Otoacoustic emissions measured with a physically open recording system

Robert H. Withnell, Desmond L. Kirk, and Graeme K. Yates[a)]
The Auditory Laboratory, Department of Physiology, The University of Western Australia, Nedlands 6907, Western Australia, Australia

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Otoacoustic emissions have historically been measured with an acoustical probe assembly hermetically sealed in the ear canal, imposing in most cases a limited stimulus bandwidth. A physically open recording system should afford the possibility of a greater stimulus bandwidth but the change in acoustical load may affect the magnitude of otoacoustic emissions obtained. Here it is reported that the authors have measured in the guinea pig transient-evoked otoacoustic emissions extending in frequency to 20 kHz and cubic distortion tone otoacoustic emissions for $f_2 = 4737$ and 8096 Hz with a physically open sound system. To address the effect of acoustical load provided by a physically open versus hermetically sealed system, the authors compared the amplitude of electrically evoked otoacoustic emissions recorded from a guinea pig in each case. The change in acoustical load in the ear canal introduced by the change in recording setup did not appear to make a substantial difference to the magnitude of otoacoustic emissions measured. A physically open recording system provides a good alternative to traditional acoustical probe assemblies sealed in the ear canal for the laboratory measurement of acoustically evoked otoacoustic emissions, with the advantage of permitting a greater stimulus bandwidth. [S0001-4966(98)03207-X]

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INTRODUCTION

Power spectra for transient-evoked otoacoustic emissions (TEOAEs) reported in the literature are commonly restricted to frequencies between approximately 1 and 6 kHz. A lower frequency limit for the TEOAE would not be surprising, given the probable stiffening of the middle ear and the reduced activity of the active process at low frequencies (Kirk and Yates, 1996), but an upper frequency limit, if present, would be unexpected. The middle ear appears quite capable of transmitting pressure from scala vestibuli to the external ear canal for frequencies up to at least 8 kHz (Magnan *et al.*, 1997), and the cochlear amplifier is strongly active up to tens of kilohertz in mammals, so otoacoustic emissions to wideband stimuli might be expected well above 6 kHz. Indeed, distortion product otoacoustic emissions have been recorded at frequencies well above 10 kHz (Fahey and Allen, 1985; Mills and Rubel, 1996). The apparent absence of the TEOAE above 6 kHz may be due to unknown factors internal to the cochlea, but it is more probable that technical limitations in the frequency response of the stimulus have contributed to their absence from recordings to date.

Kemp (1978) first measured otoacoustic emissions (OAEs) with an acoustical probe assembly that housed both microphone and speaker, the assembly being acoustically sealed to the ear canal entrance to minimize the enclosed volume of air. This original configuration was reported to have a stimulus spectrum that was flat to within ± 6 dB up to 3.5 kHz (Kemp, 1978). Subsequent sound delivery systems have also employed acoustical probe assemblies that house both the microphone and speaker/s (e.g., Kim *et al.*, 1980; Anderson, 1980; Wilson, 1980; Kemp *et al.*, 1990), but one shortcoming of such assemblies is that in most cases they have a limited stimulus bandwidth. Consequently, power spectra for TEOAEs reported in the literature seldom extend past 6 kHz, although this is partly a product of windowing of the response, low-pass filtering of the stimulus, and/or limited recording sample rate (Bray and Kemp, 1987; Prieve *et al.*, 1996).

Typically, sound-generating sources for evoking OAEs have taken the form of dynamic earphone transducers in sealed enclosures, typified by the hearing aid receiver. These have inherently limited frequency responses, the reasons for which are unclear but probably are connected with the following two effects: (i) Typical dynamic transducers such as those used in audio equipment have resonance frequencies in the range 30–250 Hz, resulting in constant displacement of the radiating diaphragm below the resonance frequency and constant acceleration (or -12 dB/oct displacement response) above. In free-field use this is countered by the radiation efficiency of the diaphragm which rises at a rate of 12 dB/oct. The result is a rising, 12 dB/oct response below resonance and a flat response above. But when such a transducer is coupled into a small cavity, the expected pressure response will be the reverse: flat up to the resonance frequency and an attenuation at the rate of -12 dB/oct above. (ii) Even if a flat frequency response can be generated in the enclosed cavity in front of the speaker, that sound must be communicated to the ear canal by a small tube or hole and the mass of air enclosed in the tube or hole will typically form a Helmholtz resonator with the series connections of the cavity volumes of the transducer and the ear canal. Such a resonantor will

[a)]Electronic mail: gyates@cyllene.uwa.edu.au

function as a low-pass filter between the transducer and the ear canal, further attenuating the sound in the canal at high frequencies.

Additional to the effect of an enclosed volume on the stimulus source, the acoustical load presented by the probe system may also influence the emissions themselves. Kemp (1978, pp. 1386 and 1387) stated that acoustically closing the ear canal had the effect of ''greatly intensifying... sound pressure fluctuations created by movement of the eardrum,'' or in other words, the amplitude of the otoacoustic emission was directly dependent upon the acoustical probe assembly being acoustically sealed to the ear canal. Consistent with this, later authors have observed that acoustical probe impedance affects the ear canal OAE sound pressures generated by the cochlea (Matthews, 1983; Zwicker, 1990; Jurzitza and Hemmert, 1992; Thornton *et al.*, 1994; Nakajima *et al.*, 1994; Puria and Rosowski, 1997).

Thornton *et al.* (1994) considered two types of OAE apparatus and suggested that differences in measured TEOAEs were the product of differences in acoustical loading of the ear canal by the acoustical probes. The authors assumed, however, that the nonlinear derived TEOAE is not influenced by the frequency response of the recording system, arguing that the frequency dependence of the system is removed by the subtraction in the response recovery process. This is not the case, however, and it is likely that the differences in the TEOAEs they recorded using the two systems were a consequence of the different frequency responses of the loudspeakers and/or microphones.

Zwicker (1990) reported that the spectral structure of OAEs could be altered by different acoustical probe impedances, but this was based only on the 900–1100-Hz region in one human subject. Matthews (1983) and Jurzitza and Hemmert (1992) considered that acoustical probe impedance could significantly affect OAEs recorded, but in both cases this was based on a theoretical treatment. Puria and Rosowski (1997) examined forward and reverse transmission in a human temporal bone preparation over the frequency range 0.1–4.2 kHz. They reported a significant effect on reverse transmission by comparing two different acoustical probe assemblies sealed in the ear canal with differing acoustical impedances, while the drive source in the cochlea was kept constant. It is unclear, however, how these measurements relate to the living human.

Clearly our current understanding of the effects of acoustical load on the ear canal OAE sound pressures generated by the cochlea is incomplete. In attempting to address this problem using acoustically delivered stimuli, one inevitably finds that changing the acoustical load in the ear canal alters the intensity of the stimulus at the eardrum. However, the problem can be successfully addressed by using electrical stimuli which generate OAEs but are themselves independent of external acoustical conditions, with two recording conditions that produce different acoustical loads in the ear canal (e.g., Nakajima *et al.*, 1994). Stimulation of the cochlear partition with an electrical current appears to generate a motile response of the outer hair cells which is then detected in the ear canal as an OAE (Hubbard and Mountain, 1983; Mountain and Hubbard, 1989; Kirk and Yates, 1996). If the stimulus conditions are maintained constant, then, without precluding the possibility that external acoustical impedance might influence the emission mechanism, any difference measured in the amplitude of emissions under different recording conditions can be attributed solely to the difference in acoustical load in the ear canal. Nakajima *et al.* (1994) have measured the magnitude of electrically evoked otoacoustic emissions using an acoustical probe assembly that was hermetically sealed within the ear canal, and altered the acoustical load of the probe assembly by increasing the volume from 0.03 to 0.75 cm^3 with a 7-cm-long plastic tube. For the larger volume probe assembly, they found marked dips in emission level, at $\sim$1.5, 3, and 4.5 kHz. The arithmetic relationship between these frequencies suggests a standing wave effect in the 7-cm-long tube, indicating that the authors may not have corrected for this effect. If this is so, then it would seem that any difference between these acoustic loads may have been confined to $<$500 Hz, that is the smaller probe volume and consequently higher acoustic impedance produced larger sound pressures for frequencies $<$500 Hz.

An alternative to an hermetically sealed acoustical probe assembly is a physically open recording system. Such a system has been considered previously, recognizing the potential for greater stimulus bandwidth (Kemp *et al.*, 1986). However, a physically open system might be expected to reduce greatly the magnitude of the otoacoustic emissions measured (Kemp, 1978; Kemp *et al.*, 1986) if the cochlea is a high-impedance drive source and scala vestibuli pressure-induced movement of the eardrum does not alter with changes in acoustical load, i.e., the measured pressure may be load dependent.

In this paper, we consider a physically open recording system and the effect of acoustical load by addressing the following two questions:

(1) *Is it possible to measure OAEs without having the acoustical probe assembly hermetically sealed in the ear canal?*
(2) *What effect does changing the acoustical load have on the amplitude of OAEs measured in the ear canal?*

I. METHODS

Pigmented guinea pigs (500–800 g) were anesthetized with Nembutal (30–35 mg/kg i.p.) and Atropine (0.06 mg i.p.), followed approximately 15 min later by Leptan (0.15–0.2 ml i.m.). Neuroleptanaesthesia (Evans, 1979) was maintained using supplementary doses of Nembutal and Leptan. The guinea pigs were tracheostomized and artificially respired on Carbogen (5% CO_2 in O_2), with body (rectal) temperature maintained at 37 to 38 °C. The head was positioned using a head-holder which could be rotated for access to the ear canal. Alloferin (0.15 ml i.m.) was administered to reduce stapedius muscle contractions. During paralysis potentially noxious stimuli produced no change in heart rate.

A. Surgical procedure for the measurement of acoustically evoked otoacoustic emissions (AEOAEs)

The bulla was opened postauricularly and a silver wire electrode placed on the round window niche for recording of

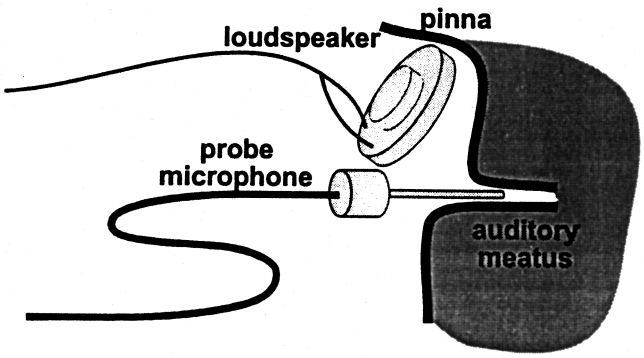

FIG. 1. Schematic of measurement setup for a physically open recording system.

the compound action potential to monitor the condition of the cochlea. A plastic tube was positioned in the bulla opening to ensure that the bulla was always adequately ventilated, although no attempt was made to seal the bulla. This could have resulted in some variation in bulla resonance from animal to animal (in the range 300–1000 Hz), but OAEs were only examined above 1000 Hz.

B. Surgical procedure for the measurement of electrically evoked otoacoustic emissions (EEOAEs)

Surgical procedure for insertion of a micropipette electrode in scala media and the method of electrical stimulation has been described previously (Kirk and Yates, 1996). The cochlea was exposed by a ventro-medial approach and an opening shaved over scala media in the first turn. A micropipette electrode filled with 160-mM KCl and with Ag/AgCl wire leads was placed in the basal turn of scala media.

C. Recording of otoacoustic emissions

We measured TEOAEs, cubic distortion tones (CDTs), and EEOAEs with stimulus delivery and response acquisition computer controlled with custom software and a sound card (Crystal Semiconductor Corporation CS4231A). Ear canal sound pressures were measured with a Sennheiser MKE 2-5 electrostatic microphone coupled to a metal probe tube (1.8-mm outer diameter) placed approximately 2 mm into the external auditory meatus. The probe tube microphone was estimated to obstruct the area of the ear canal by 40%. The output from the probe tube microphone was amplified by either 20 or 40 dB, then digitized at a rate of 44.1 or 48 kHz. Corrections for probe tube response and microphone response have been made.

D. Measurement of AEOAEs

Acoustical stimuli were delivered open-field by a Foster dynamic earphone (type T016H01A0000), positioned so as to obtain a relatively flat ear canal sound-pressure spectrum, as shown in the schematic in Fig. 1. Ear canal sound pressures were recorded in response to transient and two-tone acoustical stimuli. Responses were bandpass filtered using two-pole Butterworth filters prior to digitization of the signal. TEOAEs were extracted using the nonlinear derived response technique (Kemp *et al.*, 1990). The two-tone stimuli for the generation of CDTs had a frequency ratio of 1.2 with $f_2 = 4.737$ or 8.096 kHz.

E. Measurement of EEOAEs

EEOAEs were recorded under two conditions: (i) with the probe tube sealed in the ear canal, or (ii) with the probe tube inserted into the ear canal but not sealed. In the first condition, the seal was effected by placing a sleeve [either a metal tube (3 mm o.d.×9.5 mm) or silicone tube (3.5 mm o.d.×8.5 mm)] over the probe tube and then placing the probe tube in the meatus with the end of the sleeve abutting the entrance to the meatus. Visual inspection confirmed that the end of the sleeve, in abutting the entrance to the meatus, created an acoustical seal. In the case of GP079, petroleum jelly was additionally placed on the end of the sleeve to ensure a seal.

The EEOAE frequency response was measured from 100–20 000 Hz in 250-Hz steps using custom software. Voltage to the micropipette electrode was kept constant over the frequency range of measurement, resulting in a 10 ± 2 μA current. At each frequency, data was acquired over 0.2–0.5 s. Measurement of the EEOAE frequency response was repeated to obtain a series of measurements at each frequency.

The care and use of animals reported on in this study were approved by the Animal Experimentation Ethics Committee of The University of Western Australia and all procedures conformed with the Code of Practice of the National Health and Medical Research Council of Australia.

II. RESULTS

A. AEOAEs

The open system which we use here to deliver the acoustical stimulus results in a much wider frequency response than we have been able to achieve by any other method. Figure 2 shows three examples from different animals of the spectrum typically recorded in the guinea pig ear canal (curve a), together with the TEOAE spectrum obtained with those stimuli (b). The noise level (c) is also shown in each case. The stimulus spectra are flat to within approximately ± 5 dB from 1 to 20 kHz in the top two cases, 1 to 18 kHz in the third. The TEOAEs extend over approximately the same frequency range as the stimuli, far wider than has previously been recorded (e.g., Hilger *et al.*, 1995).

Acoustical spectra demonstrating the presence of the $2f_1 - f_2$ intermodulation distortion product is shown in Fig. 3 for $f_2 = 4737$ and 8096 Hz and $f_2/f_1 = 1.2$. The CDT ($2f_1 - f_2$) is approximately 45 and 35 dB below the primary tones, respectively, comparable with closed system measurements (e.g., Brown and Gaskill, 1990; Avan *et al.*, 1996).

It is apparent from Figs. 2 and 3 that OAEs are indeed measurable with a physically open recording system. The remaining question is to what degree have the emissions been altered by the open sound system?

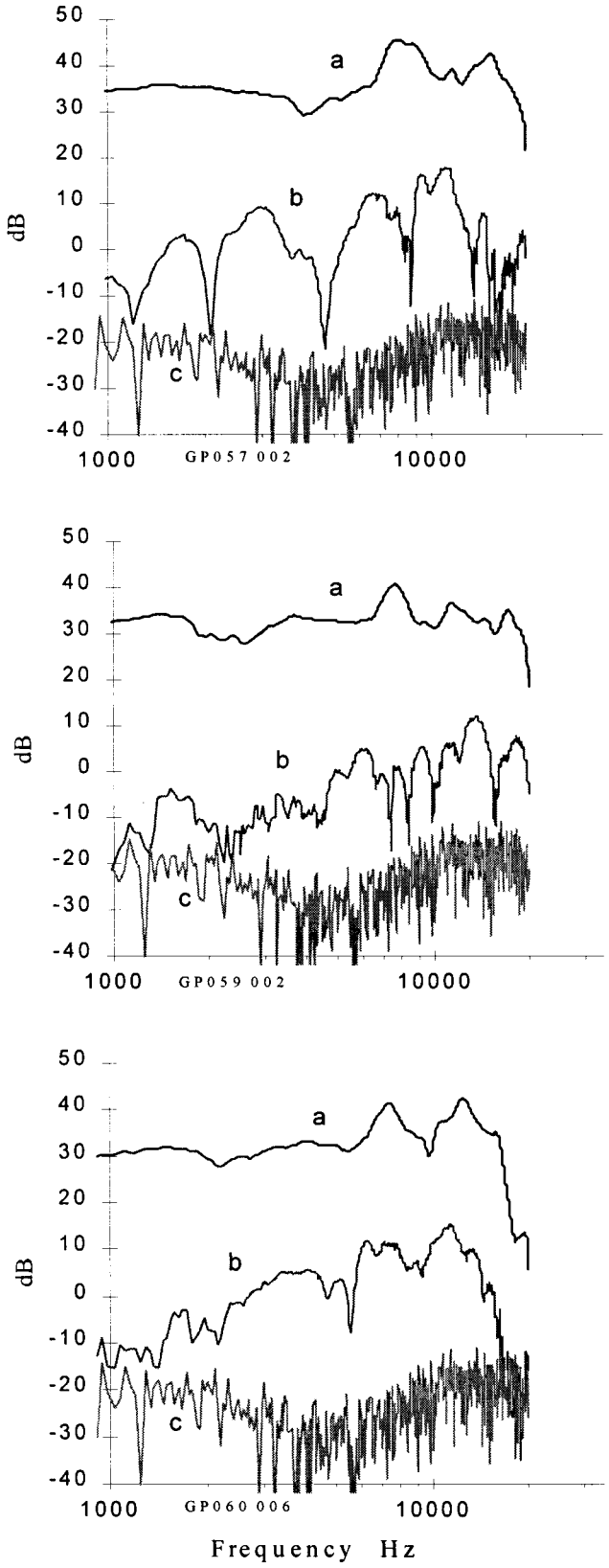

FIG. 2. Three examples from different animals using a physically open recording system of (a) spectrum of acoustical stimulus recorded in the ear canal of a guinea pig, (b) TEOAE obtained with that stimulus, and (c) noise level. Corrected for probe tube characteristics.

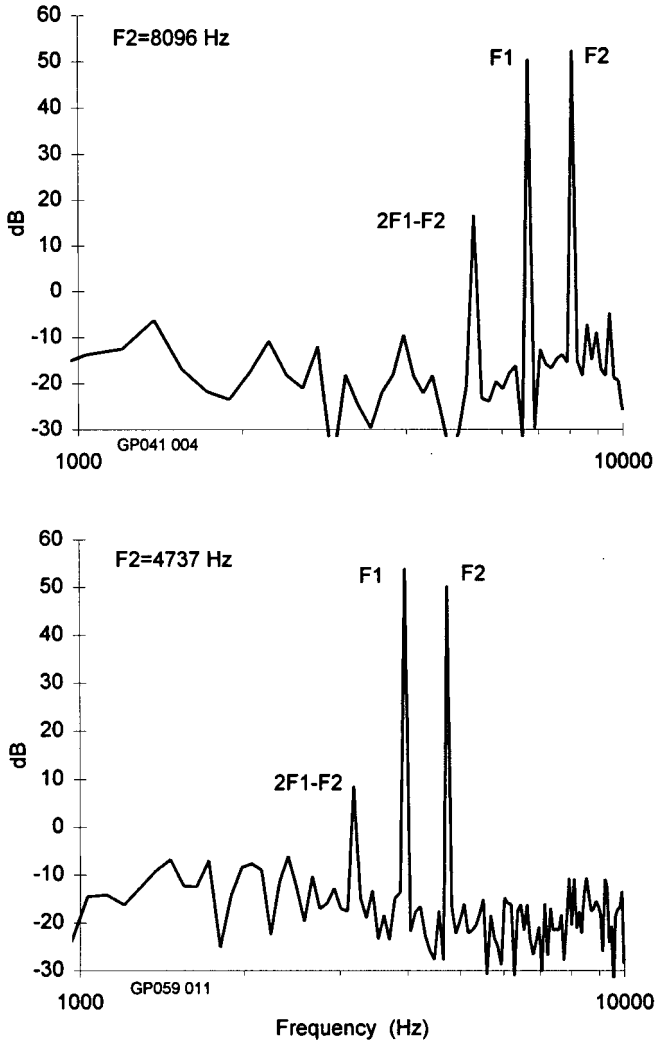

FIG. 3. Two examples of the sound spectrum recorded in the guinea pig meatus in response to two pure tones. The primary tones, at 8096/6747 and 4737/3947 Hz, are accompanied by a strong peak at the difference tone (5398 and 3157 Hz).

B. EEOAEs

Figure 4 shows a representative frequency response function of EEOAEs from electrical stimulation in scala media in the first turn in both the sealed and open conditions. The curve for the open condition represents the average of 15 measurements made at each frequency, each measurement acquired over 0.2 s, while the curve for the sealed condition represents the average of ten measurements made at each frequency, each measurement acquired over 0.2 s. The error bars represent one standard deviation. Above 5 kHz there is effectively no difference in the amplitude of the emissions measured under the sealed and open conditions. Below 5 kHz the functions increasingly separate with decreasing frequency to a mean difference of 7 to 8 dB at 1 kHz between the sealed and open conditions.

Figure 5 shows the mean of the differences between the sealed and open condition versus frequency from data pooled from four animals. Five measurements made at each frequency for the sealed and the open conditions were paired and the difference for each pair calculated. However, to reduce the variance in the data due to noise, data was included only if the standard deviation of each set of five measure-

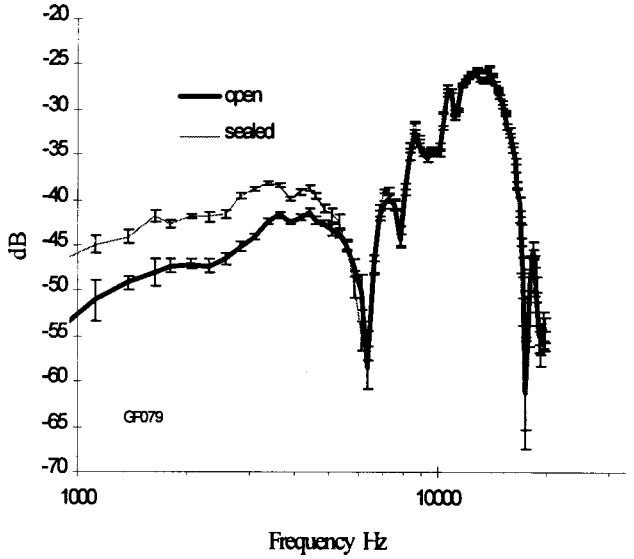

FIG. 4. Sealed and open otoacoustic emission sound-pressure levels measured in response to a 10 μA current injected into the first turn of scala media. Error bars are also shown.

ments for both the sealed and open conditions was less than 1 dB. This resulted in 0–20 difference values from all four animals being used to calculate the overall mean and standard deviation of the differences at any one frequency. For approximately 50% of frequencies, the mean of the differences was derived from the maximum number of difference values, i.e., 20. From Fig. 5 it can be seen that below 4 kHz, the means of the differences range from 2 to 7 dB while from 4 to 20 kHz it is essentially $\leqslant 2$ dB. Error bars in Fig. 5 represent one standard deviation.

To examine the reliability of the technique of placing a probe tube in the meatus in the open condition, the effect of position of the probe tube in the x-y plane (± 1 mm from central position) was examined in one animal as was the

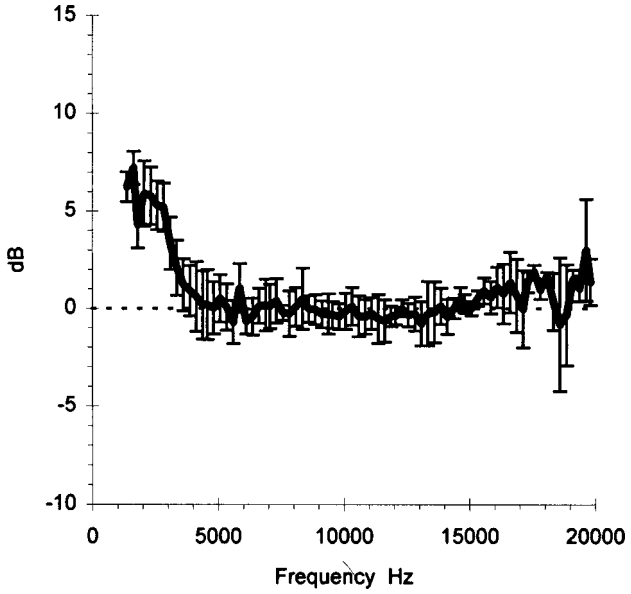

FIG. 5. The mean of the differences between the sealed and open condition versus frequency from data pooled from four animals. Error bars represent one standard deviation.

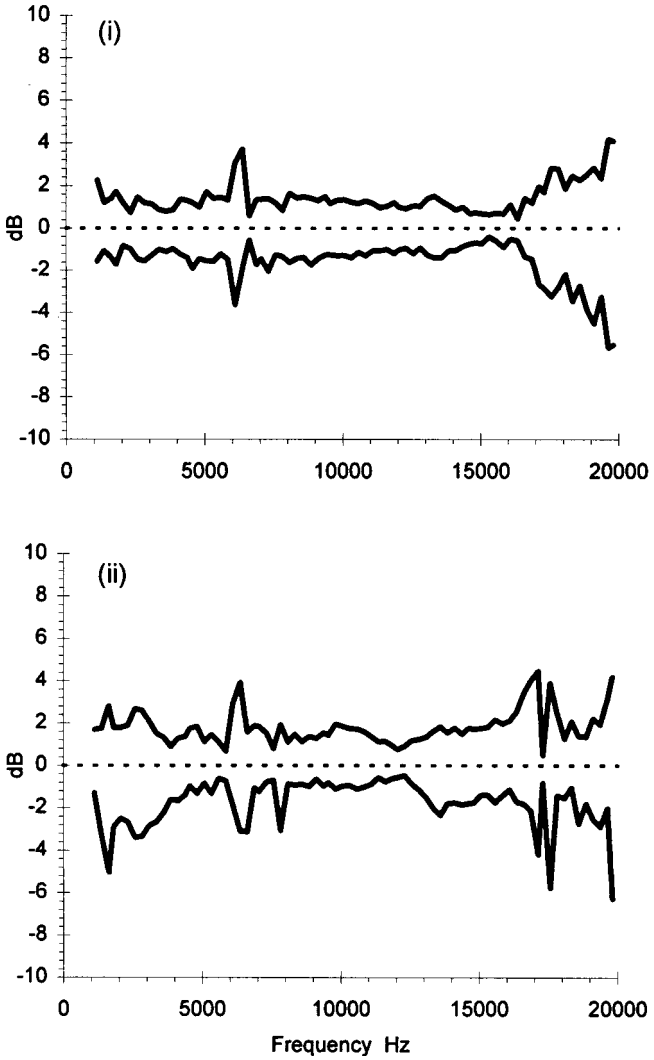

FIG. 6. Maximum variation from the mean sound-pressure level with changes in the position of the probe tube in (i) x-y plane, (ii) depth, in one animal.

effect of depth of the probe tube (from 1 to 3-mm depth in 1-mm steps). This is illustrated in Fig. 6(i) and (ii) with the maximum recorded value minus the mean and minimum recorded value minus the mean for each frequency plotted versus frequency. The variation from the mean value is predominantly less than 2 dB which would suggest that the technique would have reasonable intersubject reproducibility.

III. DISCUSSION

This paper compares the amplitude of EEOAEs measured with a physically open system versus a sealed system in the ear canal. EEOAEs rather than AEOAEs were compared to avoid the confounding effect of different acoustical probe assemblies on the acoustical stimulus level. We have demonstrated that OAEs are largely unaltered by changing the acoustical load in the ear canal. One could infer from this finding that, in the guinea pig, the generation mechanism of OAEs is largely unaffected by changes in ear canal impedance.

In the past it has been assumed that a small-volume, well-sealed enclosure is necessary to record otoacoustic emissions (Matthews, 1983; Kemp *et al.*, 1990). Evidently this is not the case in guinea pigs. In this paper, distortion product, transient-evoked, and electrically evoked emissions have all been demonstrated for a system in which the external ear canal is only partially (perhaps 40%) obstructed by the microphone probe tube. The largest difference in emissions for an open system relative to a sealed system was about 7 dB at 1 kHz, reducing progressively to effectively no difference above 5 kHz. An open-field stimulus system permits the use of much wider-band stimuli and we have been able to show that this, in turn, results in wide-band emissions. A probe microphone placed in the ear canal of a guinea pig with a sound source placed near the entrance provides a superior alternative to the traditional acoustical probe assembly for the laboratory measurement of evoked OAEs in the guinea pig.

Recordings of OAEs to date have utilized a small volume, well-sealed enclosure. Perhaps the most commonly used system in this regard is the ILO88 and later versions. The ILO88 shows a greatly reduced OAE if the acoustical probe is not well sealed in the ear canal (Kemp *et al.*, 1990), but this may be due more to the reduction in the strength of the stimulus than to a direct effect on the emission. Also, a good acoustical probe seal is important in the clinical setting to reduce environmental noise which would otherwise confound recording of OAEs (Kemp *et al.*, 1990).

The significant advantage of a physically open recording system is the greater stimulus bandwidth obtainable when combined with an appropriate loudspeaker; we have recorded TEOAEs up to 20 kHz in the guinea pig, providing what we believe is the first published evidence of TEOAEs obtained as a result of stimulating the 10–20 kHz region of the basilar membrane in a mammalian species.

ACKNOWLEDGMENTS

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