SPATIAL VIBRATION PATTERNS OF THE GERBIL EARDRUM

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1. INTRODUCTION

Located between the external ear and the inner ear, the middle ear extends from the eardrum to the oval window and includes a chain of three ossicles (malleus, incus and stapes) suspended in an air-filled cavity. The middle ear plays a key role in hearing and is the site of many infections, congenital defects, injuries and other diseases that contribute to hearing loss. To date, non-invasive diagnostic procedures and the quality of middle-ear prostheses are often inadequate. A better understanding of middle-ear mechanics would contribute to advancements in diagnosis and treatment of hearing loss. To this end, many groups have conducted research on mammalian middle ears. Gerbils in particular have become widely used in this field.

Studies investigating eardrum vibrations in mammalian ears have shown simple vibration patterns at low frequencies and more complex ones at high frequencies (Tondorf & Khanna, 1972; Decraemer & Khanna, 1996; Rosowski et al., 2007). The motion of the malleus-incus complex has traditionally been described as a simple rigid rotation around a fixed axis (Békésy, 1960), but studies in cats have shown evidence of shifting of the axis of rotation, and of manubrial bending at high frequencies (Decraemer et al., 1991 & 1994; Funnell et al., 1992). There is, however, a lack of such data for the gerbil.

The use of laser Doppler vibrometry (LDV) has become very common in the study of middle-ear vibrations. LDV is an optical technique used to measure the velocity of a vibrating surface at the nanometer level without mass loading. In this work we present LDV measurements at multiple points along the manubrium of the malleus and along a line on the eardrum perpendicular to the manubrium, in order to study the spatial vibration patterns.

2. MATERIALS AND METHODS

Measurements were carried out on 5 Mongolian gerbils (*Meriones unguiculatus*) from Charles-River (St-Constant, QC). The experimental protocol is described briefly here; a more detailed description was given by Ellaham et al. (2007).

After the gerbil is sacrificed and decapitated, the lower jaw is removed to expose the bulla which encloses the middle-ear cavity. The external ear is removed and parts of the bony ear canal are drilled away to maximize exposure of the tympanic membrane and to reveal the umbo (Fig. 1). A large hole is drilled in the bulla to equalize the pressures on the two sides of the eardrum, and to permit experimental steps to correct for temporal effects (Ellaham et al., 2007).

The gerbil head is attached to a coupler with dental cement at the opening of the ear canal with an orientation that allows an optimal view of the eardrum (Fig. 1). The coupler is an acoustically sealed aluminum cavity. An ER-2 Tube-phone (Etymōtic Research) is used for sound delivery and an ER-7C probe-microphone system (Etymōtic Research) is used to monitor the sound pressure level (SPL) at 2 to 3 mm from the eardrum. A 15-cm PE-50 tube (I.D. = 0.58mm, O.D. = 0.96mm) is used as a vent to prevent static pressure from building up inside the coupler. An antireflection-coated glass window (T47-518, Edmund Optics) covers the top of the cavity. Measurements are performed inside a double-walled sound-proof room (Génie Audio, St-Laurent, QC) to attenuate interference from outside noise.

This experimental setup is positioned under an operating microscope (OPMI 1-H, Zeiss) mechanically coupled to the sensor head of a laser Doppler vibrometer (Polytec HLV-1000). Glass micro beads (diameter 90-150 µm, Sigma) are placed at the points of measurement (Fig. 1) to increase reflectivity and thus improve the signal-to-noise ratio (SNR) of the measured signal. Measurements are acquired starting about 2 hours after the animal is sacrificed. The stimulus is a 128-ms sinusoidal sweep over the frequency range of 0.1 to 10 kHz. The displacements acquired are normalized to the SPL and averaged over 100 samples. The frequency responses below 0.15 kHz are not presented because of low SNR's at the lowest frequencies.

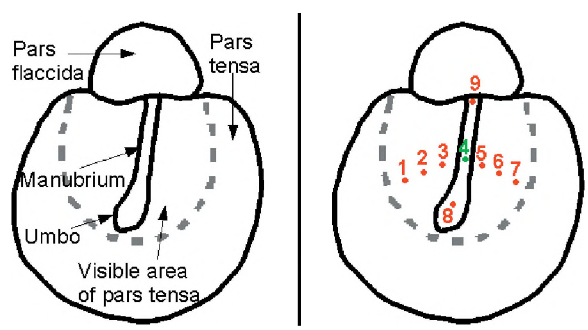

Fig. 1: LEFT: Schematic illustration of the tympanic membrane. Outlined in grey is the area of the pars tensa visible under the microscope. RIGHT: Locations of measurements.

3. RESULTS

3.1. Eardrum vibrations

A large number of measurements was performed on all five gerbils. We present here only the normalized displacements from one specimen, measured across the width of the visible portion of the pars tensa at points 1 to 7 (Fig. 2). The frequency response is flat at low frequencies, and features a peak at about 6.5 kHz and a larger peak at about 9.5 kHz. The frequency responses all have a similar shape over the whole frequency range. Displacements measured on the pars tensa are larger than those on the manubrium, with the magnitude increasing with the distance from the manubrium on both the anterior and posterior sides of the eardrum.

A comparison between symmetrically located points on each side of the manubrium reveals that displacements seem to be larger on the anterior side in all specimens studied. In some specimens, measurements were taken in both the inferior and superior portions of the pars tensa; displace¬ments were found to be larger in the inferior portion.

3.2. Manubrial vibrations

Normalized displacements recorded along the manubrium showed the same frequency-response shape as on the pars tensa. Manubrial displacements are generally largest at the umbo and decrease as the distance from the umbo to the point of measurement increases. In one gerbil, the shapes of the responses change beyond 6 kHz, and over a small range of frequencies (from 8 to 9 kHz) the manubrial displacements at a point superior to the umbo are actually larger than those at the umbo. These discrepancies may be attributable to significant temporal effects in that specimen.

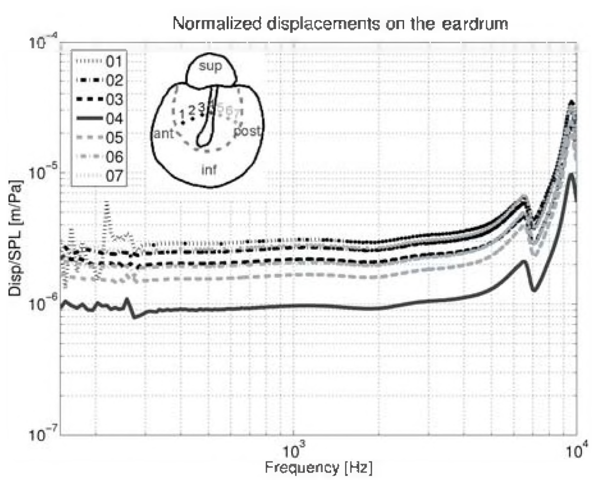

Fig. 2: Normalized displacements on the eardrum. Point 4 is on the manubrium (solid line, dark grey). Measurements on the anterior side of the pars tensa are shown in black, those on the posterior side are shown in light grey, using dashed, dot-dashed, and dotted lines as we move away from the manubrium.

4. CONCLUSION

This paper presents displacement measurements at multiple points on the gerbil eardrum. Spatial vibration patterns across the eardrum and along the manubrium are analyzed over the frequency range from 0.15 to 10 kHz. The similarity of the shapes of the frequency responses at all points of measurement indicates that the motion of the gerbil eardrum follows a simple pattern, with all points vibrating in phase. The complex patterns observed at a few kHz in other species (Tondorf & Khanna, 1972; Decraemer & Khanna, 1996; Rosowski et al., 2007) seem to occur beyond 10 kHz in our experiments. The manubrial displacements observed are consistent with the traditional concept of a simple rotation around a fixed axis extending from the anterior mallear ligament to the posterior incudal ligament. The manubrium appears to vibrate as a rigid body over at least most of the frequency range. Further measurements will be required in order to investigate the possible effects of manubrial bending and of shifting of the axis of rotation.

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