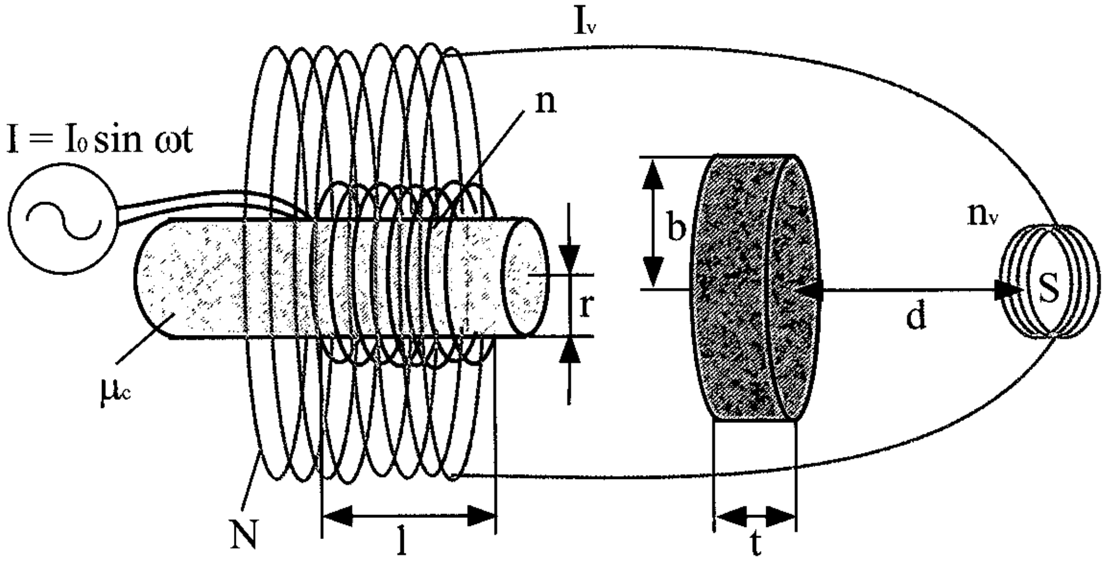

$$\boxed{F = \frac{n_v I_v S M t \mu_0 b^2}{2(b^2 + d^2)^{3/2}}}$$

n: Turns per unit length of the driving coil
l: Length of the driving coil [m]
N: Turns of the induction coil
r: Radius of the driving coil [m]
μ_c: Permeability of the core material [N/A^2]
μ_0: Permeability of the vacuity [N/A^2]
b: Radius of the magnet [m]
t: Thickness of the magnet [m]
M: Magnetization vector [A/m]
d: Distance between the magnet and the vibrator coil [m]
S: Area of the vibrator coil [m^2]
n_v:Turns per unit length of the vibrator coil

Figure 4.2. Theoretical calculation of the repulsive force which acts on the magnet and vibrator coil. The calculated force, *F*, acts on the tympanic membrane as a result of magnetic interaction between the magnetic field of the magnet and that of the vibrator coil, and this force mainly depends on the radius of the magnet and the distance between the magnet and the vibrator coil.

5. Preliminary analysis

5.1. Design of a vibrator coil using the FEM middle-ear model

Mass loading of the tympanic membrane and ossicles may affect ossicular dynamics and sound transmission to the inner ear (Rong et al., 2001). In order to evaluate the optimal position and mass of the vibrator coil, a Finite Element Method (FEM) middle-ear model was constructed as shown in Fig. 5.1 (Koike et al., 1996), and the effects of position and mass of the vibrator coil on the frequency responses of the intracochlear sound pressure, i.e., middle-ear transmission factor, were simulated.

In this study, the value of intracochlear sound pressure, P_c, was obtained by

$$P_c(\text{dB SPL}) = 20 \times \log (2\pi f V_s Z_c / P_{REF}),$$

where f is the frequency of the stimulus, V_s is the volume displacement of the stapes footplate, Z_c is the input impedance of the cochlea, and $P_{REF} = 2 \times 10^{-5}$ [Pa] is the reference pressure.

The optimal position of the vibrator coil attached to the tympanic membrane was evaluated. An excitation force of 6.4×10^{-7} [N] was received only by the surface to which the vibrator coil was attached. This value corresponded to a sound pressure of 80 dB SPL. The following five positions were evaluated (Fig. 5.2):

(a) the tip of the malleus manubrium,

(b) the short process of the malleus,

(c) the entire malleus manubrium,

(d) the area around the tip of the malleus manubrium, and

(e) the inferior part of the tympanic membrane.

Effects of the mass of the vibrator coil were also evaluated. In this analysis, an excitation force of 6.4×10^{-7} [N] was loaded on the area around the tip of the malleus manubrium, as shown in Fig. 5.2(d). The mass of the vibrator coil was changed by increasing the density of the tip of the malleus. Three cases were examined as follows:

(a) 20 mg,

(b) 40 mg (approximately the same as the mass of the ossicular chain and tympanic membrane; 42 mg), and

(c) 100 mg.

5.2. Effects of the position and the mass of the vibrator coil on the intracochlear sound pressure

The effects of the position of the vibrator coil on the intracochlear sound pressure are shown in Fig. 5.3. When the vibrator coil was attached to the short process of the malleus (Fig. 5.2(b)) and the inferior part of the tympanic membrane (Fig. 5.2(e)), the intracochlear sound pressure was lower than that obtained when the vibrator coil was attached to the other three places. However, there was no large difference between the other three places. This result indicates that the vibrator coil should be attached to the tip of malleus manubrium or to the portion including it.

The effects of the mass of the vibrator coil on the intracochlear sound pressure are shown in Fig. 5.4. In this calculation, an excitation force of 6.4×10^{-7} [N] was loaded on the area around tip of the malleus manubrium (Fig. 5.2(d)). The intracochlear sound pressure decreased with increasing mass, especially at high frequencies.

The mass of the vibrator coil and its position were related to the high frequency performance of electromagnetic hearing transducer as mentioned above. These results indicate that in order to maintain fine sound amplifier properties at high frequencies, it is necessary to use a lightweight coil and to attach it to the area around the tip of the malleus manubrium.

Therefore, in the following experiments, the electromagnetic hearing transducer was evaluated with a lightweight vibrator coil attached to the area around the tip of the malleus manubrium.

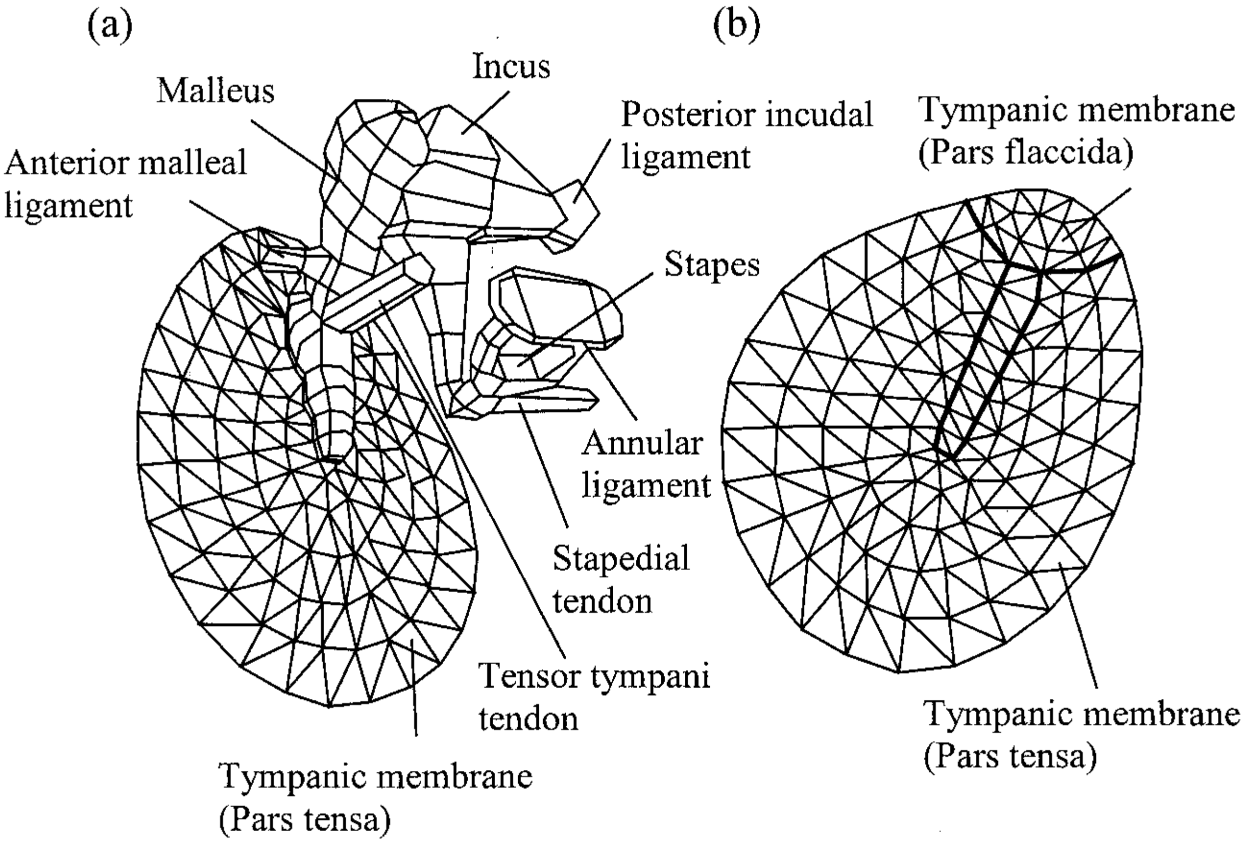

Figure 5.1. Finite element method (FEM) middle-ear model. (a)View from the cochlea. (b) View from the external ear canal.

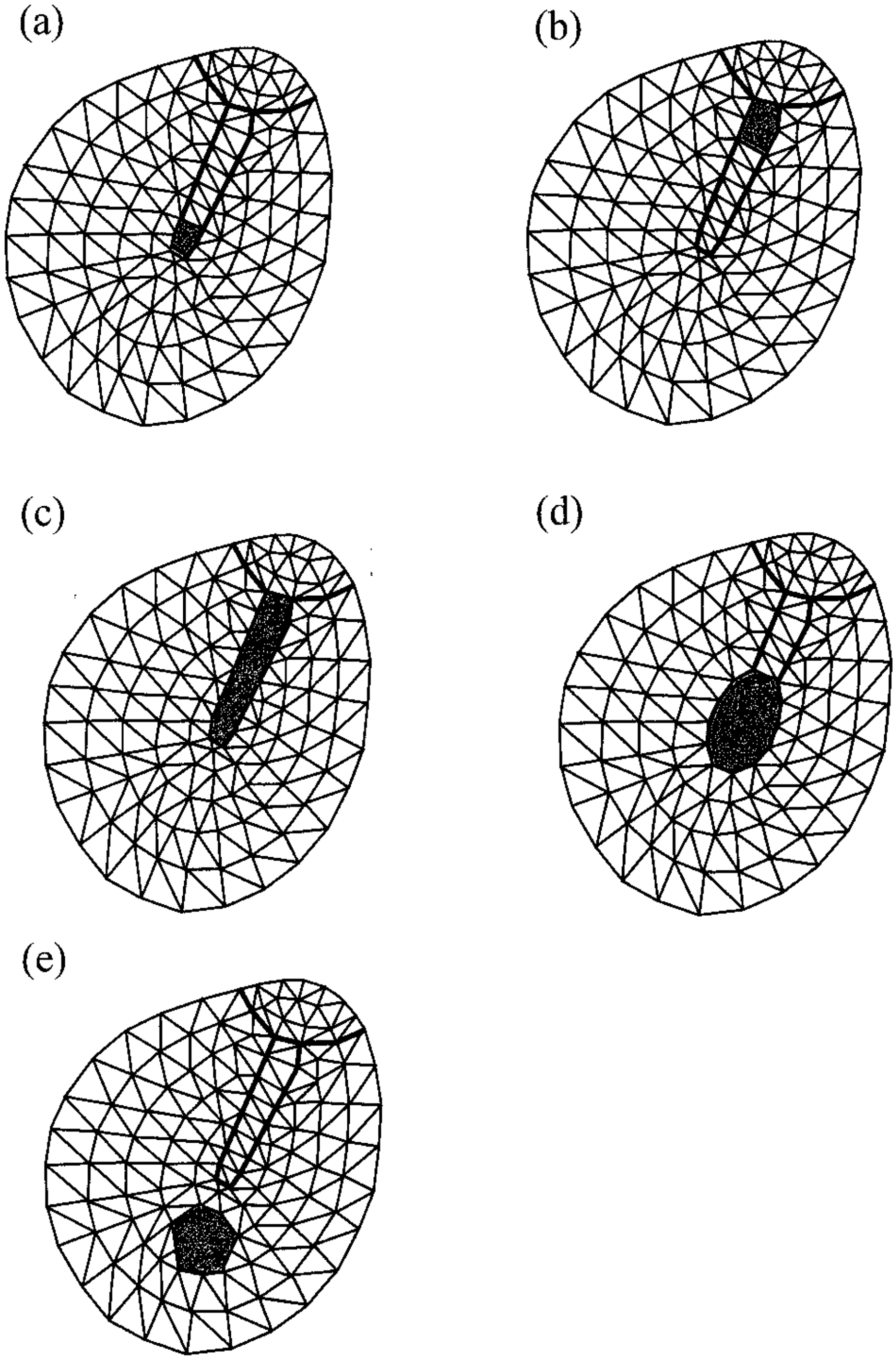

Figure 5.2. Position of the vibrator coil. (a) Tip of the malleus manubrium. (b) Short process of the malleus. (c) Entire malleus manubrium. (d) Area around the tip of the malleus manubrium. (e) Inferior part of the tympanic membrane.

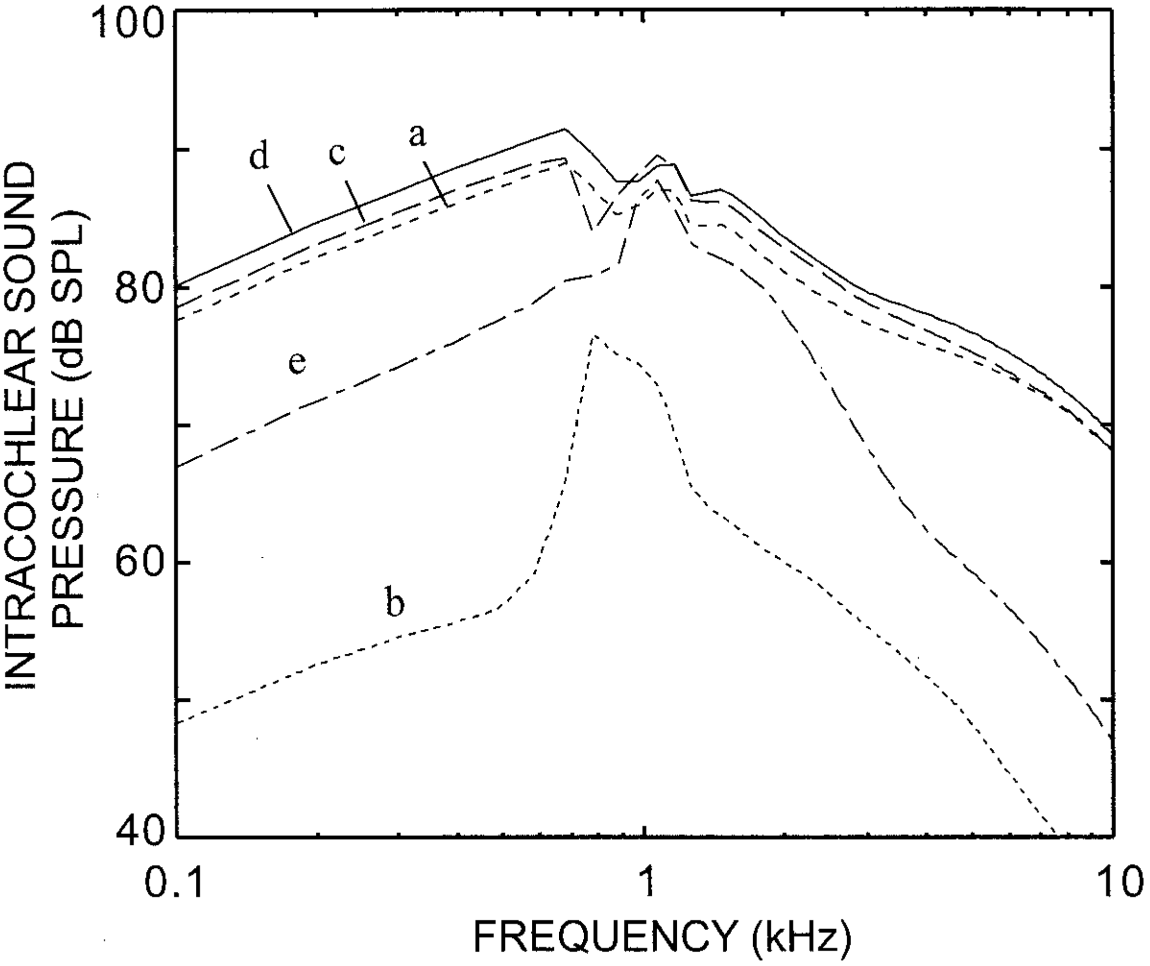

Figure 5.3. Effect of the position of the vibrator coil on the intracochlear sound pressure. (a) Tip of the malleus manubrium. (b) Short process of the malleus. (c) Entire malleus manubrium. (d) Area around the tip of the malleus manubrium. (e) Inferior part of the tympanic membrane. When vibrator coil was attached to the short process of the malleus (b) or to the inferior part of the tympanic membrane (e), intracochlear sound pressure was low. However, there was no large difference between the other three positions.

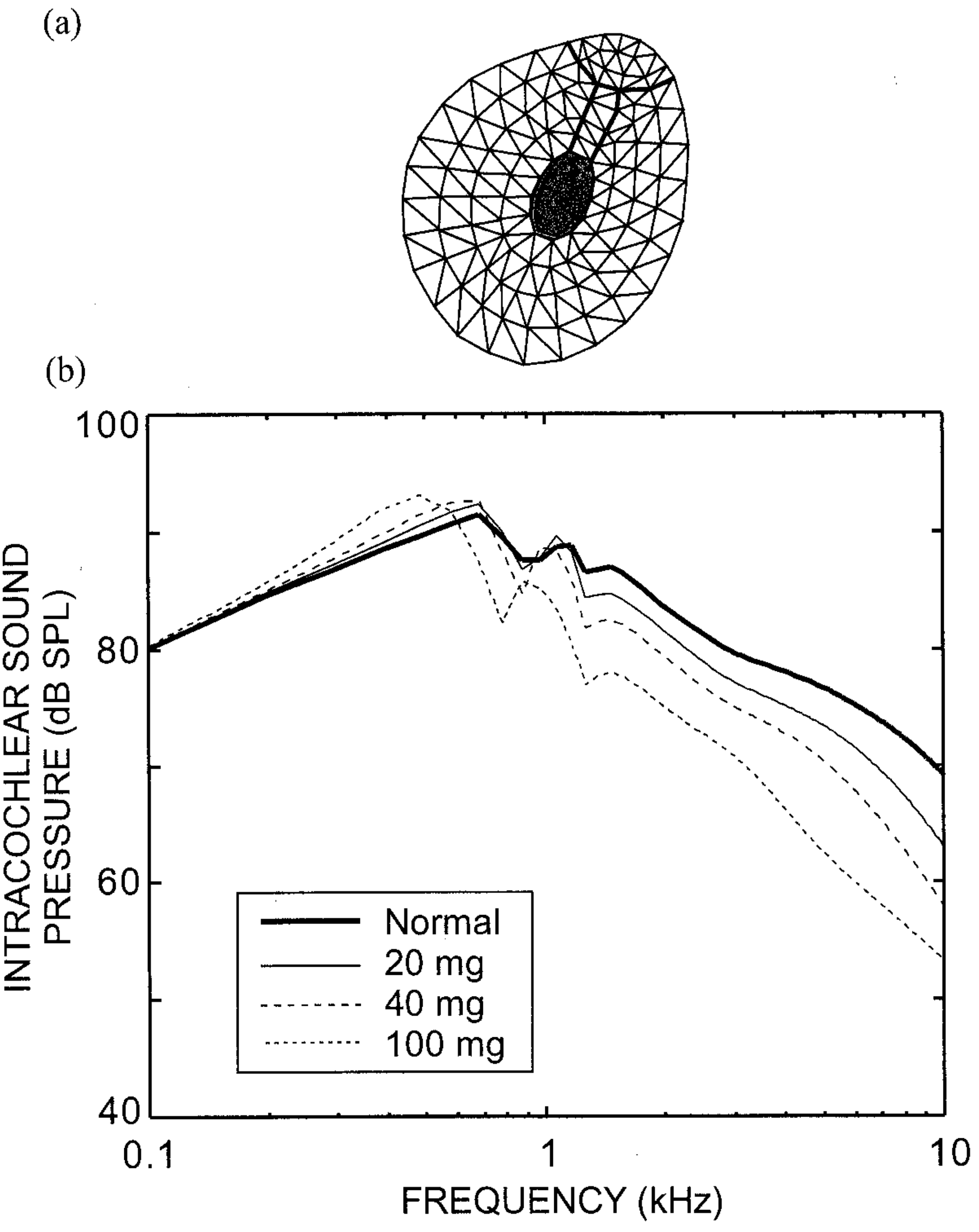

Figure 5.4. Effect of the mass of the vibrator coil on the intracochlear sound pressure. (a) Position of the vibrator coil. Vibrator coil was attached to the area around the tip of the malleus manubrium. (b) Frequency responses to the intracochlear sound pressure. The intracochlear sound pressure decreased with increasing mass, especially at high frequencies..

6. Methods for evaluation of the electromagnetic hearing transducer

6.1. Experiments using an artificial middle ear

6.1.1. Artificial middle ear

On the basis of the results of FEM analysis, some prototypes of electromagnetic transducers were constructed. In order to evaluate the efficiency of the transducer, an artificial middle ear was made, and the displacement of this middle ear vibrated by the transducer was measured with a laser Doppler velocimeter (LDV). The transducer was then improved so as to cause larger displacement of the artificial membrane. The following were examined:

(a) Optimal shape of the coils.

(b) Optimal coil turns of the coils.

(c) Effective core material of the induction coil.

(d) Distance between the magnet and the vibrator coil.

A schematic of the artificial middle ear is shown in Fig. 6.1. The artificial middle ear was composed of a stiff plastic tube (8 mm in diameter and 15 mm in length), a silicone membrane, and a stiff plastic chip, which corresponded to the external ear canal, tympanic membrane, and malleus, respectively. The total mass of the membrane and plastic chip was the same as the equivalent mass of the human middle ear.

6.1.2. Methods

A block diagram of the measurement system is shown in Fig. 6.2(a) and photo 6.1 shows the LDV system. The LDV (LV-1100, ONO SOKKI) coupled to a compound microscope (NIKON) allows measurement of the vibration velocity of the membrane by focusing a laser beam from the optical head of the instrument onto a small spot. The output laser beam from the sensor head via a pinhole was focused onto the center of the membrane through the objective lens. The diameter of the beam at the center of the artificial membrane was approximately 5 μm. The reflected beam returns to the sensor head by the same way. The frequency of the reflected beam is changed according to the velocity of the membrane v, which is written as:

$$v = c\,(1 - f_I/f_R), \qquad (6.1)$$

where c, f_I and f_R are the velocity of the laser beam, the frequency of the injected beam and the frequency of the reflected laser beam, respectively. The voltage output of the velocimeter that was proportional to the velocity was analyzed by an FFT analyzer (CF-350, ONO SOKKI), and the data were recorded by a computer.

The peak-to-peak displacement (d_{p-p}) of the center of the membrane was directly calculated from the voltage output of the LDV converted from the output velocity decoder by the formula shown below:

$$d_{p-p} = k\,(A_{volt}/\pi f), \qquad (6.2)$$

where A_{volt} is voltage amplitude, f is frequency, and k is a constant related to the selected scale.

First, in order to evaluate the properties of the artificial middle ear itself, the vibration of the membrane caused by the constant sound pressure, i.e., acoustical stimulus, was measured. As shown in Fig. 6.2(b), an earphone (ER-10C, Etymotic Research) was placed in the plastic tube, and the displacement of the vibration at the center of the membrane was measured when an constant acoustical stimulus of a sweeping frequency from 0.1 kHz to 10 kHz was applied to the membrane. In the case of acoustical stimulation, stimulus level was maintained at 80 dB SPL. Then, as shown in Fig. 6.2(c), the vibrator coil was attached to the membrane of the artificial middle ear and vibrated by a transducer, and displacement of the vibration at the center of the membrane was measured. In the case of the transducer, a sinusoidal current of 80 mA was applied to a driving coil. A vibrator coil was glued to the plastic plate and attached to the membrane with oil.

6.2. Experiments using guinea pigs

6.2.1. Cochlear microphonics (CM)

The cochlear microphonic is a small electrical signal that can be measured by an electrode placed on the round window of the cochlea. As shown in Fig. 6.3, the CM arises from the sum of electrical potentials in the hair cells of the cochlea and tends to mirror the waveform of the input sound to the ear; the amplitude of the CM has a linear relationship with the sound pressure transmitted to the cochlea (Avan et al., 1992).

In this study, CM measurement was performed to evaluate the electromagnetic hearing transducer in guinea pigs *in vivo*. Frequency responses of the CM obtained from guinea pigs when the tympanic membrane was vibrated by the transducer and that when sound pressure, i.e., an acoustical stimulus, was applied to the tympanic membrane were compared. Then, the time history response of the earphone and that of the transducer were also measured and compared.

6.2.2. Methods

Figure 6.4(a) shows a schema of the CM measurement system. Albino guinea pigs (photo 6.2), weighing 200 - 400 g, were anesthetized with pentobarbital sodium (35 mg / kg). Animals were tracheostomized and connected to an artificial respirator. Muscle relaxant, suxamethonium chloride, was injected into muscle to suppress movement of the animals. After anesthetic induction, animals were placed on a temperature-controlled heating pad to maintain the rectal temperature at 38°C. After an animal's head was rigidly clamped, the pinna was removed, and the cochlea was exposed through the posterior bulla. In order to measure the CM, a silver ball electrode was placed on the round window and a stainless steel ground electrode was placed in the neck muscle.

In the case of the acoustical stimulus, as shown in Fig. 6.4(b), the earphone (ER-10C) was coupled to the ear external canal and sound pressures of 70, 80, and 90 dB SPL were applied to the tympanic membrane. In the case of a transducer, as shown in Fig. 6.4(c), a vibrator coil was attached to the tympanic membrane and vibrated by applying a sinusoidal current of 80 mA to the driving coil. In addition, in order to avoid electrical and electromagnetic effects from induction and driving coils on the CM recording system, these two coils were placed more than 20 cm apart from the silver ball electrode.

The peak-to-peak potential of the CM was directly calculated from the CM wave displayed on the monitor of the CM measurement system, shown in photo 6.3 (MEB-9102, NIHON KODEN).

As shown in Fig. 6.5, the time history responses of the earphone and the transducer were also measured and compared. Input signal frequencies were 0.5, 1, 2, 4, and 8 kHz (tone burst of ten waves). In individual stimuli, the input signal level was modulated so that the CM amplitude was approximately 100 μV. Furthermore, a fast Fourier transform (FFT) was performed on the individual CM waveforms, and the resultant magnitude spectra were compared.

The care and use of the animals in this study were approved by the Institutional Animal Care and Use Committee at Tohoku University School of Medicine.

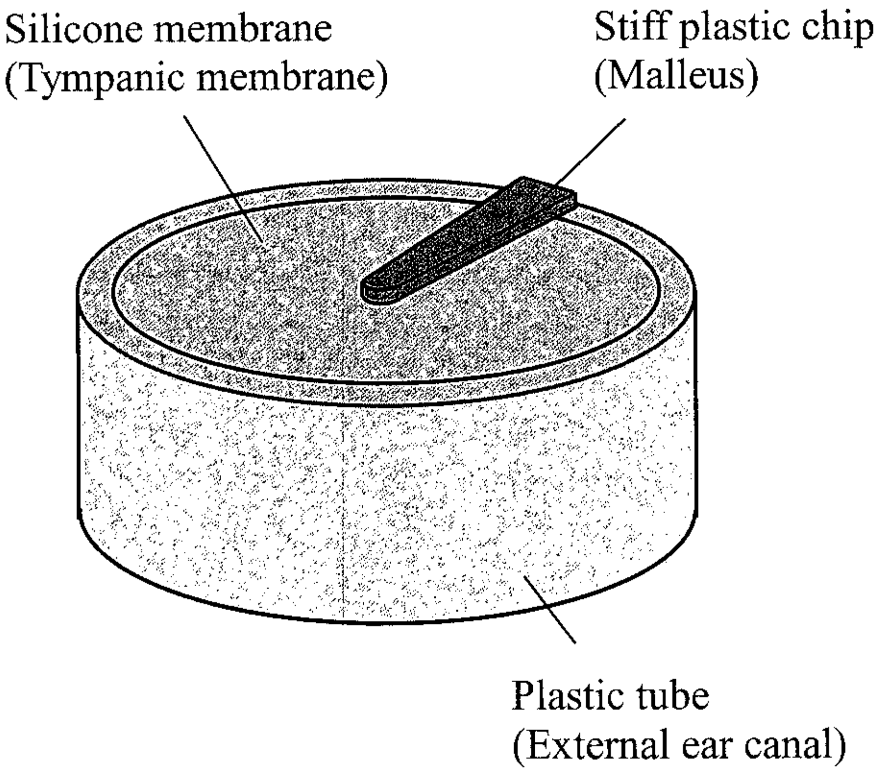

Figure 6.1. Schematic of the artificial middle ear. The artificial middle ear was composed of a stiff plastic tube (8 mm in diameter and 15 mm in length), a silicone membrane and a stiff plastic chip, which correspond to the external ear canal, tympanic membrane, and malleus, respectively. Total mass of the membrane and plastic chip was the same as the equivalent mass of the human middle ear (42 mg).

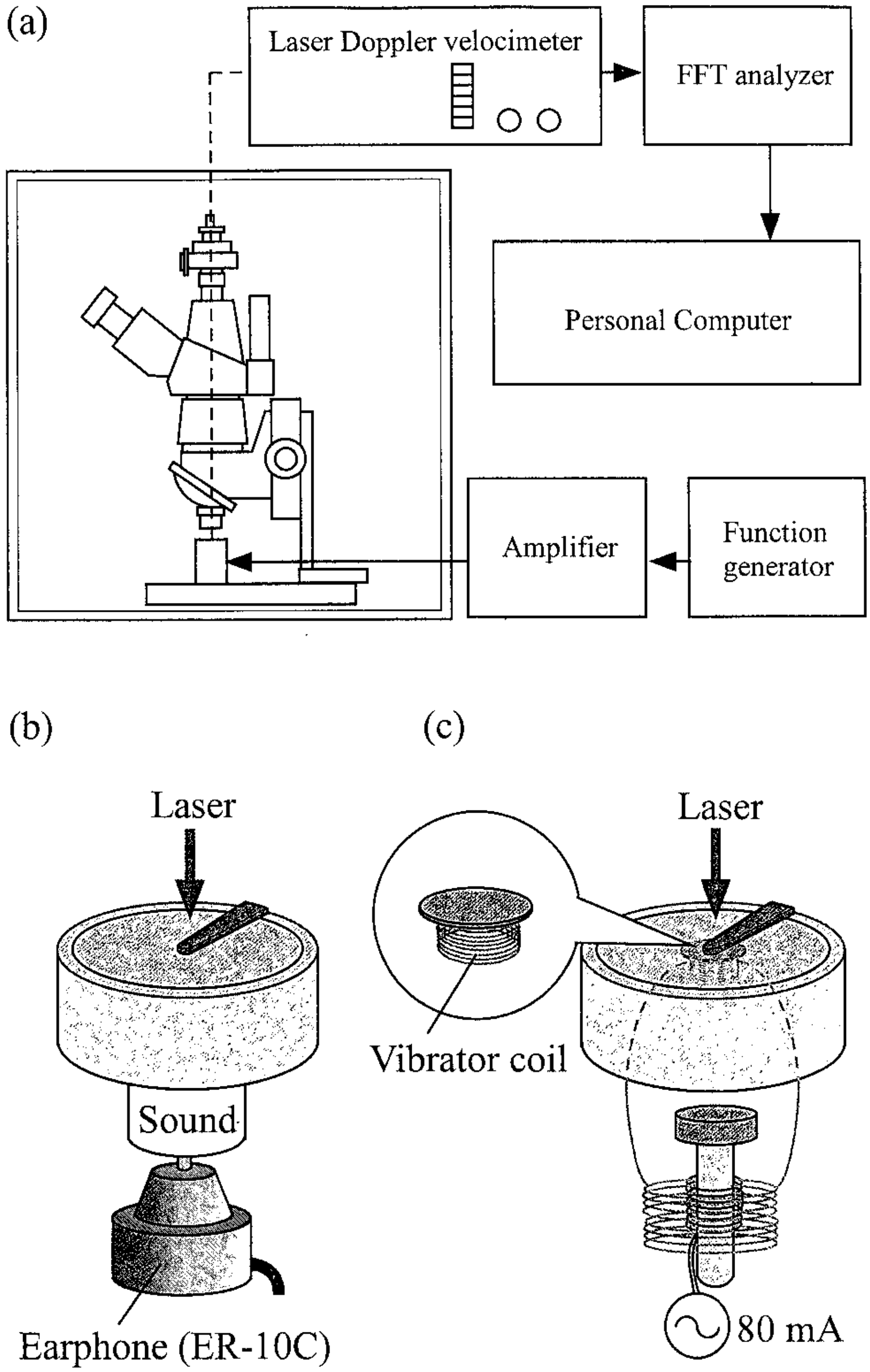

Figure 6.2. Method and measurement of the vibration of the artificial middle ear. (a) Block diagram of the measurement system. The voltage output of the velocimeter that was proportional to the velocity was analyzed by the FFT analyzer, and the analysis data were recorded by the computer. (b) Schematic of the excitation method of the artificial membrane by an acoustical stimulus. (c) Schematic of the excitation method of the artificial membrane by the transducer.

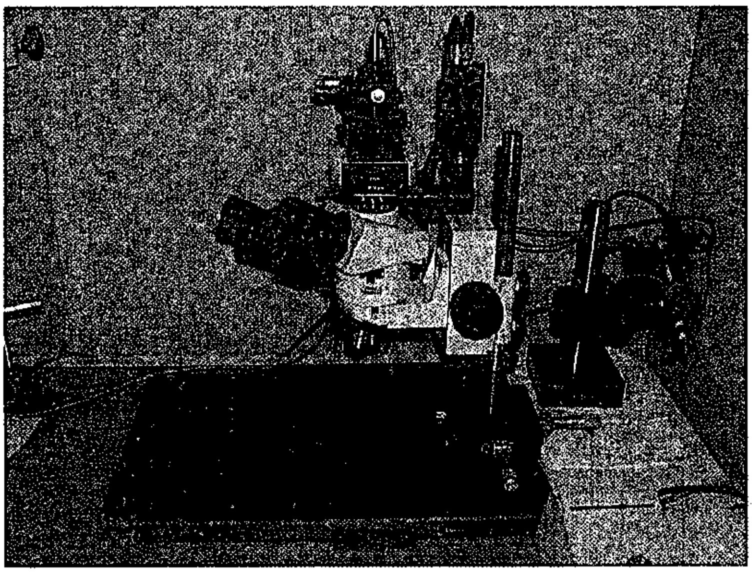

Photo 6.1. Photograph of the LDV system. The LDV system is in a sound-isolated booth.

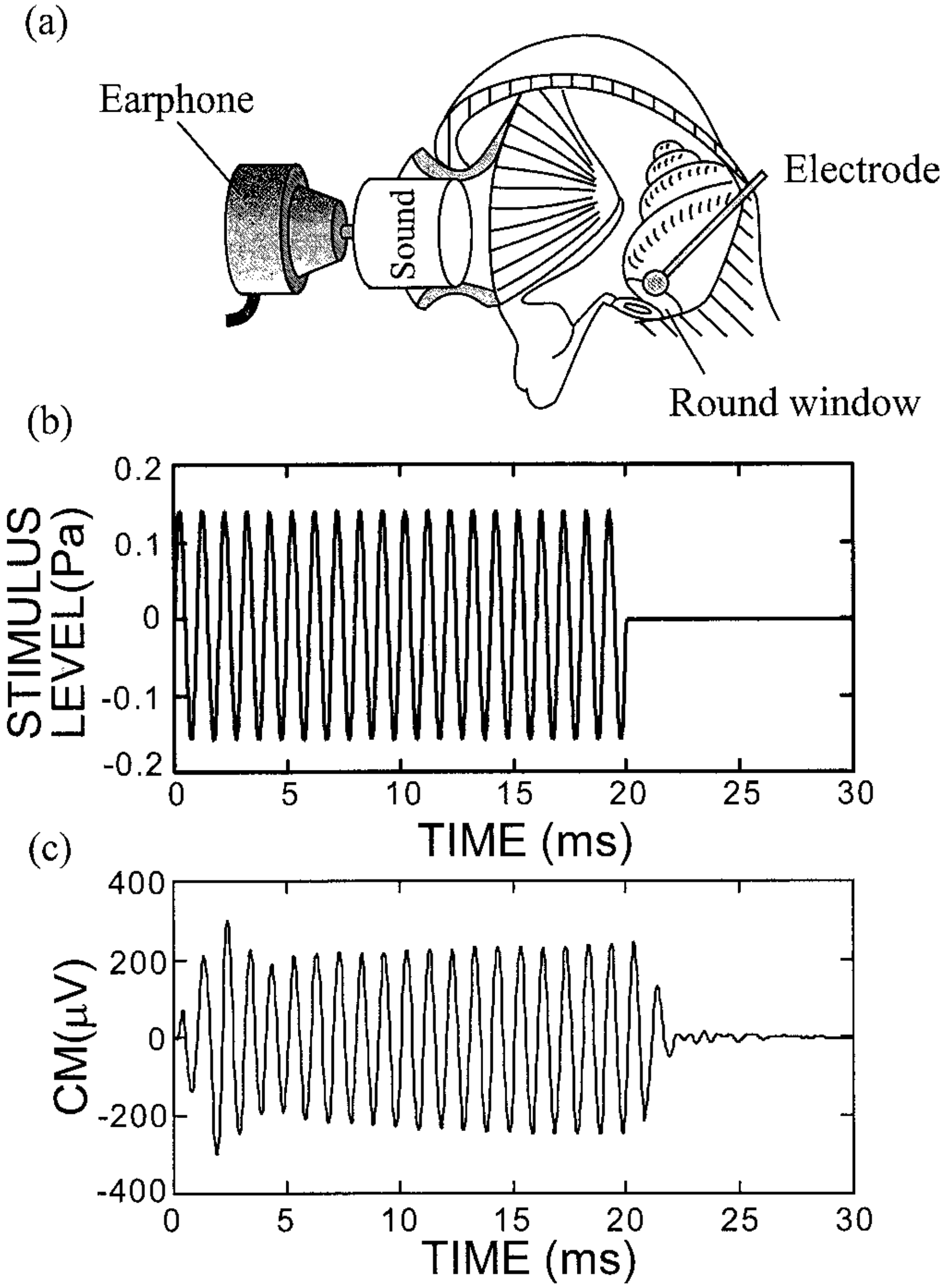

Figure 6.3. Cochlear microphonic (CM). (a) Schematic of an example of CM measurement. The CM is a small electrical signal that can be measured by an electrode placed near the hair cells of the cochlea. (b) Time history of the input acoustical stimulus (1 kHz, torn burst). (c) Time history of CM potential in a guinea pig. The CM tends to mirror the waveform of the sound input to the ear.

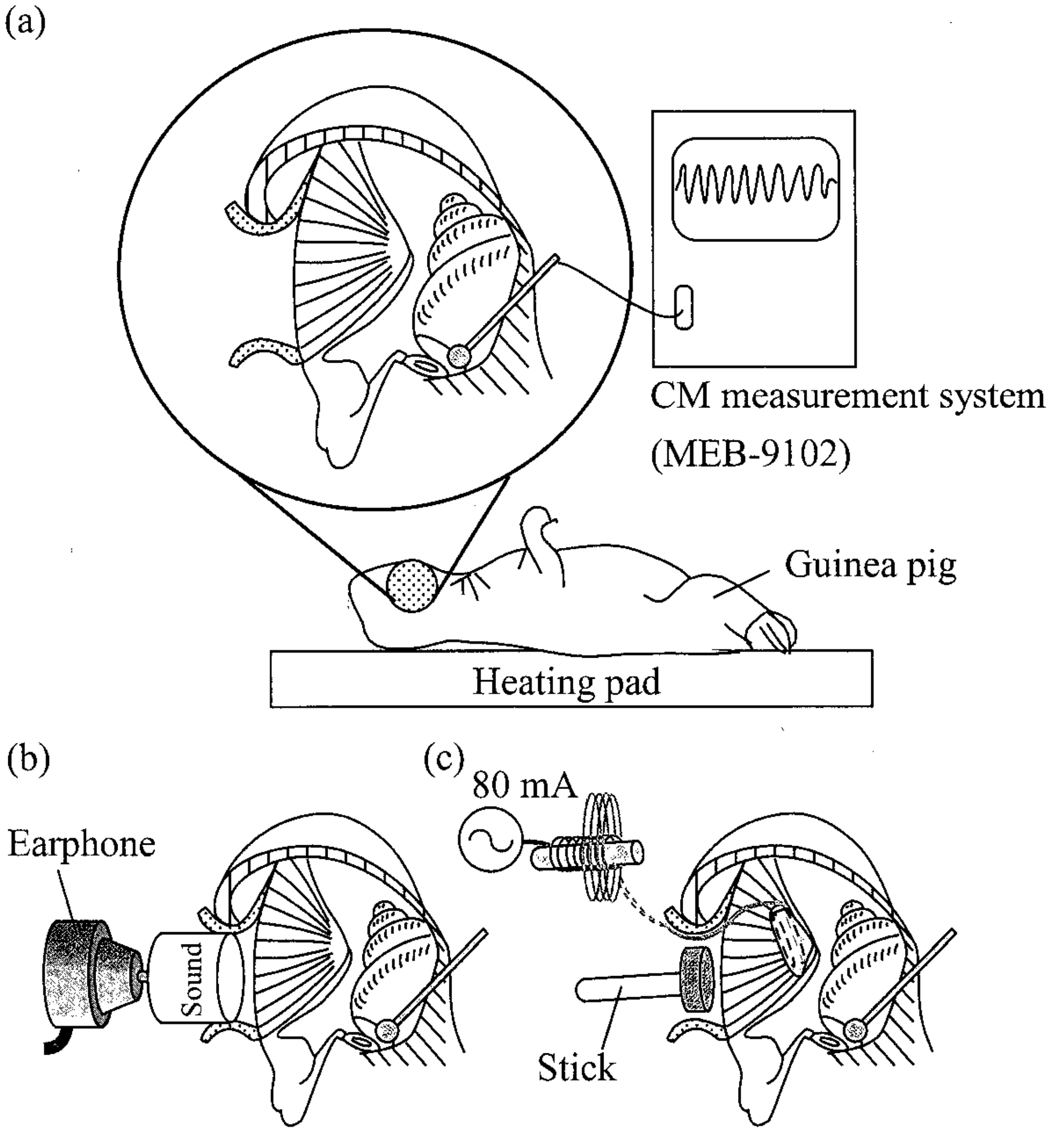

Figure 6.4. Experimental setup for measuring CM. (a) Schematic of the CM measurement system in this study. Albino guinea pig were anesthetized and placed on a temperature-controlled heating pad. In order to measure CM, a silver ball electrode was placed on the round window. (b) Experimental setup using the earphone. In the case of an acoustical stimulus, the earphone was coupled to the external ear canal and sound pressures of 70, 80, and 90 dB SPL were applied to the tympanic membrane. (c) Experimental setup using a transducer. In the case of the transducer, the vibrator coil was attached to the tympanic membrane and vibrated by applying a sinusoidal current of 80 mA to the driving coil.

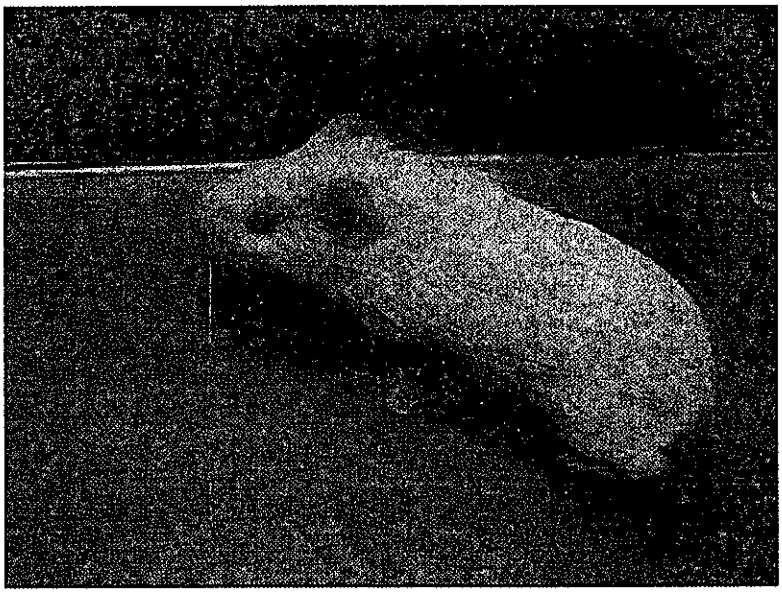

Photo 6.2. An albino guinea pig.

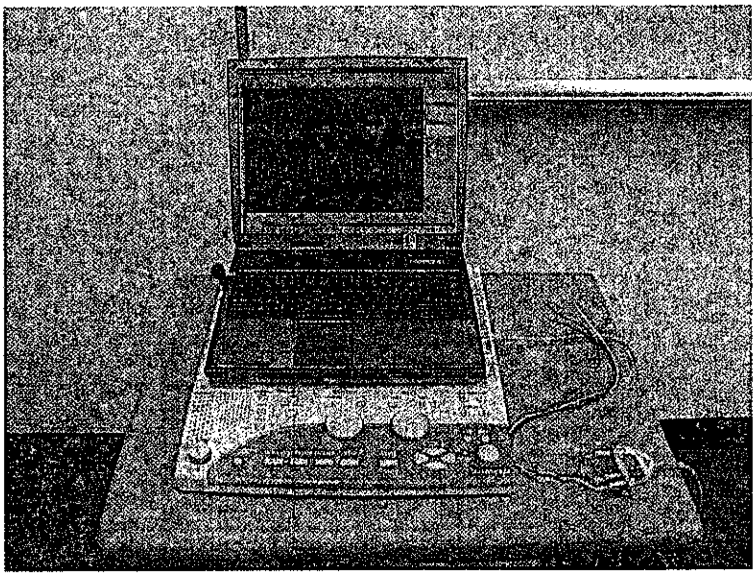

Photo 6.3. CM measurement system (MEB-9102, NIHON KODEN)

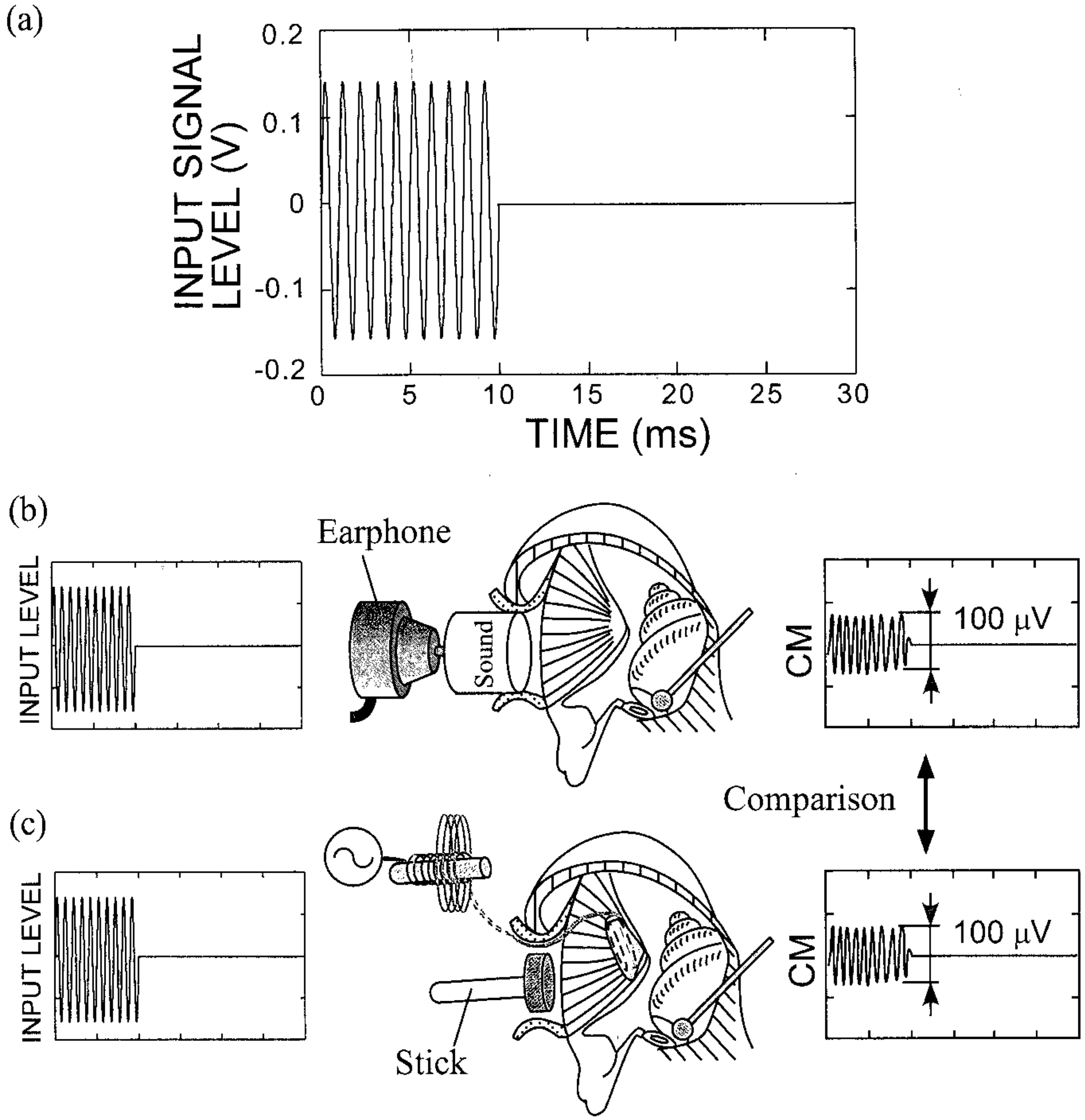

Figure 6.5. Time history of the earphone and the transducer. (a) Time history of electrical input signal. Input signal was torn burst of 10 waves, frequencies were 0.5, 1, 2, 4 and 8 kHz. (b) Schematic of the measurement of time history responses of the earphone. (c) Schematic of the measurement of time history responses of the transducer. In individual stimuli, input signal level was modulated so that CM amplitude was 100 μV.

7. Results

7.1. Response of the artificial middle ear

7.1.1. Frequency responses of the artificial middle ear

The frequency responses of the displacement at the center of the artificial middle ear obtained when an acoustical stimulus of 80 dB SPL was applied to the artificial middle ear are shown in Fig. 7.1. The displacement was relatively flat in the 0.1 - 0.5 kHz region, and above resonant frequency at 0.7 kHz. It decreased with an increase in frequency. Furthermore, the response curve obtained by the artificial middle ear had some peaks. These results were compared with the results of displacement of the umbo of the tympanic membrane obtained by FEM analysis of the human middle ear (Koike et al., 1996) and that obtained by actual measurement using human temporal bone (Gyo et al., 1987). The general tendency of the curve obtained by the artificial middle ear was similar to the results reported by others, except for the existence of some peaks, and was considered to be due to the fact that the damping component of the artificial middle ear was smaller than that of the actual middle ear.

These results indicated that the frequency characteristics of the artificial middle ear were similar to those of an actual human middle ear, except for the existence of some peaks. Therefore, the artificial middle ear could be used as one of the methods for evaluation of the transducer.

7.1.2. Optimization of the design of the transducer

The transducer was improved so as to cause larger displacement of the artificial membrane. The effect of the shape of the vibrator coil on the frequency responses of the displacement at the center of the artificial middle ear is shown in Fig. 7.2. Two