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Research paper

Nonlinear properties of otoacoustic emissions in normal and impaired hearing

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Abstract

Click-evoked otoacoustic emissions (CEOAEs) exhibit nonlinearities in amplitude and time domains. The first objective of this study was to investigate whether there is any correlation between the temporal and amplitude nonlinearities of CEOAEs in normals. Additionally there is evidence that pathology affects the normal cochlear nonlinearity. The second objective was to investigate whether pathology affects the temporal nonlinear components.

Conventional and maximum length sequence (MLS) CEOAEs were recorded in normal subjects and in patients with mild hearing loss. The slope of the input–output (I/O) function of the conventional CEOAE measured the amplitude nonlinearity. Two measures of temporal nonlinearity were the magnitude of the suppression that occurs with increase in stimulus rate and the amplitudes of the second and third order temporal interaction components (Volterra slices).

The amplitude nonlinearity is well correlated with both the magnitude of the rate suppression and the amplitudes of the Volterra slices. The 'linear' CEOAE amplitude showed no differences between the normal and patient groups but the differences in the Volterra slices were substantial. This suggests that the first sign of damage to the cochlea is that the system becomes more linear. Hence the Volterra slices may provide a sensitive measure of cochlear damage.

Keywords: Nonlinear systems; Maximum length sequences; Cochlear amplifier; Otoacoustic emissions; Volterra kernels; Cochlear pathology

1. Introduction

Otoacoustic emissions (OAEs) demonstrate several nonlinear phenomena. In the amplitude domain, the input–output (I/O) functions display nonlinear compressive characteristics (Kemp, 1979; Grandori et al., 1995). In the frequency domain, it is possible to demonstrate two-tone suppression (Kemp and Chum, 1980a; Brass and Kemp, 1993). Distortion product otoacoustic emissions (DPOAEs) provide a clear example of nonlinearity in the frequency domain (Kemp, 1979).

In the time domain, click-evoked OAEs (CEOAEs) show nonlinear interaction effects to pairs of clicks close in time (Kemp and Chum, 1980b; Kapadia and Lutman, 2000) and to trains of clicks (Hine and Thornton, 2002). A technique to record CEOAEs at high stimulus rates has been developed using a maximum length sequence (MLS) as the click stimulus (Thornton, 1993a,b; Picton et al., 1993; Thornton et al., 1994). With increasing stimulus rate, nonlinear interactions, referred to as rate suppression, have been reported (Hine and Thornton, 1997). Picton et al. (1993) suggested that the changes that occur with increase in MLS stimulus rate could be related to nonlinear processes in the cochlea that determine the amplitude I/O function. Kapadia and Lutman (2001) proposed a simple model comprising a static nonlinearity, representing the outer-hair cell nonlinearity, preceded by a bandpass filter, representing the ringing of a region of the basilar membrane. A prediction of this model is that the rate suppression would

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increase as the slope of the amplitude I/O function decreases. The first objective of this study was to test this prediction.

When MLS stimulation is used, it has been shown that nonlinear temporal interaction waveforms can be recorded in addition to MLS CEOAEs. (Thornton, 1997; Thornton et al., 2001; Slaven et al., 2003). The second objective of this study was to investigate whether there is any correlation between the amplitude of these nonlinear waveforms and the slope of the amplitude I/O function. The final objective was to examine the effect of hearing loss on these nonlinear waveforms.

2. Volterra slices

Using MLS stimulation it has been shown that nonlinear temporal interaction waveforms can be recorded (Thornton, 1997; Thornton et al., 2001). These nonlinear waveforms are referred to as Volterra slices and their properties, when recorded from normally-hearing subjects, have been described in detail (Slaven et al., 2003).

The MLS stimulation yields the full set of slices from this series of multidimensional functions. The Volterra slices are denoted as S_{ij} where i is the order of the Volterra kernel and j is the slice number. Thus S_{11} represents the first order waveform. There is only one slice for the first order and this is the MLS CEOAE waveform, which closely corresponds to the conventional CEOAE. The first slice of the second order kernel is one of the nonlinear interaction slices and is represented by S_{21}. The abbreviations S_2 and S_3 represent all the slices of the second and third orders, respectively.

3. Properties of MLS OAEs

This section summarises some of the previously measured data on how the properties of the first order (S_{11}) CEOAEs recorded using the MLS technique vary with stimulus rate. Fig. 1 shows, at the top, a conventionally recorded CEOAE obtained with regular stimulation at 40 clicks/s. Below that are MLS CEOAEs (S_{11}) recorded at rates from 100 to 5000 clicks/s. The maximum click rate, which is the reciprocal of the minimum inter-click interval, is used because this, unlike the average rate, is independent of the length of the MLS (Thornton et al., 2001). The MLS CEOAE waveforms are well correlated with the conventional, slow rate, CEOAE and it can be seen that the S_{11} waveform does indeed correspond to the conventional CEOAE. It can also be seen that the longer latency part of the CEOAE reduces in amplitude with increase in stimulus rate. In contrast, the short latency region of the CEOAE is much more robust.

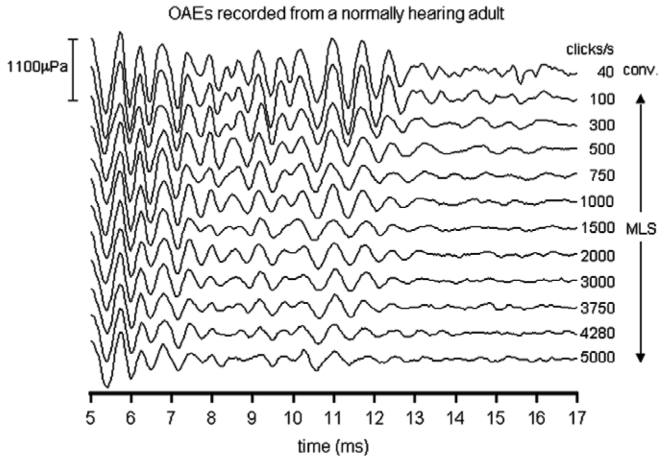

Fig. 1. Data from a normally-hearing subject. Conventional CEOAE recorded at 40 clicks/s (top trace) and MLS CEOAEs recorded at stimulus rates from 100 to 5000 clicks/s.

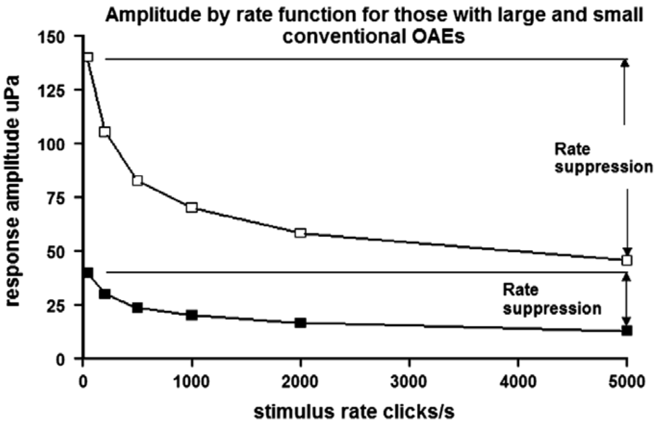

Fig. 2. The CEOAE amplitude in µPa is plotted by stimulus rate for two normally-hearing subjects. The rate suppression is defined as the difference in response amplitudes at 40 and 5000 clicks/s. The amount of rate suppression is approximately proportional to the CEOAE amplitude at 40 clicks/s.

Fig. 2 shows the root-mean-square (RMS) response amplitude, recorded from the 9–13 ms segment of the CEOAE, for two individuals. Both show the rate suppression seen in the waveforms of Fig. 1, but the individual with the larger CEOAE recorded at 40 clicks/s (CEOAE_{40}) shows much more rate suppression than the individual with the much smaller CEOAE_{40}. The correlation between the CEOAE_{40} amplitude and the amount of suppression for normally-hearing subjects is >0.99 (Hine and Thornton, 1997). Thus, the amount of suppression, measured in µPa, is approximately a constant proportion of the CEOAE_{40} amplitude. This implies that the rate suppression, expressed in dB (i.e., $20\log_{10}(\mathrm{CEOAE}_{40}/\mathrm{CEOAE}_{5000})$), is approximately constant across subjects. In fact the data reported here show a mean rate suppression of 9.5 dB with 95% confidence limits of 8.6–10.4 dB.

4. Methods and materials

One experiment, which obtained data on I/O functions and rate suppression, recorded MLS CEOAEs (S_{11}) from a group of normally-hearing subjects aged between 18 and 40 years. Subjects were screened and had to meet the following criteria.