measure stapes motions. Recently, Laser Doppler Vibrometer (LDV) systems have been widely used due to their reliability and accuracy in measurements of middle-ear vibrations. The measurements using the LDV system have been applied to temporal bones from human (Gan et al., 2004; Stenfelt and Goode, 2005) and animal cadavers (Sueur et al., 2006; Akache et al., 2007), and intra-operative measurements of live human (Goode et al., 1993; Huber et al., 2001; Whittemore et al., 2004; Chien et al., 2009). The measurements using the LDV system have been in one dimension, and several methods of obtaining 3-D components of the stapes motions have been developed recently. They have also been applied to measurements in human (Heiland et al., 1999; Hato et al., 2003; Sim et al., 2010) and experimental animals such as cat (Decraemer et al., 2000), gerbil (Decraemer et al., 2007; Ravicz et al., 2008), and guinea pig (Huber et al., 2008).

In measurements of the 3-D motion components using LDV systems, artifact in measured velocities and error in estimating the position of the stapes are present, and they are reflected in the 3-D components obtained. Signal-to-noise level in the measured velocities is presumed to be increased by increasing stimulation intensity and magnitude of the stapes motions, resulting in a reduced ratio of the error of the 3-D motion component to the corresponding 3-D motion component. However, the relation between the stimulation intensity and the error in measured velocities has not been quantitatively analyzed, and improvement of the measurement by increasing the stimulation intensity may have a limitation. In most previous measurements and resulting calculations of the 3-D motion components of the stapes (Hato et al., 2003; Eiber et al., 2007; Huber et al., 2008), the position and direction of the stapes in the measurement frame were estimated, and location of the measurement points on the stapes and the relative angular position of the laser beam with respect to the stapes were obtained based on the estimation. Efforts to obtain a more precise position of the stapes with respect to the LDV measurement frame have been made (Decraemer et al., 2007; Sim et al., 2010), but the methods require complicated and delicate setups and procedures. Furthermore, these procedures are limited under specific measurement conditions such as intra-operative and live-animal measurements.

In this study, the motions of the stapes of guinea pig ears were measured at multiple points on the footplate using a scanning Laser Doppler Vibrometer (SLDV) system in response to acoustic stimuli in the ear canal as well as mechanical stimuli using a custom-made three-axis piezoelectric actuator. Effects of the stimulation intensity on errors of the resulting 3-D motion components were examined using the *maximum possible error* (*MPE*) and *error ratio* (*ER*) introduced in our previous work (Sim et al., 2010). Effects of the stapes position error on the 3-D motion components were mathematically formulated and were simulated for several different magnitudes of angular position error of the stapes footplate.

2. Material and methods

2.1. Specimen preparation and mounting

Right ears from four guinea pigs were used: two for measurements with mechanical stimuli by our custom-made three-axis piezoelectric actuator; two for measurements of physiological motions with acoustical stimuli. Guinea pigs were sacrificed by the provider, and were delivered and immediately refrigerated (4 °C). All measurements were performed within 2 days after the sacrifice. Surgical access to the footplate of the stapes was undertaken within 4 h and was accessed from the posterior part of the bulla without damaging the middle ear and inner ear structures. The facial nerve and surrounding bone were partially removed. During the surgical access, the ear was moistened periodically with a physiological saline solution. In order to place a three-axis piezoelectric stimulator on the stapes head, parts of the middle-ear structures, including the tympanic membrane and the malleus-incus complex, were removed without damaging the stapes and its annular ligament at the oval window.

After surgical opening, the guinea pig head was mounted in a custom-made head-holder, alignment of the stapes footplate was estimated with a surgical microscope and was indicated by “direction-indicator” in the head-holder, and the head-holder was placed in the test rig such that the long and short axes of the footplate (x and y axes) were parallel and perpendicular to the three axes of the test rig frame. The relative position of the scanning Laser Doppler Vibrometer (SLDV) system with respect to the test rig frame was measured to get the relation between the SLDV measurement frame (XYZ coordinate system) and the footplate-fixed frame (xyz coordinate system). The XYZ coordinate system of the SLDV measurement frame was set such that the laser beam was along the Z direction, and the XY plane was perpendicular to the laser beam. In the footplate-fixed frame, the long axis of the footplate was set as the x axis, the short axis of the footplate as the y axis, and the direction normal to the xy plane as the z axis footplate-fixed frame. The posterior, inferior, and lateral directions were set as positive directions for the x, y, and z axes for the right ear.

2.2. Measurement with mechanical stimuli

With acoustical stimuli applied to the ear canal, relative magnitudes of the 3-D components in motions of the stapes cannot be controlled. To enhance the desired 3-D motion components and observe effects of measurement errors on each of the decoupled 3-D motion components, the preparation was stimulated by our custom-made three-axis piezoelectric actuator (Fig. 1). The actuator, mounted on stacks of micromanipulators, was advanced to the stapes head, and firm contact between the needle tip of the actuator and the stapes head was obtained through microscopic control (Eiber et al., 2007; Huber et al., 2008). Next, the contact was fastened with a monofilament nylon thread of 0.03 mm diameter (*9-0 Nylon, S&T AG, Switzerland*), which was enclosed in the needle, looped around the stapes head, and pulled by a 0.5 N of a force meter. With the three-axis piezoelectric actuator, the excitation in the z_h direction mainly was expected to generate a piston-like motion (translation in z direction at the footplate center), while the excitations in the x_h and y_h directions were expected to mainly generate rocking motions about the long and short axes of the footplate (rotations about x and y axes). Though small amounts of undesired motion components were always contained in the induced vibrations, the measured displacements showed a predominant motion in the desired direction of excitations (Eiber et al., 2007).

Specimens GP1 and GP2 were excited by the three-axis piezoelectric actuator with harmonic stimuli at frequencies of 0.5, 1, and 2 kHz. The stapes of GP1 was excited by three different modes of stimuli, on which one motion component (either the piston-like or one of the two rocking motions) was dominant compared to the other two components. Magnitudes of the non-dominant motions were less than a third of magnitude of the dominant motion, as magnitudes measured on the stapes head (measured velocity on the stapes head in x_h, y_h, and z_h directions). Several different magnitudes of the stimuli were applied at each mode to see the relation between the stimulation magnitude and errors on the decoupled 3-D components. GP 2 was stimulated by the same amount of excitation for the x_h, y_h, and z_h directions, and this