types of shapes were evaluated, namely, cylinder-shaped and disk-shaped vibrator coils, as shown in Fig. 7.2(a). These results were compared with the frequency characteristics of the artificial middle ear itself, mentioned in Fig. 7.1. When either vibrator coil was attached to the artificial middle ear, the resonant frequency of the artificial middle ear vibrated by the transducer was lower than that obtained when an acoustical stimulus of 80 dB SPL was applied. It was considered that because the vibrator coil added a slight mass to the artificial middle ear, the resonant frequency was decreased. Above 1 kHz, displacement at the center of the membrane with the disk-shaped vibrator coil was larger than that with the cylinder-shaped vibrator coil. Furthermore, the curve of the displacement at the center of the membrane with the cylinder-shaped vibrator coil was more complicated, while that with the disk-shaped vibrator coil was as smooth as the displacement at the center of the membrane caused by the acoustical stimulus. This was considered to be due to the mechanical instability of cylinder-shaped vibrator coil. As the aspect ratio of the cylinder-shaped vibrator coil was much larger than the disk-shaped one, the cylinder-shaped vibrator coil may be rolled from side to side when the magnetic repulsive force acts on the vibrator coil.

The effect of the distance between the magnet and the vibrator coil on the frequency responses of the displacement at the center of the artificial middle ear is shown in Fig. 7.3. In this analysis, the distance between the magnet and the disk-shaped vibrator coil was changed from 1 mm to 3 mm. The proximity of the distance between the magnet and the vibrator coil caused a larger displacement at the center of the artificial middle ear. Furthermore, in the case of 1 and 2 mm, displacement at the center of the artificial middle ear vibrated by the transducer exceeded the displacement obtained when an acoustical stimulus of 80 dB SPL was applied to the artificial middle ear over the entire frequency range. These results indicate that the electromagnetic hearing transducer examined in this study may possibility be used with patients suffering from hearing loss.

Through these experiments, the tendency of the optimal shape and alignment of the transducer was indicated, as shown in Table 7.1. Displacement at the center of the artificial middle ear was greater with an increasing number of coil turns of driving, induction, and vibrator coils. In addition, greater displacement of the artificial middle ear was obtained when the material of the magnet and the core of the induction coil was Ne-Fe-B magnet and amorphous material, respectively.

Finally, the optimal shape and alignment of the transducer were determined. The prototype of the transducer is shown in Photo 7.1. The three coils were designed so as to permit installation into the human external ear canal, and amorphous material with high permeability was used for the core material of the induction coil. The magnet used in this study was a Ne-Fe-B magnet, which has high magnetic flux density. The mass of the vibrator coil, including the plastic plate for the attachment, was 18.3 mg.

7.2. Response in guinea pig

7.2.1. Frequency responses of the CM amplitude

The frequency responses of the CM amplitude obtained from a guinea pig when acoustical stimuli of 70, 80 and 90 dB SPL were applied to the tympanic membrane are shown in Fig. 7.4. When the acoustical stimulus was increased from 70 to 90 dB SPL, frequency responses of the CM amplitude exhibited upward parallel shifts. Furthermore, the increase of the CM amplitude for every 10 dB SPL increment of acoustical stimulus was 10 dB over the whole frequency range. This finding indicated a linear relationship between acoustical stimulation of middle ear and CM amplitude, and showed that the value of the CM amplitude could be used as a index for evaluation of the transducer *in vivo*. Therefore, we selected 90 dB SPL stimuli for the comparison with the CM amplitude caused by the transducer in individual experiments of CM measurements.

7.2.2. Effect of the mass of the vibrator coil on the CM amplitude

The effect of the mass of the vibrator coil on the CM amplitude obtained from a guinea pig is shown in Fig. 7.5. In this measurement, the vibrator coil was attached to the tympanic membrane; the current, however, was not applied to the driving coil and an acoustical stimulus of 90 dB SPL was applied to the tympanic membrane. This result was then compared with the CM amplitude obtained when no vibrator coil was attached to the tympanic membrane. Over the entire frequency range, CM amplitude obtained when the acoustical stimulus was applied to the tympanic membrane with the vibrator coil was lower than that without the vibrator coil. However, the maximum decrease in the CM amplitude was within 10 dB. This result was same as that of result of the effect of mass in the FEM analysis (Fig. 5.4).

7.2.3. Frequency responses of the CM amplitude caused by the transducer

Figure 7.6 shows the frequency responses of the CM amplitude obtained from guinea pigs when the tympanic membrane was vibrated by the transducer and when acoustical stimulus was applied to the tympanic membrane. Over the entire frequency, CM amplitude caused by the transducer was larger than that caused by acoustical stimulus. Maximum gain was obtained at 3 kHz. However, below 0.8 kHz and above 5 kHz, the difference between the value of CM amplitude caused by the transducer and that by the acoustical stimulus was approximately 5 dB, while the difference at 2 kHz was more than 10 dB.

Figure 7.7 shows the equivalent sound pressure level of the electromagnetic hearing transducer obtained when an electrical current of 80 mA was applied to the driving coil. As the earphone used in this study could not output sound pressure of more than 90 dB SPL, saturation of the CM amplitude could not be confirmed. However, Avan et al. (1992) reported that the linearity of the CM amplitude was saturated between 90 and 110 dB SPL. Therefore, because of the linear relationship between the acoustical stimulus level and the CM amplitude, the value of the CM amplitude can be converted to the value in dB SPL. Therefore, on the basis of the result of Fig. 7.6, the equivalent sound pressure was calculated by converting the difference between the CM amplitude caused by the transducer and that by the acoustical stimulus to the value in dB SPL.

Equivalent sound pressure level [dB SPL] can be represented as follows:

$$90 + 20 \times \log \frac{CM_{trans}}{CM_{so}} , \qquad (7.1)$$

where CM_{trans} and CM_{so} [μV] are CM amplitude caused by the transducer and acoustic stimulus of 90 dB SPL, respectively.

When electrical current of 80 mA flowed into the driving coil, the transducer produced equivalent sound pressure of 93 - 106 dB SPL and maximum equivalent sound pressure was obtained at 3 kHz.

7.2.4. Time history responses

Time history responses of the earphone and the transducer and magnitude spectra of the CM waveforms at 0.5, 1, 2, 4 and 8 kHz are shown in Figs. 7.8 - 12, respectively. Especially at high frequencies, the CM waveforms caused by the transducer and the acoustical stimulus included swell waves. These swell waves were considered to be compound action potentials (CAP). The origin of the CAP is the sum of activity of the auditory nerve, different from the CM which is the sum of electrical potentials in the hair cells of the cochlea. At all frequencies, peaks of the magnitude spectra of the CM waveforms caused by the transducer at the input signal frequency were relatively sharp, while magnitude spectra of the CM waveforms caused by the acoustical stimulus were broader frequency bands. In addition, distortion of the time history responses of the transducer was lower than the responses of the earphone. Especially at 0.5 kHz, the magnitude of the second harmonics components of the CM waveform caused by the acoustical stimulus was larger than that caused by the transducer. These results demonstrated the apparent similarity between the time history response of the transducer and that of the input signal waveform.

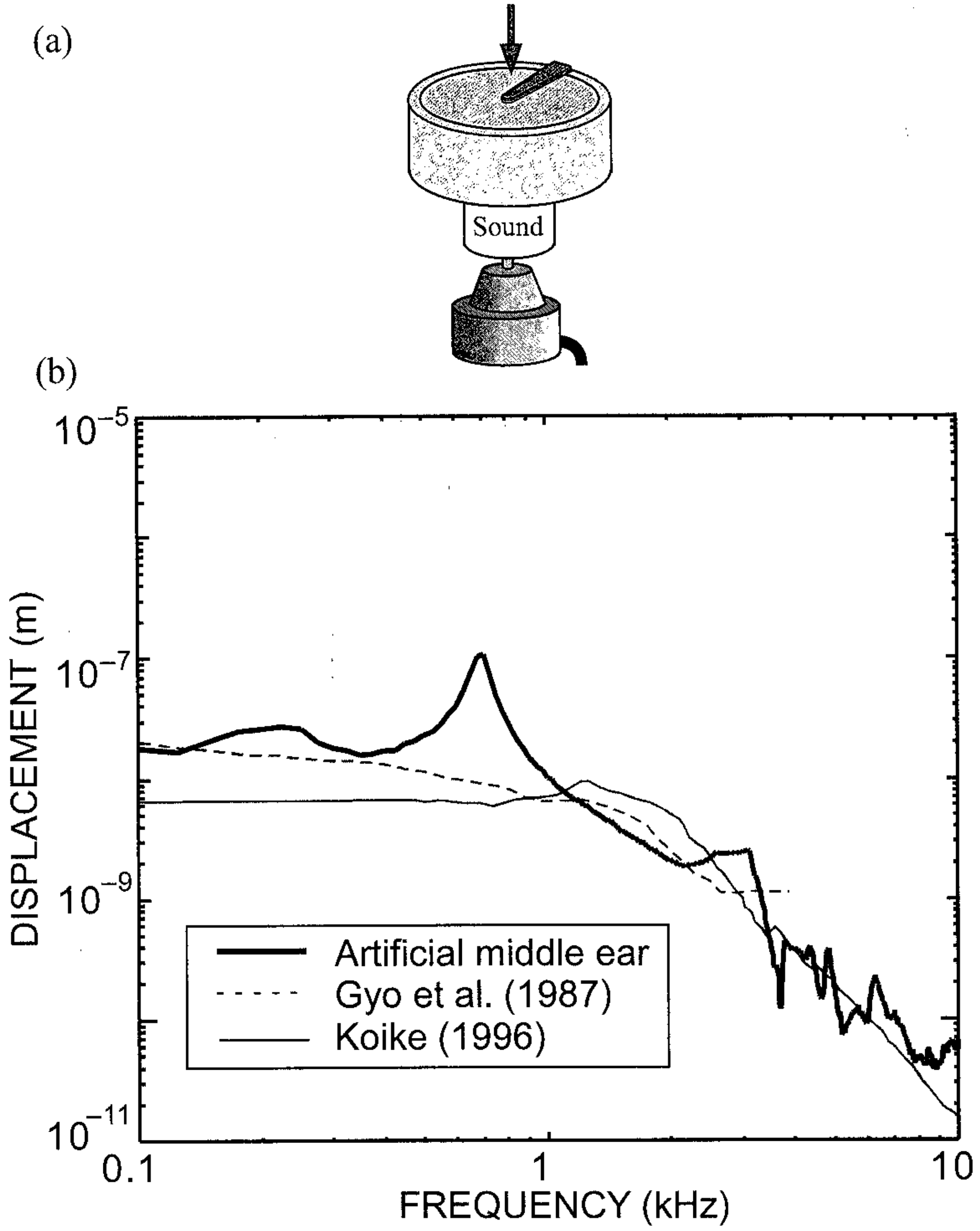

Figure 7.1. Validity of the artificial middle ear. (a) Experimental set up for measurement of the characteristics of the artificial middle ear. (b) Frequency characteristics of the displacement of the center of the artificial middle ear obtained when an acoustical stimulus of 80 dB SPL was applied to the artificial middle ear. This result was compared with the results of displacement of umbo of the tympanic membrane obtained by the FEM analysis of the human middle ear (Koike et al., 1996) and actual measurement using human temporal bone (Gyo et al., 1987). The frequency characteristics of the artificial tympanic membrane were similar to those of an actual human middle ear.

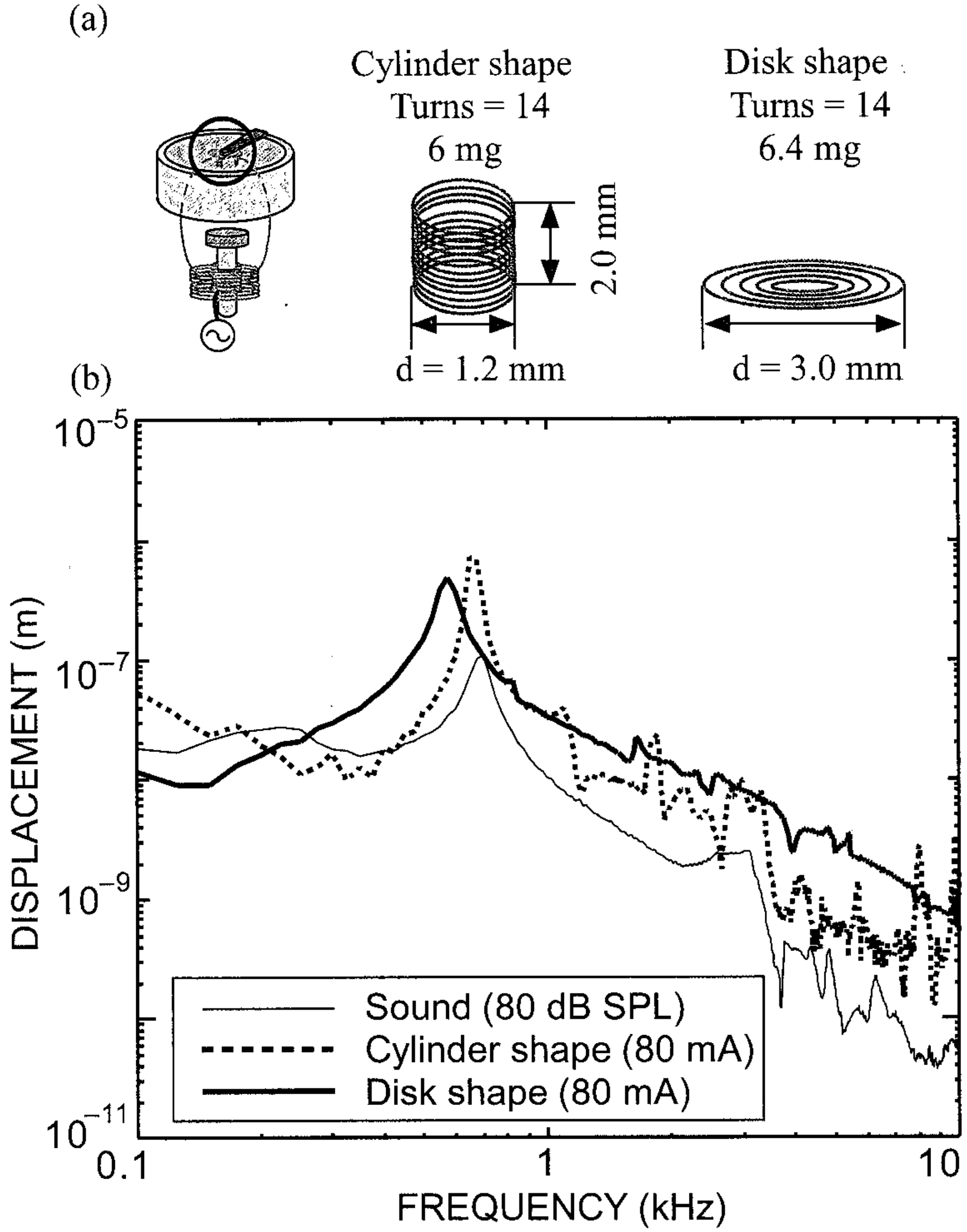

Figure 7.2. Effects of the shape of the vibrator coil on the frequency responses of the displacement at the center of the artificial middle ear. (a) Two types of shape of the vibrator coil; "cylinder" shape and "disk" shape. (b) Frequency responses at the center of the artificial middle ear with a cylinder- or a disk-shaped vibrator coil caused by the transducer. Above 1 kHz, displacement at the center of the membrane with the disk-shaped vibrator coil was larger than that with the cylinder-shaped vibrator coil.

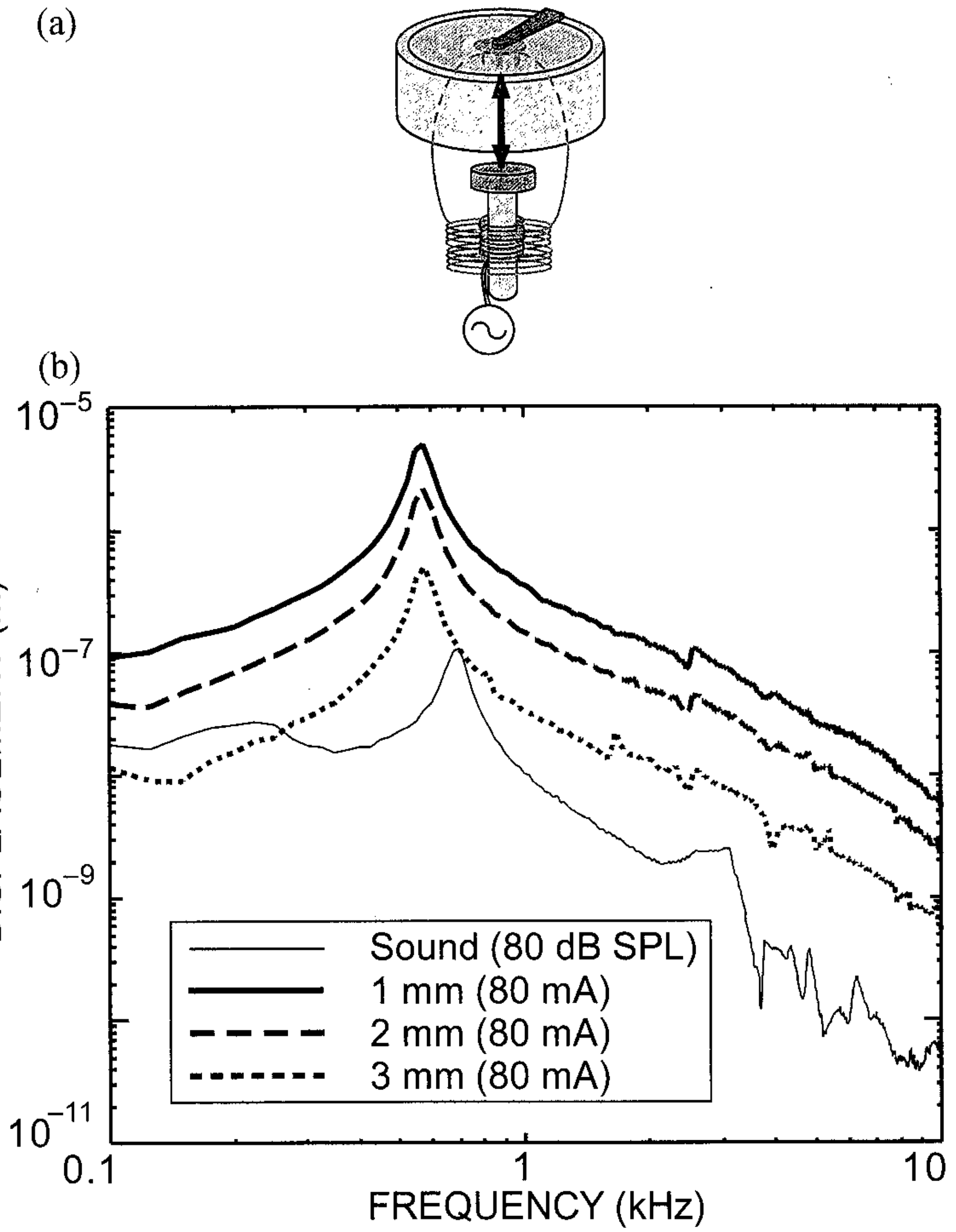

Figure 7.3. Effects of the distance between the magnet and the vibrator coil on the frequency responses of the displacement at the center of the artificial middle ear. (a) Experimental setup. (b) Frequency responses of the displacement at the center of the artificial middle ear. The proximity of the distance between the magnet and the vibrator coil caused larger displacement at the center of the artificial middle ear.

Table 7.1. Tendency of the optimal shape and alignment of the transducer

Parameter	Displacement at the center of the artificial middle ear
Number of coil turns of the driving coil	Many > Few
Number of coil turns of the induction coil	Many > Few
Number of coil turns of the vibrator coil	Many > Few
Material of the magnet	Ne-Fe-B > Sm-Co
Core material of the induction coil	Amorphous material > Iron
Distance between the magnet and the vibrator coil	Short > Long

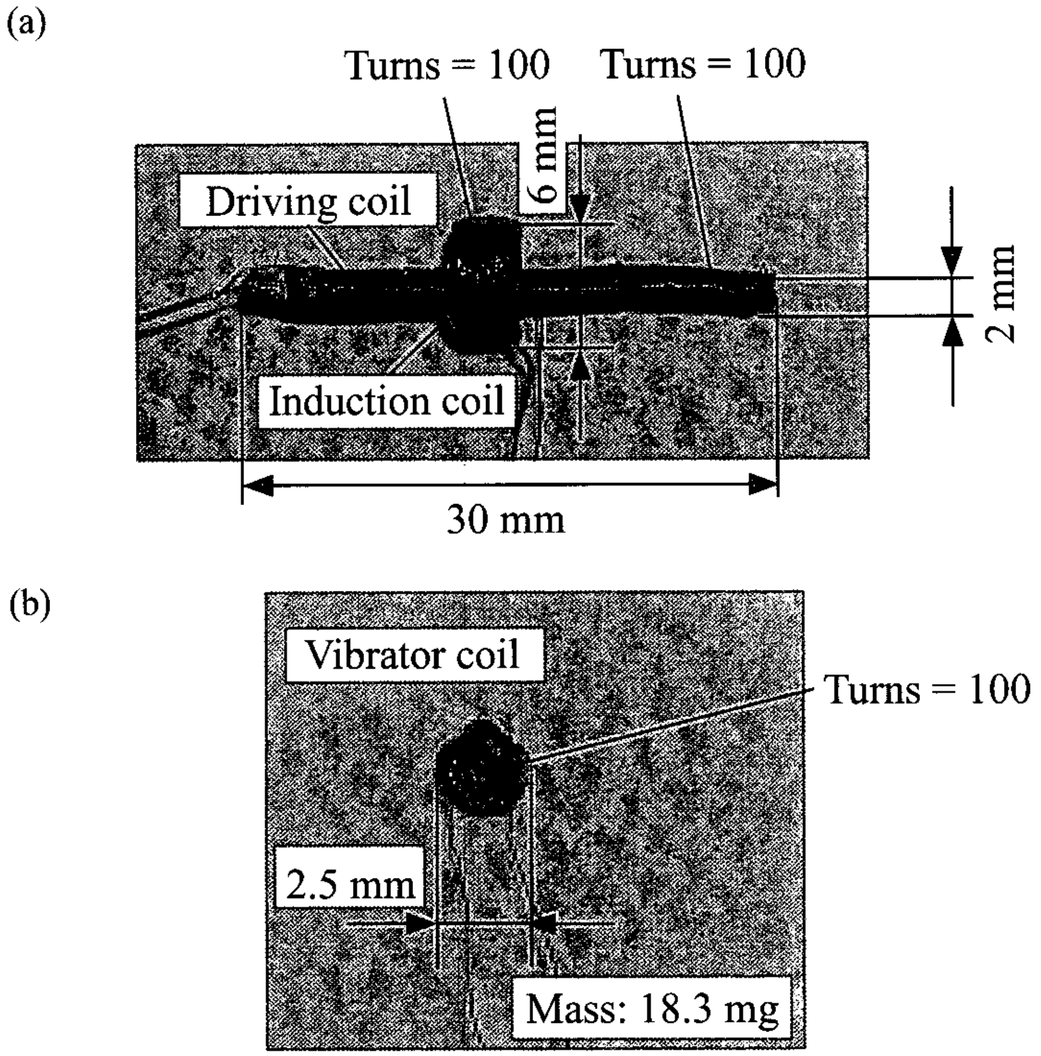

Photo 7.1. Prototype of the transducer. (a) Driving and induction coils. (b) Vibrator coil. The three coils were designed so as to be suitable for installation in the human external ear canal, and amorphous material with high permeability was used for the core material of the induction coil. The magnet used in this study was law Ne-Fe-B magnet, which has high magnetic flux density. The mass of the vibrator coil including the plastic plate for the attachment was 18.3 mg.

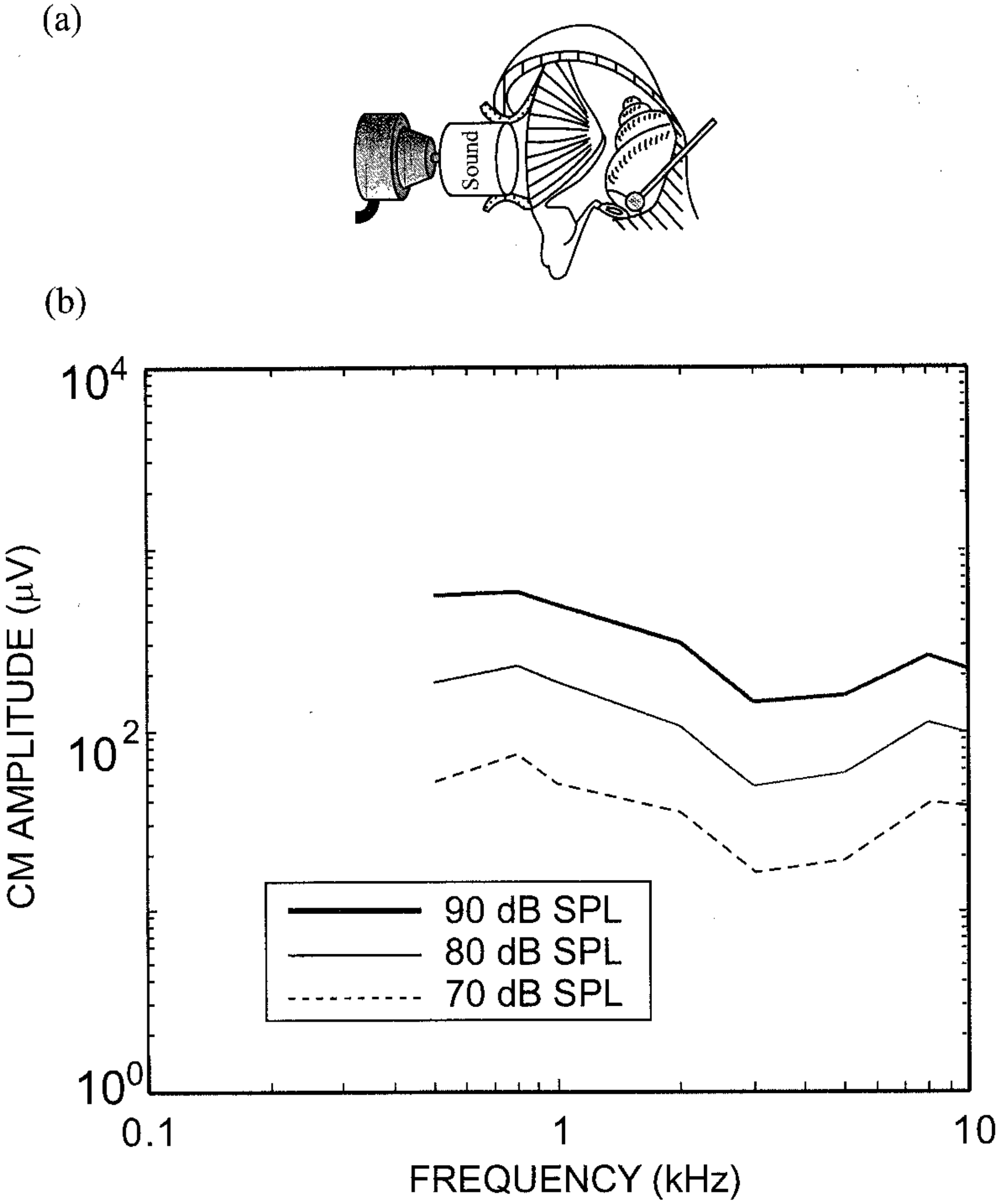

Figure 7.4. Linearity of the CM amplitude. (a) Experimental setup for measurement of CM amplitude caused by the earphone. (b) Frequency responses of the CM amplitude obtained from a guinea pig when acoustical stimuli of 70, 80, and 90 dB SPL were applied to the tympanic membrane. When the acoustical stimulus was increased from 70 dB SPL to 90 dB SPL, frequency responses of the CM amplitude exhibited upward parallel shifts.

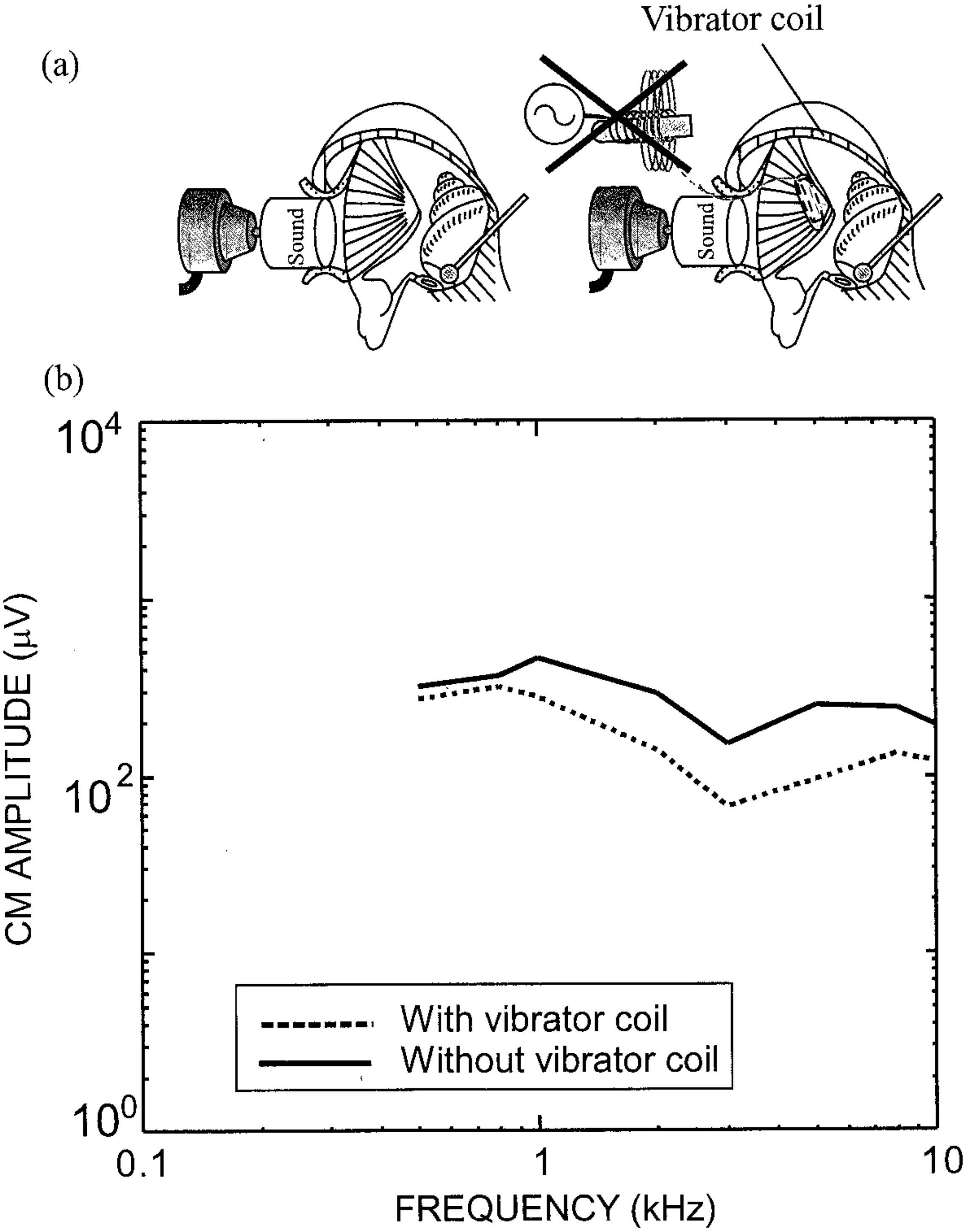

Figure 7.5. Effects of the mass of the vibrator coil on the CM amplitude. (a) Experimental setup for measurement of the effects of mass of the vibrator coil on the CM amplitude. In this measurement, the vibrator coil was attached to the tympanic membrane, but the current was not applied to the driving coil; an acoustical stimulus of 90 dB SPL was applied to the tympanic membrane. This result was then compared with the CM amplitude obtained when no vibrator coil was attached to the tympanic membrane. (b) Frequency responses of the CM amplitude. Over the entire frequency range, CM amplitude caused by the acoustical stimulus with vibrator coil was lower than that without the coil. However, the maximum decrease in the CM amplitude was within 10 dB.

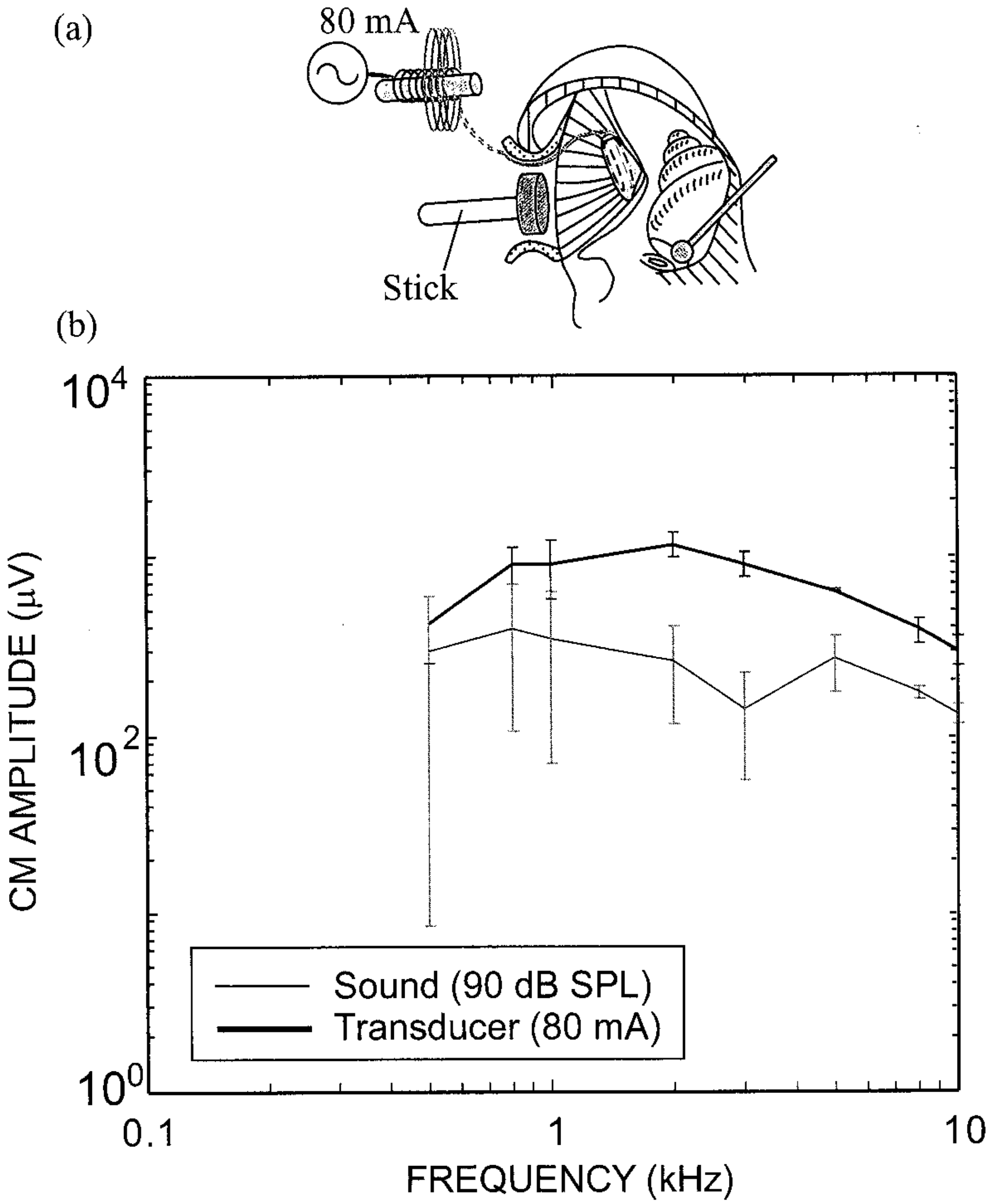

Figure. 7.6. Frequency responses of the CM amplitude caused by the transducer. (a) Experimental setup using the transducer. (b) Frequency responses of the CM amplitude obtained from guinea pigs when the vibrator coil was vibrated by the transducer and when acoustical stimulation was applied to the tympanic membrane (n = 3). Vertical lines represent one standard deviation. In the case of the transducer, a sinusoidal current of 80 mA flowed into the driving coil. Over the entire frequency, CM amplitude caused by the transducer was larger than that caused by the acoustical stimulus. Maximum gain was obtained at 3 kHz.

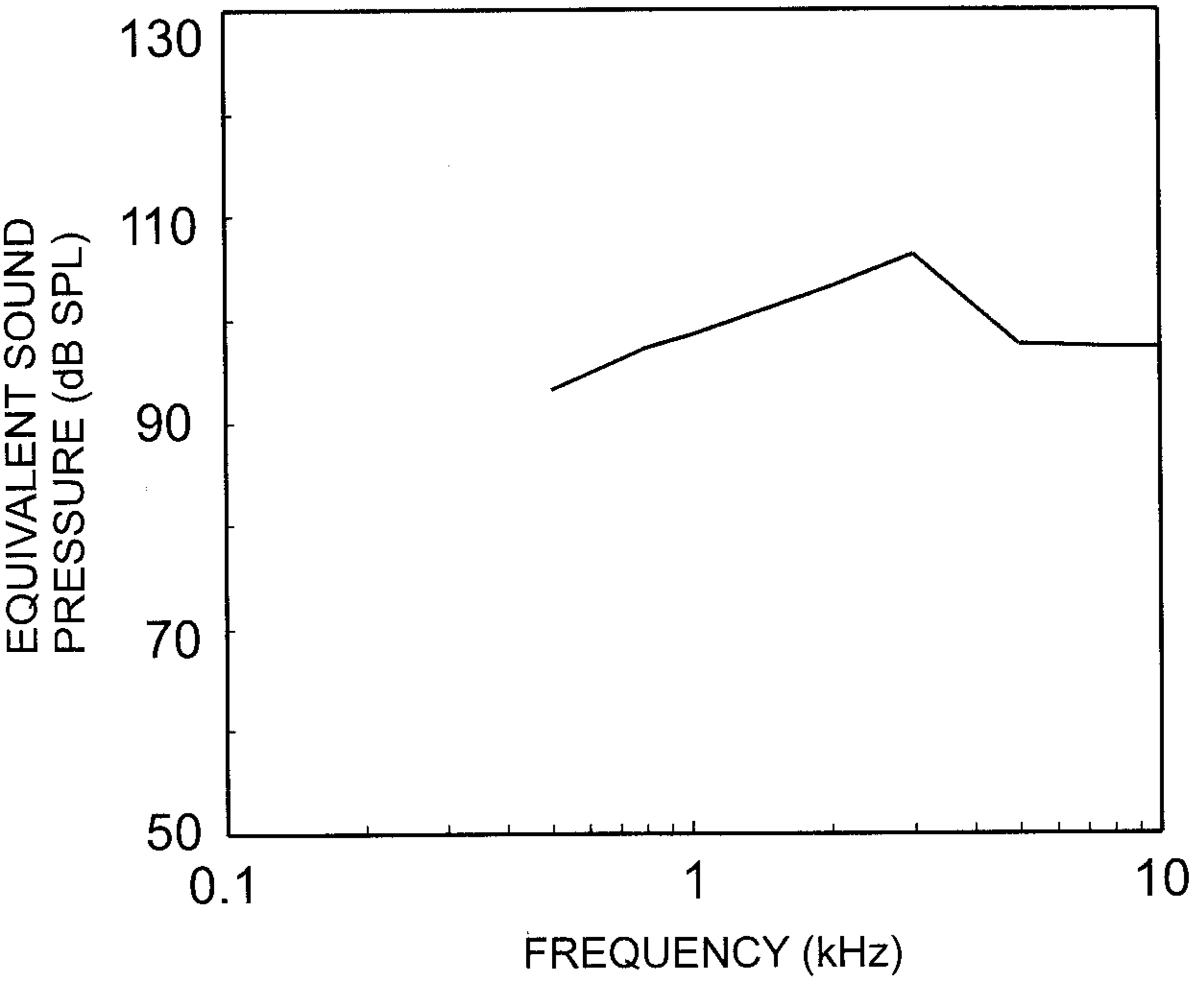

Figure 7.7. Equivalent sound pressure level of the electromagnetic hearing transducer obtained when electrical current of 80 mA was applied to the driving coil. As the earphone used in this study could not generate sound pressure of more than 90 dB SPL, saturation of the CM amplitude could not be observed. However, as Avan et al. (1992) reported that the linearity of the CM amplitude saturated between 90 and 110 dB SPL, the value of the CM amplitude can convert to the value in dB SPL. Therefore, on the base of the result of Fig. 7.6, equivalent sound pressure was calculated by converting the difference of the CM amplitude caused by the transducer and acoustical stimulus to the value in dB SPL.

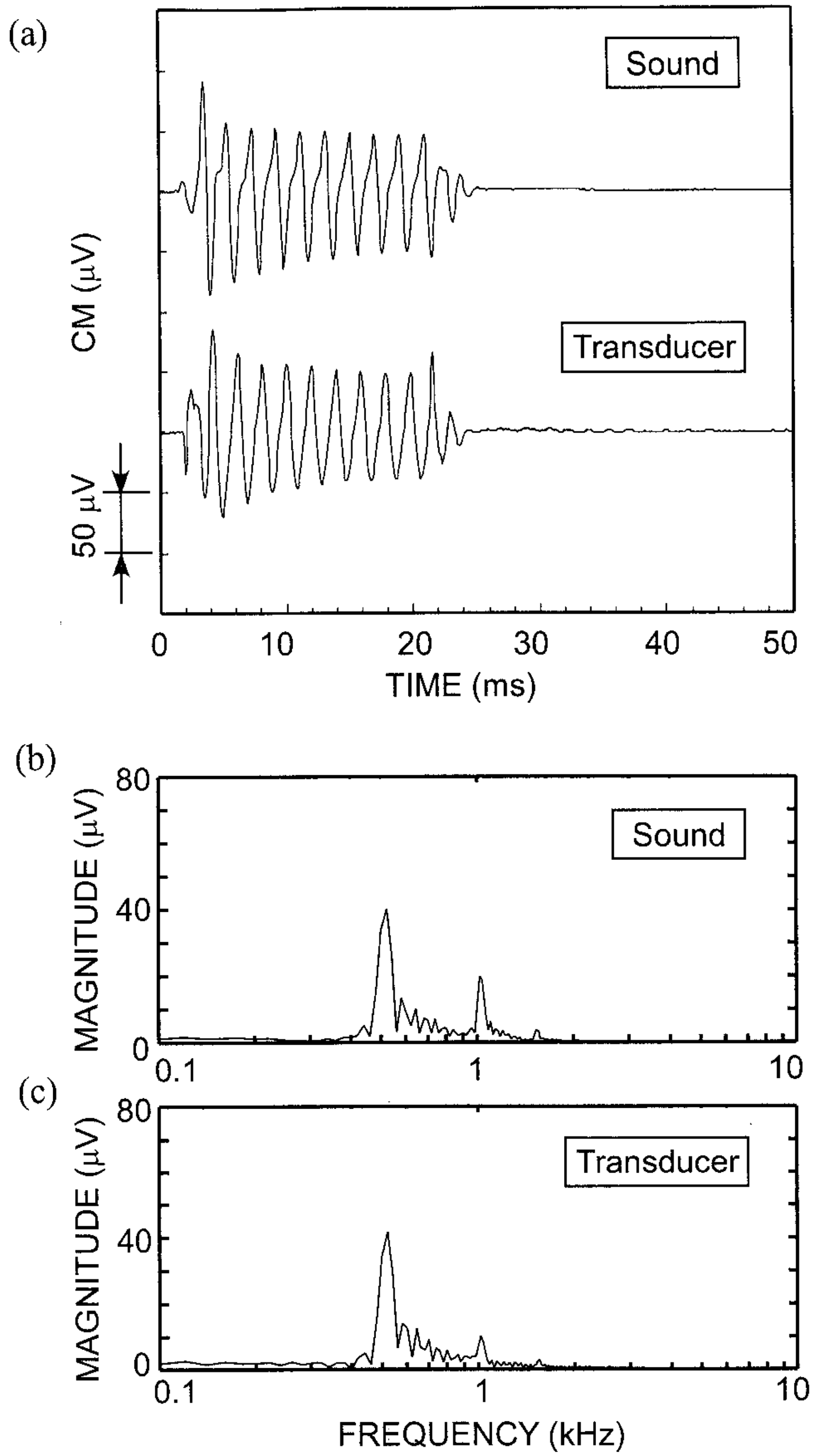

Figure 7.8. Time history of the CM caused by acoustical stimuli and the transducer when the frequency of the electrical input signal was 0.5 kHz. (a) Time history responses of the earphone and the transducer. (b) Magnitude spectra of the CM waveforms caused by the acoustical stimulus. (c) Magnitude spectra of the CM waveforms caused by the transducer.

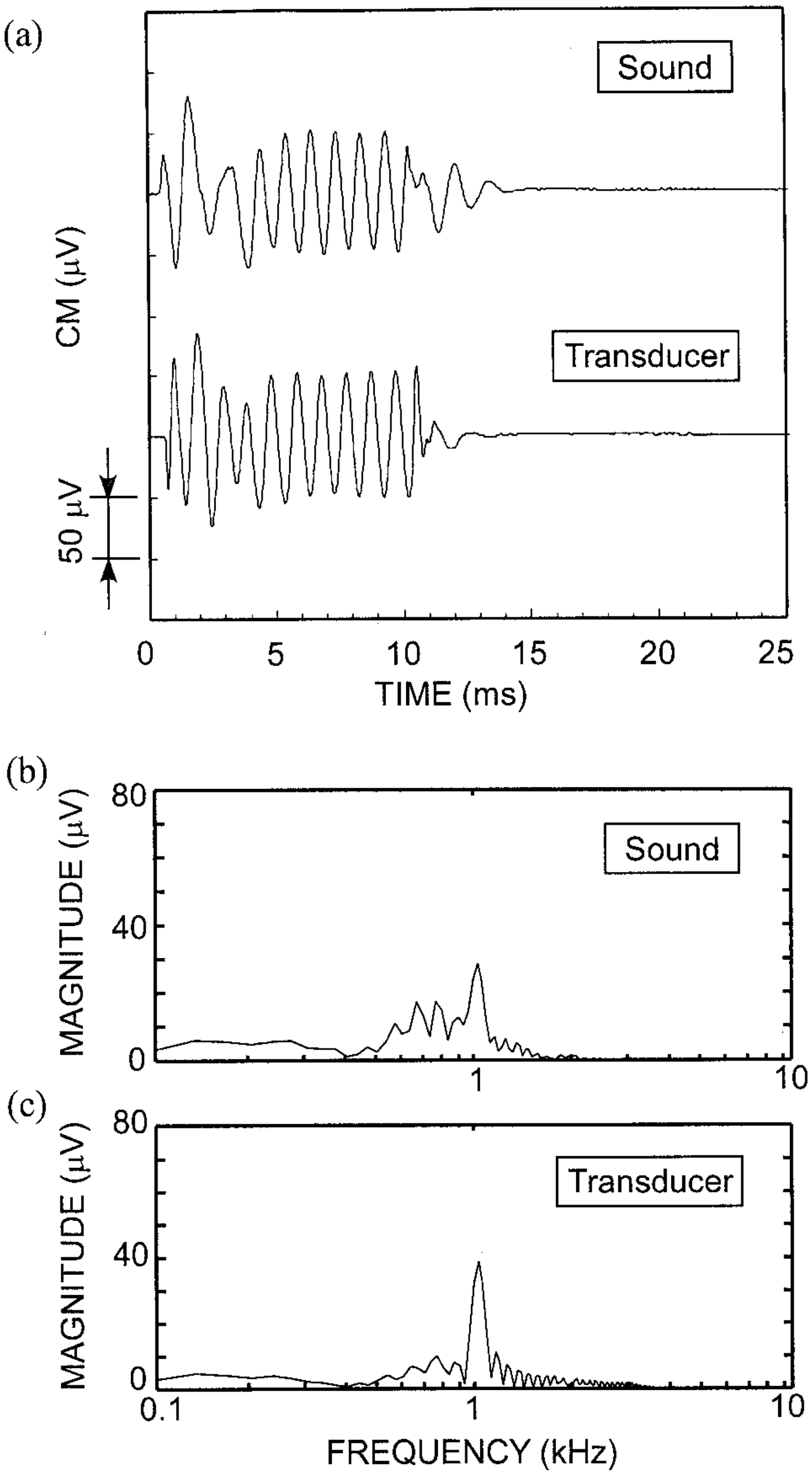

Figure 7.9. Time history of the CM caused by acoustical stimuli and the transducer when the frequency of the electrical input signal was 1 kHz. (a) Time history responses of the earphone and the transducer. (b) Magnitude spectra of the CM waveforms caused by the acoustical stimulus. (c) Magnitude spectra of the CM waveforms caused by the transducer.

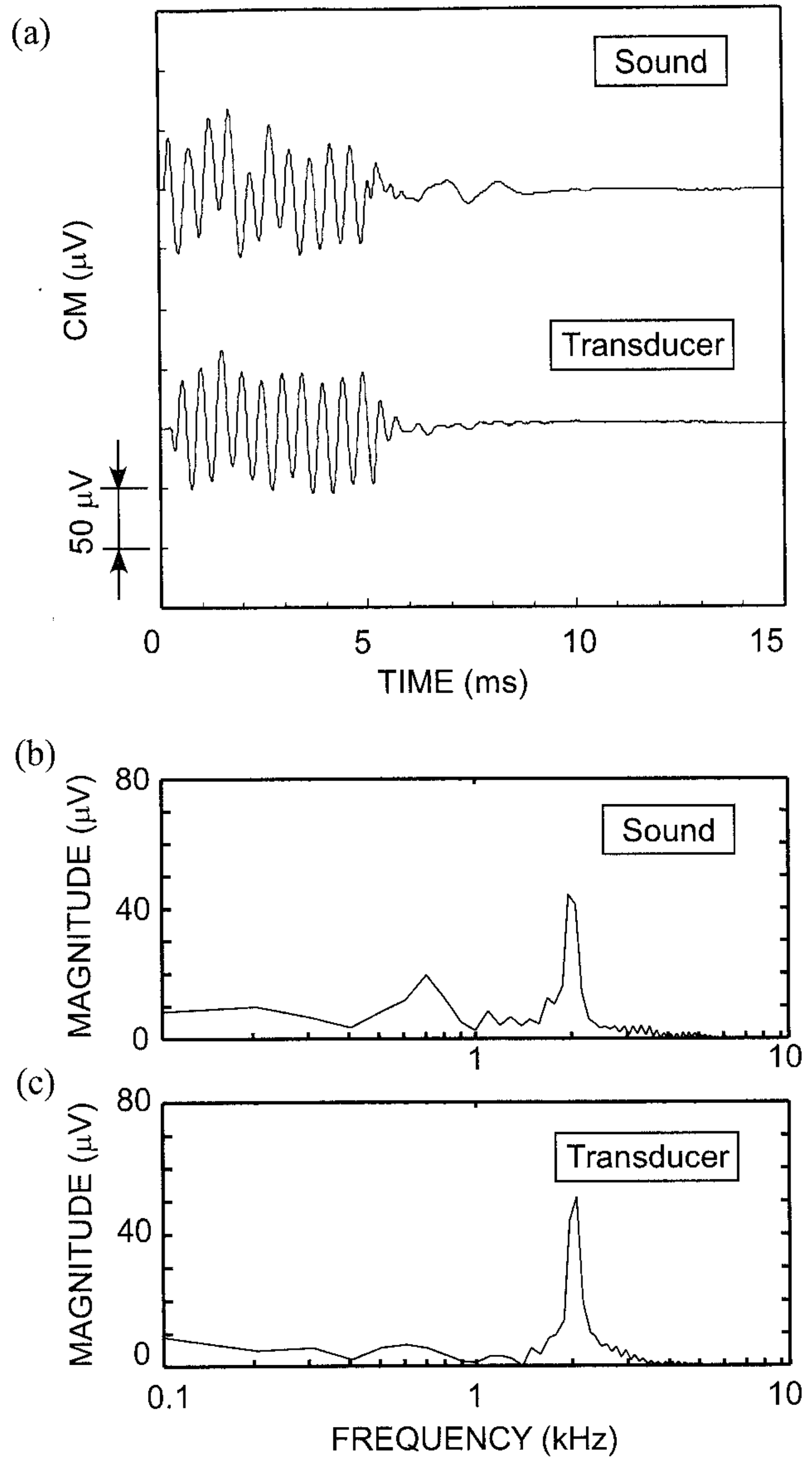

Figure 7.10. Time history of the CM caused by acoustical stimuli and the transducer when the frequency of the electrical input signal was 2 kHz. (a) Time history responses of the earphone and the transducer. (b) Magnitude spectra of the CM waveforms caused by the acoustical stimulus. (c) Magnitude spectra of the CM waveforms caused by the transducer.

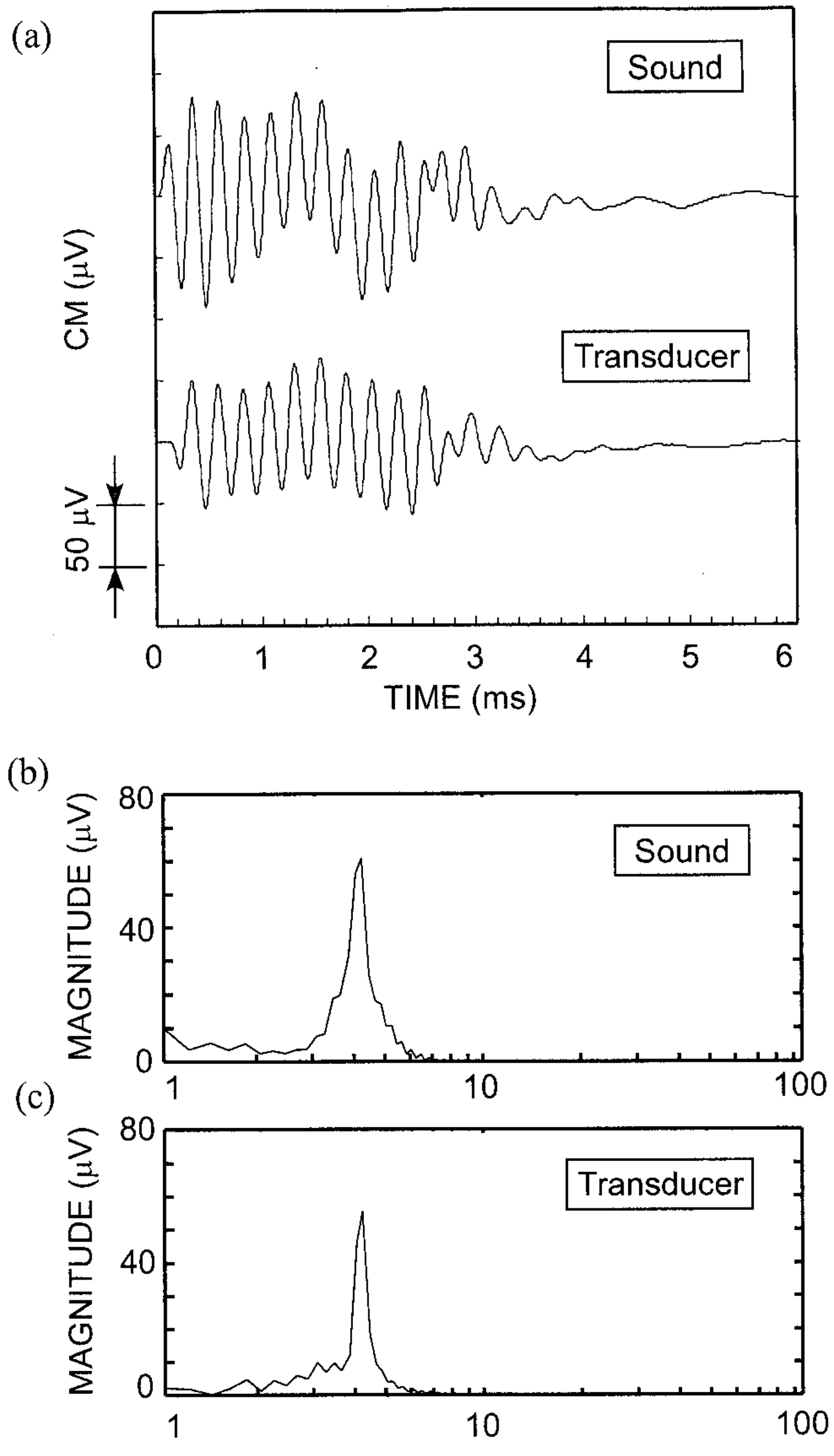

Figure 7.11. Time history of the CM caused by acoustical stimuli and the transducer when the frequency of the electrical input signal was 4 kHz. (a) Time history responses of the earphone and the transducer. (b) Magnitude spectra of the CM waveforms caused by the acoustical stimulus. (c) Magnitude spectra of the CM waveforms caused by the transducer.

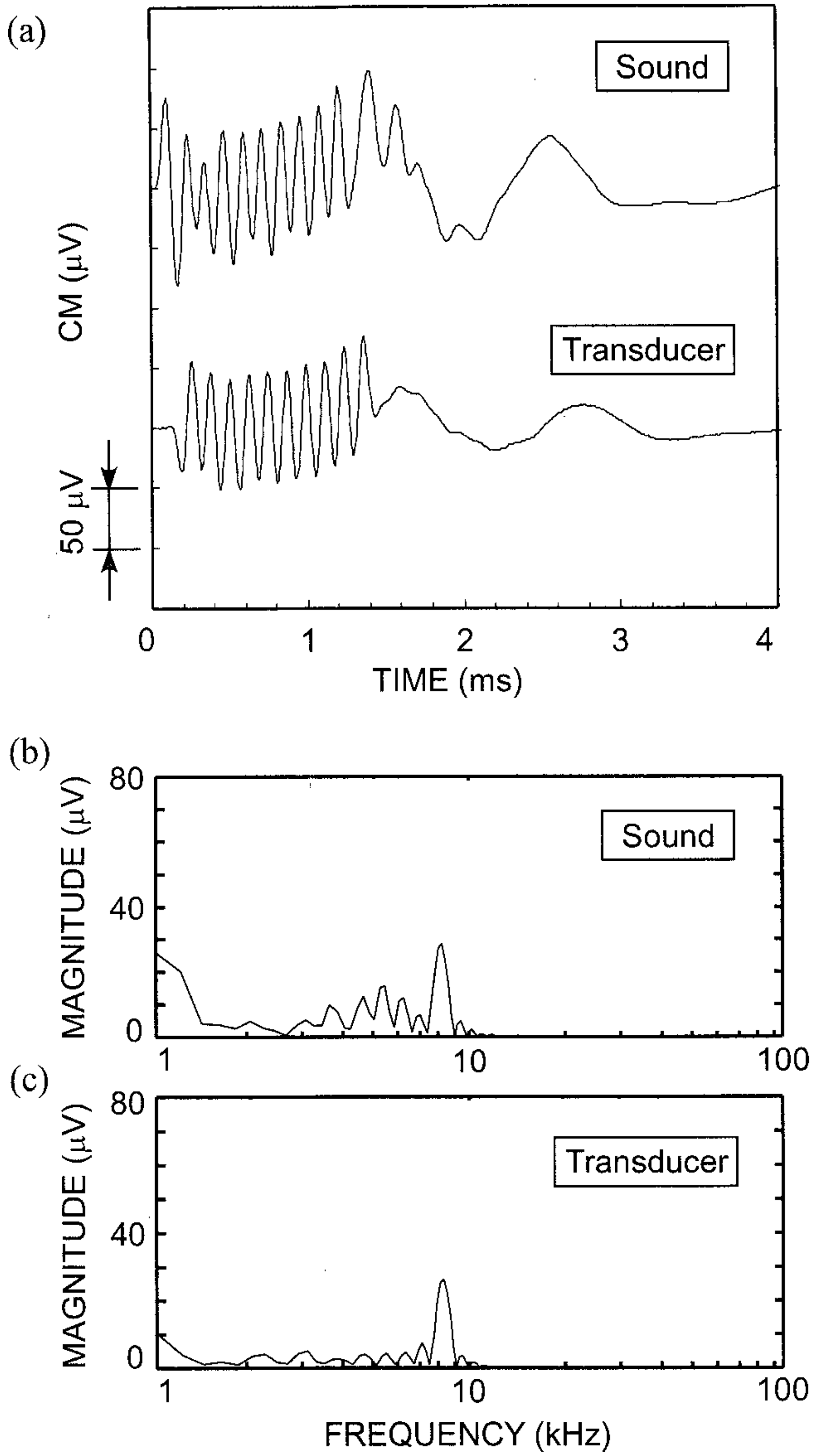

Figure 7.12. Time history of the CM caused by acoustical stimuli and the transducer when the frequency of the electrical input signal was 8 kHz. (a) Time history responses of the earphone and the transducer. (b) Magnitude spectra of the CM waveforms caused by the acoustical stimulus. (c) Magnitude spectra of the CM waveforms caused by the transducer.

8. Discussion

8.1. Frequency responses of the CM amplitude caused by the transducer

The animal experiments revealed that CM amplitude caused by the transducer was larger than that caused by acoustical stimulus over the entire frequency region. However, the difference between them was approximately 5 dB at frequencies below 0.8 kHz and above 5 kHz. The reason for the low output of the transducer in the low and high frequency range can be explained as follows.

At low frequencies, it is considered that electromotive force generated at the induction coil increased with an increase in frequency, as shown by in Eq. (4.2). In order to confirm this hypothesis, induction and driving coils, the same coils as used in the transducer, were made, and the electromotive force generated at the induction coil was measured. As shown in Fig. 8.1., the electromotive force below 0.8 kHz was less than one-fifth of that at 10 kHz.

At high frequencies, the mass of the vibrator coil might affect the CM amplitude. Indeed, as shown in Fig. 7.5, the effect of the mass of the vibrator coil on CM amplitude was significant in the high frequency range.

There is another possible explanation for this result, namely that the linear relationship between the sound pressure level and the CM amplitude is not guaranteed when the sound pressure level is high. Avan et al. (1992) reported that the linearity of the CM amplitude was saturated between 90 and 110 dB SPL. Additionally, experimental results in guinea pigs by Suga et al. (1971) showed that the acoustical stimulus level where the CM amplitude was saturated was low at low frequencies.

In the present study, as the earphone used could not output a sound pressure of more than 90 dB SPL, saturation of the CM amplitude could not be confirmed.