Measurement of Dynamic Frequency Characteristics of Guinea Pig Middle Ear by a Laser Doppler Velocimeter*

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The objective of the present study is to clarify the dynamic behavior of the middle ear by measuring the middle ear vibration directly. The velocity amplitudes of the tympanic membrane and ossicles of guinea pigs are measured before and after the manipulation of the cochlea and bulla using a laser Doppler velocimeter coupled to a compound microscope. The frequency characteristics of the middle ear vibration after the manipulation are different from those before it. These differences are explained by considering mass and damping components of the cochlear impedance and mass and stiffness components of the bulla's impedance.

Key Words: Biomechanics, Seeing and Hearing Mechanism, Measurement, Middle Ear, Tympanic Membrane, Ossicles, Manipulation, Laser Doppler Velocimeter

1. Introduction

Middle ear transmits sound signals from the external auditory meatus to the cochlea through the mechanical linkage of the tympanic membrane and ossicular chain. Many investigations on the middle ear of human cadavers[(1)-(6)], cats[(7)-(9)] and guinea pigs[(10)] have been reported. They have discussed the impedance of the middle ear and cochlea, or the vibration mode of the ossicles at low frequencies. However, those at mid and high frequencies have not been well analyzed.

In this paper, using a laser Doppler velocimeter coupled to a compound microscope, velocity amplitudes of the tympanic membrane and ossicles of the guinea pig were measured directly at the frequencies between 0.1 and 10 kHz, and the dynamic relationship between the tympanic membrane and umbo were clarified. Moreover, the velocity amplitudes of the ossicles were also measured before and after the manipulation of the middle or inner ear, and the effects of this manipulation on the dynamic behavior of the middle ear were analyzed.

2. Material and Methods

2.1 Animal preparation

Albino guinea pigs weighing between 200 and 350 g were examined. All of them had prompt pinna reflex and were free from middle ear diseases. They were initially anesthetized by intraperitoneal injection of pentobarbital sodium (35 mg/kg). Then, the animals were tracheotomized and artificially ventilated with room air after intramuscular injection of a muscle relaxant, suxamethonium chloride. The body

* Received 16th April, 1999. Japanese original: Trans. Jpn. Soc. Mech. Eng., Vol. 63, No. 607, C (1997), p. 649-653 (Received 29th March, 1996)

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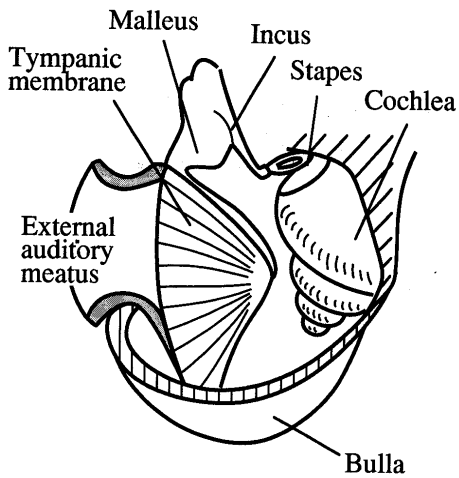

Fig. 1 Structure of a guinea pig ear

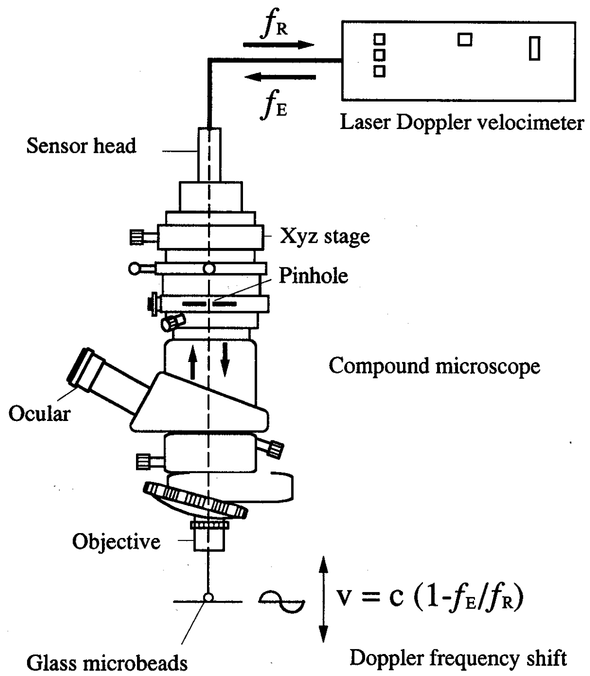

Fig. 2 Schematic diagram of a compound microscope coupling with a laser Doppler velocimeter

temperature of the animals was maintained at around 37°C using a thermostatically-controlled heating blanket. The pinna and bulla walls were removed to expose the middle ear as shown in Fig. 1.

2.2 Measurement system

A laser Doppler velocimeter coupled to a compound microscope allows us to make measurements of the velocity of the restricted portion of the middle ear by focusing a laser beam from the optical head of the instrument onto a small spot. The schematic diagram of the compound microscope coupled with the laser Doppler velocimeter is shown in Fig. 2. Glass microbeads, whose index of reflection was 2.2 and diameter was below 20 μm, were placed on the middle ear as laser beam reflectors. The output laser beam from the

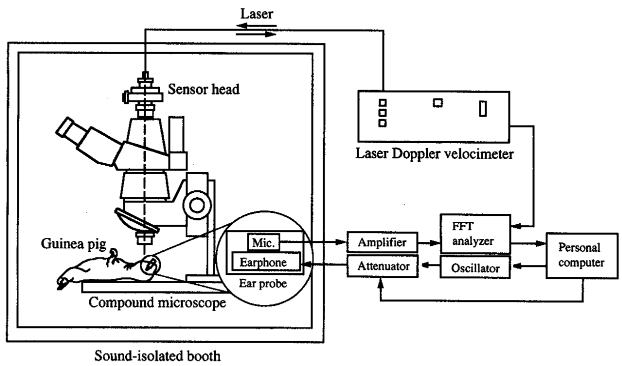

Fig. 3 Block diagram of the measurement system

sensor head via a pinhole was focused onto the microbead through the objective lens. The diameter of the beam at the microbead was approximately 5 μm. The beam reflected in the glass microbead returns to the sensor head through the same way mentioned above. The frequency of the reflected beam is changed according to the velocity of the microbead v, which can be written as

$$v=c(1-f_E/f_R) \quad (1)$$

where c, f_E and f_R are the velocity of the laser beam, the frequencies of the output and reflected laser beams, respectively.

The block diagram of the measurement system is shown in Fig. 3. A sound of sweeping sinusoidal frequency f between 0.1 and 10.0 kHz and the constant sound pressure (65 dB SPL) was led to the external auditory meatus by the earphone. The velocity amplitudes and phases of the tympanic membrane and the ossicles were measured by the laser Doppler velocimeter, and the velocity signals were analyzed by the Fast Fourier Transform (FFT) analyzer. The oscillator, attenuator and FFT analyzer were controlled by the personal computer through the General Purpose Interface Bus (GPIB).

3. Measurement Results

3.1 Repeatability of vibration measurement

The velocity responses of the footplate (see Fig. 4) to the harmonic stimulation were measured seven times in one ear. The mean velocity and standard deviation were calculated, and the results are shown in Fig. 5. The solid and dotted lines show mean velocity and standard deviation, respectively. The standard deviation was small enough and the repeatability was good.

3.2 Tympanic membrane

The measurement points were selected at the umbo and the midpoints between the umbo and the anterior (ANT), posterior (PST) and inferior (INF) tympanic membrane annulus (see Fig. 6). The velocity responses of these points to harmonic stimulation

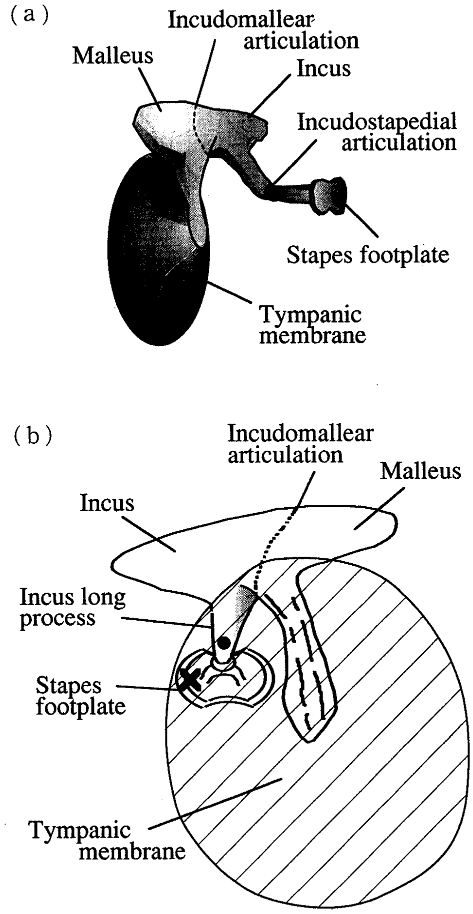

Fig. 4 Middle ear of a guinea pig. (a) Perspective view. (b) View from the external auditory meatus. This configuration is obtained when the tympanic membrane is viewed from the left-hand side of the above figure. A cross indicates the measurement points

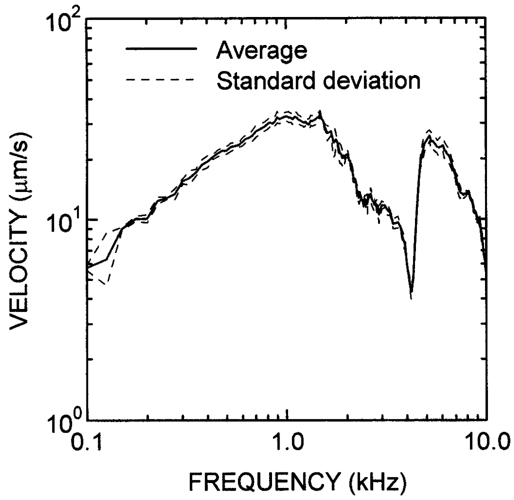

Fig. 5 Velocity response of the stapes footplate to harmonic stimulation. Seven measurements were made in one ear

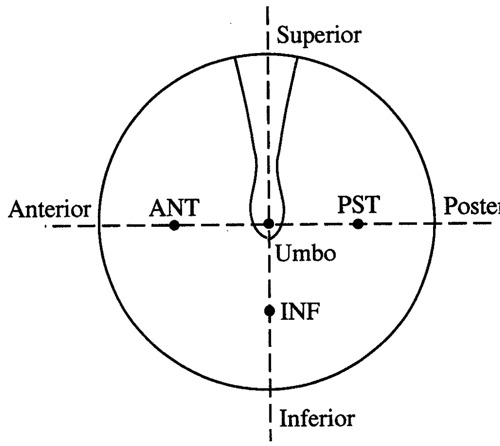

Fig. 6 Measurement points of the tympanic membrane

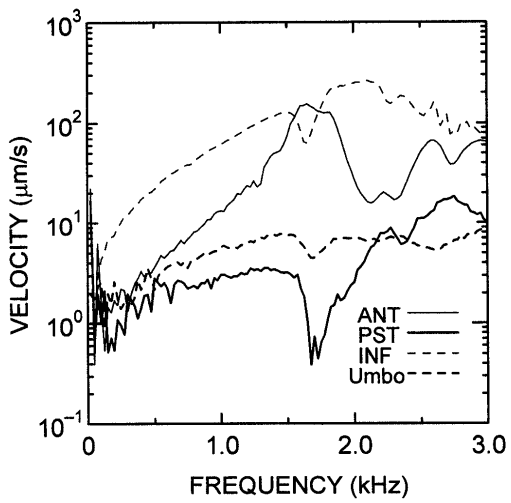

Fig. 7 Velocity responses of the tympanic membrane to harmonic stimulation. The points of ANT, PST, INF and unbo are shown in Fig. 6

were measured in three ears. The typical result is shown in Fig. 7. Around 1.7 kHz, the points of PST and INF showed minimum amplitude, and that of ANT showed maximum one. Although the velocity response curve of the umbo had a small notch around 1.7 kHz, it was relatively flat.

3.3 Effect of cochlear fluids

The velocity amplitudes of the stapes footplate were measured in four guinea pigs before and after manipulations of the cochlea, i.e. making a hole in the cochlear wall and extracting fluid. Typical results are shown in Fig. 8. Each velocity curve showed a peak at the frequency of around 1.0 kHz, and the sharp peak was obtained especially when the cochlear fluid was extracted. At the low frequencies, the difference between the three curves was not obvious. However, at the high frequencies, the velocity amplitude in the case of extracting the fluid was larger than those in the other cases.

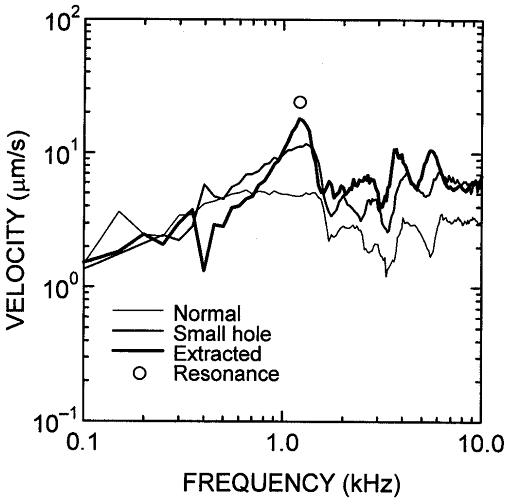

Fig. 8 Velocity responses of the stapes footplate to harmonic stimulation before and after the manipulation of the cochlea

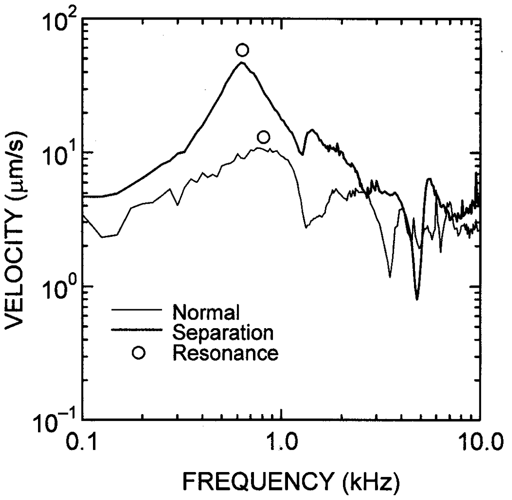

Fig. 9 Velocity responses of the incus long process to harmonic stimulation before and after the separation

3.4 Incudostapedial joint separation

The velocity amplitudes of the incus long process (see Fig. 4) were measured in three ears before and after separating the incudostapedial joint. Typical results are shown in Fig. 9. The resonance frequency in the intact ear was 0.9 kHz, and the frequency decreased to 0.6 kHz after separation.

3.5 Effect of bulla

The tympanic membrane and ossicles are surrounded by the bulla as shown in Fig. 1. In order to examine the effect of the bulla on the dynamic behavior of the middle ear, the velocity amplitudes at the stapes footplate (see Fig. 4) were measured before and after opening the bulla in two ears. When the bulla is closed, the laser beam cannot be applied to the microbead. Therefore, after making a hole in the bulla wall, a thin glass plate was put on it, and the gap

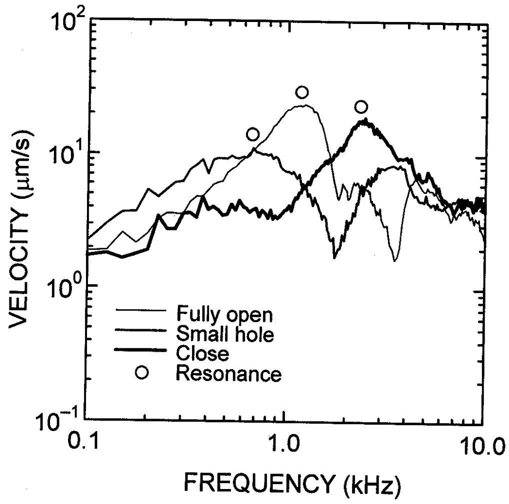

Fig. 10 Velocity responses of the stapes footplate to harmonic stimulation before and after the manipulation of the bulla

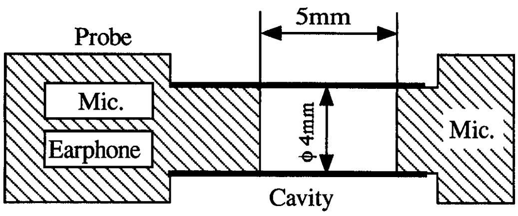

Fig. 11 Measurement method of sound pressure level at the both ends of the cavity

between the glass plate and the bulla wall was sealed with silicone filling gel. Through the glass plate, the vibration of the footplate was measured. Next, a hole five millimeters in diameter was made in the glass plate, then the measurement was done. The typical results are shown in Fig. 10. The resonance frequency of the stapes footplate with the fully opened bulla was 1.1 kHz, and that in the case of making the small hole was 0.6 kHz. When the bulla is closed, the resonance frequency was 2.5 kHz.

4. Discussion

In these experiments, the distance from the probe, which contains an earphone and a microphone, to the tympanic membrane was approximately 5 mm. Consequently, there is a possibility that the sound pressure just in front of the tympanic membrane was different from that at the probe tip. Therefore, we estimated sound pressure level just in front of the tympanic membrane by using a cavity, which was 4 mm in diameter and 5 mm in length. Figure 11 illustrates the way of making an estimation of the sound pressure in front of the tympanic membrane. The probe was inserted into the left end of the cavity, and a microphone, which corresponded to the tympanic membrane, was set at its right end. A sound stimulation

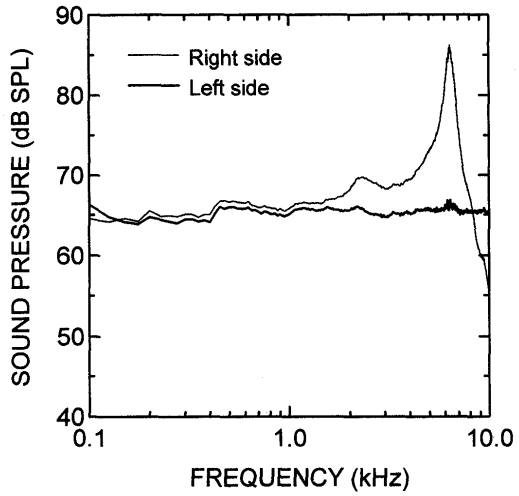

Fig. 12 Sound pressure level at the both ends of the cavity

from the probe earphone was led to the cavity, and sound pressure was measured simultaneously at each end of the cavity with the microphones. Results are shown in Fig. 12. Although input sound pressure level at the left was about 65 dB SPL over a frequency range from 0.1 to 10.0 kHz, sound pressure level at the right side had a peak at the frequency of 6.4 kHz. This peak arises from a resonance of the cavity. The resonance frequency shifts according to the length of the external auditory meatus and the impedance of the tympanic membrane. Therefore, it is estimated that the peak at 5.2 kHz in Fig. 5 arises from the resonance of the external auditory meatus.

The mechanical impedance of a middle ear can be expressed by

$$Z=C+j\left(2\pi fM-\frac{K}{2\pi f}\right), \qquad (2)$$

where M, K and C are the mass, stiffness and damping constant of the middle ear, respectively, $j=(-1)^{0.5}$ and f is the stimulus frequency[11]. Resonance occurs when Z takes minimum value, in other words, when the imaginary part of Z is zero. Therefore, the resonance frequency f_{RES} is given by

$$f_{RES}=\frac{1}{2\pi}\sqrt{\frac{K}{M}}. \qquad (3)$$

From Eqs. (2) and (3), it is said that the velocity is almost controlled by the damping constant around the resonance frequency. Below the resonance frequency, an approximate value of the impedance is given by

$$Z\approx C-j\left(\frac{K}{2\pi f}\right), \qquad (4)$$

because f is low and the mass component is negligible. In this case, the middle ear behavior is dominated by the stiffness component. In contrast, above the resonance frequency, the impedance can be expressed by

$$Z\approx C+j(2\pi fM), \qquad (5)$$

because f is high and the stiffness component is negligible. In this case, the middle ear behavior is dominated by the mass component. As shown in Fig. 8, around the resonance frequency of 1.0 kHz, the velocity curve obtained in the case of extracting cochlear fluid had a sharp peak compared with the other cases. At low frequencies, the difference between the curve before the manipulation and that after it was small. In contrast, at high frequencies, the velocity amplitude in the case of extracting fluid was larger than those of the other cases. Therefore, it is expected that the cochlear fluid behaves as a mass and damping. Zwislocki[10] reported that the cochlea impedance of a guinea pig behaved as a damping, by using an analog circuit model. Lynch[8] measured the cochlea impedance of a cat and concluded that the cochlea fluid behaved as a mass and damping. These results are in agreement with ours.

After incudostapedial joint separation, the stiffness component of the middle ear impedance decreases drastically, because the effect of the stiffness of the stapedial annular ligament disappeared. The mass and damping components also decrease, because the stapes and cochlea are removed from the vibration system. In this case, the impedance can be expressed as

$$Z=(C-\Delta C)+j\left(2\pi f(M-\Delta M)-\frac{K-\Delta K}{2\pi f}\right), \qquad (6)$$

and the resonance frequency is given by

$$f_{RES}=\frac{1}{2\pi}\sqrt{\frac{K-\Delta K}{M-\Delta M}}. \qquad (7)$$

As shown in Fig. 9, the resonance frequency after separation was lower than that before separation. Therefore, it is expected that the decrease in the stiffness (ΔK) is larger than that in the mass (ΔM) in the case of separation.

When a small hole is made in the bulla wall, the air in the hole behaves as a mass[12]. Therefore, in this case, the resonance frequency can be expressed as

$$f_{RES}=\frac{1}{2\pi}\sqrt{\frac{K}{M+\Delta M}}. \qquad (8)$$

When the bulla is closed, the resonance frequency is given by

$$f_{RES}=\frac{1}{2\pi}\sqrt{\frac{K+\Delta K}{M}}, \qquad (9)$$

because the air in the bulla behaves as a stiffness[10]. According to this theory, the resonance frequency will decrease when the small hole is made in the bulla wall, and when the bulla is closed, it will increase. These estimations agree with the measurement results shown in Fig. 10.

5. Conclusion

Dynamic behaviors of the middle ear of the guinea pigs are investigated by measuring their vibration with the laser Doppler velocimeter coupled to the compound microscope. The following conclusions can be drawn.

1) The velocities of the anterior, posterior and inferior portions of the tympanic membrane vary according to the frequency. In contrast, the frequency response of the umbo is relatively flat.

2) The cochlear fluid contributes towards increasing the damping and mass components of the middle ear impedance.

3) Both the stiffness and mass components of the middle ear impedance after separating the incdostapedial joint are smaller than those before it, and the difference in the stiffness component is larger than that in the mass component. In contrast, the damping component after separation is smaller than that before it, because the contribution of damping from the cochlear fluid vanishes when the incdostapedial joint is cut off.

4) The air in the small hole in the cochlear wall contributes towards increasing the mass component, and the air in the closed bulla contributes towards increasing the stiffness component.

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