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Research paper

Spontaneous otoacoustic emissions measured using an open ear-canal recording technique

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ABSTRACT

Spontaneous otoacoustic emissions (SOAEs) and synchronized spontaneous otoacoustic emissions (SSOAEs) were recorded using both the standard closed-canal method of recording and a novel open-canal method which involved suspending the probe at the entrance to the ear canal with no occluding tip. In both conditions, a probe tube microphone was inserted down the ear canal to measure the acoustic pressure near the tympanic membrane. Open- and closed-canal recordings were obtained in twelve otologically normal ears, all of which exhibited SSOAEs, and 6 of which exhibited SOAEs. The results were analysed to identify any differences in response to frequency and amplitude. The different recording conditions appeared to have no significant effect on SOAE or SSOAE frequency, suggesting little effect on the SOAE generator within the cochlea. Below about 2 kHz, the amplitude for both types of emission was less for the open-canal recording when compared to the closed-canal recordings. Above 2 kHz, SSOAE amplitudes were greater in the open- than the closed-canal condition. Model stimulations of the ear canal and middle-ear acoustics are presented which were in qualitative agreement with the results shown for the effects on emission amplitudes.

1. Introduction

Spontaneous otoacoustic emissions (SOAEs) are sounds that can be detected in the ear canal without an acoustic stimulus being presented. The sound pressure level (SPL) of SOAEs reported in the literature ranges from approximately +30 dB (Pasanen and McFadden, 2000) to −25 dB (re 20 daPa) (Schloth and Zwicker, 1983), though the lower bound may be limited by measurement noise floor. In most cases SOAEs have not been found in individuals with hearing thresholds of greater than 20 dB HL (Probst et al., 1987). SOAEs usually appear as narrow peaks in the frequency spectrum. In general, a bandwidth of a few hertz is optimal for recording (Probst et al., 1991). They have been shown to be repeatable and stable (Frick and Matthies, 1988), so multiple recordings should be obtained to ensure replicability and to distinguish any response from the noise floor. SOAEs normally span the frequency range of 500–7000 Hz, but vary greatly between ears. Reports in the literature vary on the percentage of the population that have detectable SOAEs, varying from 35 to 40% of otologically normal individuals in older literature (e.g., Bilger et al., 1990) to 72% in more recent studies (e.g., Penner et al., 1993; Talmadge and Tubis, 1993). This variation is likely to be due to improvements in experimental techniques which allow very low amplitude SOAEs to be detected, thus leading to a higher reported prevalence. These improvements have been in microphone design, experimental design, and signal processing algorithms. In particular, the narrower the bandwidth of the spectral estimation, the lower the noise floor. The reported level may also depend on the method of defining the amplitude of the spectral peak, particularly where the peak does not fall entirely within a single spectral band, but rather is spread across two or more bands.

SOAE presence has been linked to strong and robust transient evoked OAEs (TEOAEs) (e.g., Zwicker and Schloth, 1984; Morlet et al., 1995). However, because SOAEs are not detected in everyone with normal hearing, the absence of SOAEs does not indicate abnormal auditory function, which means SOAEs currently have limited clinical use. Current cochlear mechanical theories propose that SOAEs are generated by repeated reflections of

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Abbreviations: CEOAE, Click evoked otoacoustic emission; OAE, Otoacoustic emission; REM, real-ear measurement; SOAE, spontaneous otoacoustic emission; SPL, Sound pressure level; SSOAE, synchronized spontaneous otoacoustic emission; TEOAE, transient evoked otoacoustic emission; TM, tympanic membrane.

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a travelling wave back and forth between an apical reflection site on the basilar membrane and a basal reflection site. The apical site arises from random impedance inhomogeneities, while the basal site arises from the impedance mismatch at the cochlea–stapes interface. These two reflection sites will lead to an instability (and hence SOAEs) if, on completing its round-trip journey, the returning wave has been amplified by greater than a factor of unity (due to the cochlear amplifier), and if it has completed a whole number of cycles, such that it is in-phase with the initial travelling wave (Talmadge and Tubis, 1993; Zweig and Shera, 1995; Shera, 2003). At frequencies where these two conditions are satisfied, the cochlea is unstable, and any initially infinitesimally small travelling wave will continue to grow until non-linear compression reduces the round-trip amplification to unity. The resulting sustained travelling wave will appear as an SOAE in the ear canal.

SOAEs may be influenced by changes in the acoustic impedance of the middle- and outer ear in at least two different ways. First, any change in the impedance of the stapes looking out of the cochlea will affect the basal reflectance seen by the backward travelling wave, and thus may change the stability conditions. This could lead to a change in the number, the amplitude, or the frequency of the unstable travelling waves within the cochlea, and thus the corresponding SOAEs in the ear canal. Second, the transmission characteristics which couple the travelling wave to the measurement microphone in the ear canal may change. This would affect only the amplitude of the SOAE, rather than its existence, or its frequency (though changes in amplitude may affect its detectability, and thus its reported existence) (Shera and Zweig, 1991, 1993).

The effect on SOAEs of eliciting the acoustic reflex, and of changing the ear-canal pressure has been investigated by Schloth and Zwicker (1983). These manipulations may affect both the stapes impedance looking out, and the transmission characteristics between the cochlea and the measuring microphone. On eliciting the acoustic reflex, the authors reported an increase of SOAE frequency of up to 5 Hz (0.5%) and a reduction in amplitude of 10 dB in amplitude. On changing the ear-canal pressure by ±4 kPa, the SOAE frequency increased by up to 18 Hz (2%) and the amplitude reduced by up to 10 dB. Similar results have been reported by other authors (reviewed by Margolis and Trine, 1997), with changes in frequency of up to 50 Hz being reported. Changes in SOAE frequency suggest a change within the cochlea, possibly explained by the travelling wave reflection model, while changes in amplitude may be due to both the changes within the cochlea, and changes in the transmission energy out of the cochlea. In addition, any changes in the pressure at the stapes may change the hydrostatic pressure of the cochlear fluids, which could, conceivably, alter the cochlear mechanics.

Synchronous spontaneous otoacoustic emissions (SSOAEs) occur when SOAEs become synchronized to an evoking stimulus and cause TEOAEs to persist beyond their typical time window (Probst et al., 1986). To measure SSOAEs, a click train is presented to the ear and SOAEs which are time-locked to the click are then averaged. The click rate used to evoke SSOAEs is lower than that used to elicit TEOAEs (for example, 10 clicks per second). Additionally, a later part of the response waveform is analysed (typically 20–80 ms) when compared to conventionally measured clinical TEOAEs. SSOAEs, like conventional TEOAEs, are generally measured using an acoustic probe assembly comprising at least two transducers. Firstly there is a sensitive microphone to record the acoustic pressure in the ear canal and secondly an earphone that delivers the evoking stimulus to the ear. The probe assembly is usually hermetically sealed in the ear canal. This is generally done by fitting a compliant tip (which can be rubber, foam or plastic) of an appropriate size, on to the probe before it is inserted into the ear. Observed intensities of OAEs can be strongly affected by the quality of the coupling between sensor and ear canal (Kemp, 2003), because of the effect of the change in sound pressure level reaching the tympanic membrane. The ear-canal acoustics also affect the way an OAE is measured by the probe microphone. In clinical practice, it is often difficult to achieve an ideal fit when positioning the probe tip in the ear canal due to a wide variety of meatal configurations and limited time for testing (Kemp et al., 1990). SOAEs are usually measured with the same probe assembly hermetically sealed into the ear canal, but with no stimulus presented via the earphone.

Kemp, 1986, argued that using a probe that is sealed in the closed-ear canal (rather than one positioned in the concha and operating in “free-field”) has two advantages: first, the microphone is more strongly coupled to the eardrum, particularly below 3 kHz, and second, external noise is strongly attenuated, though this is not usually a problem if measurements are made in a sound-treated booth. However, Withnell et al. (1998) suggested that some benefits can arise from open-canal recording of OAEs, whereby an OAE probe is inserted into the ear canal without a compliant tip on the end, and thus without significantly occluding the ear canal. Two suggested benefits of open- over closed-canal recordings are first (for evoked OAEs) that the acoustic stimulus has a greater bandwidth, as the upper cut-off frequency is higher, and second that the acoustic load presented to the cochlea will be altered, thereby providing an alternative recording condition, which may provide additional information.

The arguments for these benefits are based on the acoustics of the ear canal, the electroacoustical properties of the ear-phone, and the theory of OAE generation mechanisms. Kemp (1978) acknowledges the fact that the acoustical load presented by the probe system may affect emissions themselves. The OAEs may also be affected by the acoustic reflection properties of the probe assembly (Zwicker, 1990 and Keefe, 1997). Standing waves are also a potential problem, especially at high frequencies (Keefe et al., 1993). This is because the enclosed air in the ear canal between the probe assembly and the tympanic membrane (TM) acts as a non-uniform acoustic transmission line and thus the impedance at the probe tip is not simply related to the TM impedance (Keefe et al., 1993). An open-canal recording system may partially ameliorate these difficulties. Therefore, the main potential benefits from performing open-canal recording of OAEs compared to more traditional closed-canal methods are that higher frequency OAE information may be obtained and that the OAEs recorded reflect the more natural characteristics of the emission and are unaltered by the effects of the probe, so therefore may help to provide a greater understanding of cochlear mechanics.

The current paper is concerned with open-canal recording of SOAEs and SSOAEs. The issue of the bandwidth of the evoking stimulus raised by Withnell et al. (1998) is not relevant to the recording of SOAEs, though it may be important for SSOAEs. The issue of coupling motion of the eardrum (arising from SOAEs) to the response measured at the microphone is however a problem. At low frequencies, a given volume velocity at the eardrum will produce a greater acoustic pressure at the entrance to an ear canal terminated by a high acoustic impedance than at the entrance to an open-ear canal, where the impedance is very low. One way to improve the coupling in the open-canal condition may be to use a probe microphone positioned near the eardrum. An acoustical analysis of this configuration is presented in Appendix. It should be noted however, that the amplitude of the OAE at the microphone is not the only consideration; the signal-to-noise ratio is at least as important. In the absence of external noise, physiological noise is radiated from the ear-canal walls, due to the subject breathing, their heart-beat, and movement. Closing the ear canal may affect the noise amplitude in a similar way that it affects the signal.