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Research paper

An investigation into the relationship between input–output nonlinearities and rate-induced nonlinearities of click-evoked otoacoustic emissions recorded using maximum length sequences

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Abstract

The maximum length sequence (MLS) technique allows otoacoustic emissions (OAEs) to be recorded using clicks presented at very high presentation rates. It has previously been found that increasing the click presentation rate leads to increasing suppression (termed "rate-suppression") of the MLS evoked OAE (Hine, J.E., Thornton, A.R.D., 1997. Transient evoked otoacoustic emissions recorded using maximum length sequences as a function of stimulus rate and level. Ear Hear. 18, 121–128). It has been suggested that the source of rate-suppression arises from the same nonlinear processes that give rise to the well-known nonlinear growth of OAEs. Based on this assumption, a simple model of rate-suppression (Kapadia, S., Lutman, M.E., 2001. Static input–output nonlinearity as the source of nonlinear effects in maximum length sequence click-evoked OAEs. Br. J. Audiol. 35, 103–112) predicts that both input–output (I/O) nonlinearity and rate-suppression can be unified by characterising the stimulus in terms of its acoustic power which, at high rates, is proportional to the click presentation rate. The objective of this study was to test this simple model by recording MLS OAEs from a group of normally hearing adults over a range of stimulus rates from 40 to 5000 clicks/s, and of stimulus levels from 45 to 70 dB peSPL. The results are broadly in agreement with the predictions from the model, though there appears to be some tendency for the model to slightly overestimate the degree of rate-suppression for a given degree of I/O nonlinearity. It is also suggested that the model may break down more significantly in the presence of spontaneous OAEs.

Keywords: Otoacoustic emissions; Click evoked; Maximum length sequences; Rate-suppression

1. Introduction

Two nonlinear phenomena exhibited by otoacoustic emissions (OAEs) are the nonlinear growth of the rms amplitude of click-evoked OAEs (CEOAEs) with the increase in amplitude of the stimulus (e.g., Kemp, 1978), and the phenomenon termed here "rate-suppression" that is seen in OAEs obtained using the maximum length sequence (MLS) technique (e.g., Thornton, 1993a,b). Rate-suppression is the reduction in the amplitude of the OAE obtained by the MLS technique that occurs with an increase in the click presentation rate. In this paper, a simple

Abbreviations: ADC, analogue-to-digital converter; CEOAE, click-evoked otoacoustic emission; DAC, digital-to-analogue converter; IPL, input power level; I/O, input–output; K–L, Kapadia–Lutman; MLS, maximum length sequence; MLS OAE, deconvolved OAE response to MLS stimulation; OAE, otoacoustic emission; SOAE, spontaneous otoacoustic emission; SSOAE, synchronised spontaneous otoacoustic emission; TEOAE, transient-evoked otoacoustic emission

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theory connecting these two phenomena is presented and its predictions compared with measurements.

Kemp and Chum (1980) reported that the CEOAE rms amplitude, measured over the 5–20 ms window post-stimulus, grew approximately linearly for very low click levels (below about 10 dB SL). Above 10 dB SL, the CEOAE showed nonlinear growth, where the degree of nonlinearity can be quantified by the gradient in dB/dB of the plot of the CEOAE rms amplitude versus stimulus amplitude. This measure of nonlinearity will be termed here the input/output (I/O) slope, where a slope of 1 dB/dB represents linear growth, and 0 dB/dB complete saturation.

Kemp (1978) reported a typical value of the I/O slope of 0.33 dB/dB for the CEOAE over the 10–12.5-ms post-stimulus window. Since then, several authors have investigated the dependence of the I/O slope on stimulus level, and on the choice of time window over which the CEOAE amplitude is calculated.

Kemp and Chum (1980) reported an I/O slope of approximately 0.43 dB/dB, which remained roughly constant from 15 to 60 dB SL. In contrast, some authors have noted that I/O slope shows some tendency to reduce with increasing stimulus levels (e.g., Hine and Thornton, 1997), though this tendency varies depending on the individual ear and the range of stimulus levels.

Using tone-burst stimuli rather than clicks, Rutten (1980) found that the I/O slope reduced with an increase in the latency of the time window over which the rms amplitude of the OAE was evaluated. Rutten (1980) reported a typical variation in I/O slope from around 0.7 dB/dB at 10 ms latency to 0.33 dB/dB at 20 ms latency. A similar trend can be seen in CEOAE data presented by several authors (e.g., Tavartkiladze et al., 1997; Hine and Thornton, 1997; Hine et al., 2001).

The MLS technique has been used to record OAEs using click trains with interstimulus intervals that are much lower than the typical duration of CEOAEs (Thornton, 1993a; Picton et al., 1993). Rather than a direct recording of the OAE response, the MLS technique only yields an OAE waveform after deconvolution. Deconvolution derives a response on the assumption that each click in the click train evokes an identical response, and that these responses sum linearly to give the actual measured response. This deconvolved response is termed here the MLS OAE. Several authors have reported that MLS OAEs recorded at high click presentation rates are reduced in amplitude relative to CEOAEs recorded conventionally, and that this reduction becomes more pronounced as the click-presentation rate is increased (Thornton, 1993a, 1994; Picton et al., 1993; Thornton and Slaven, 1994; Hine and Thornton, 1997; Lina-Granade et al., 1997; Johannesen et al., 1998; Rassmussen et al., 1998). It is this reduction in amplitude (or "suppression") with increasing rate that is termed "rate-suppression" (Kapadia and Lutman, 2001). It should be noted that the term "rate-suppression" is simply used here to describe the nonlinear phenomenon seen in MLS OAE recordings, and should not be taken to imply that the cochlea is sensitive to MLS rate per se. Hine and Thornton (1997) found an average reduction in MLS OAE amplitude of around 9 dB at a mean click rate of 2500 clicks/s, relative to CEOAEs recorded conventionally at 40 clicks/s.

An initial suggestion that rate-suppression may arise from an ipsilateral efferent mechanism (Thornton, 1994) was contradicted by measurements of MLS OAEs from patients who had undergone unilateral vestibular nerve section (Hine et al., 1997). Picton et al. (1993) suggested that both rate-suppression and I/O nonlinearity may arise primarily from a superposition of the ringing responses on the basilar membrane due to the rapid rate of click presentation, combined with the compressive nonlinearities in the transduction mechanisms of the outer hair cells. Similar suggestions have been made regarding the nonlinear temporal interactions of pairs of clicks (Kemp and Chum, 1980; Tavartkiladze et al., 1994; Kapadia and Lutman, 2000a,b). To qualitatively explain these two-click nonlinear interactions, Kemp and Chum (1980) proposed a simple model comprising a bank of parallel frequency channels. Each channel comprised a linear bandpass filter followed by an instantaneous compressive nonlinearity. This model clearly gives a greatly simplified representation of the OAE generation mechanism. However, it captures some features of current theories of the OAE generation mechanism which may explain the phenomenon of rate-suppression: elements with prolonged impulse response functions (such as bandpass filters) followed by fast-acting nonlinear elements.

Kapadia and Lutman (2001) used such a two-element model to simulate MLS rate-suppression in a single channel, and achieved qualitatively realistic rate-suppression curves in which the degree of rate-suppression depends on the degree of I/O nonlinearity. Thus, such a model predicts that rate-suppression and I/O nonlinearity arise from a common nonlinear element. This model will be termed here the Kapadia–Lutman (K–L) model. In this model, the MLS OAE shows a nonlinear dependence on rate simply because increases in MLS rate lead to increases in the rms amplitude of the stimulus. This can be interpreted physiologically by noting that the rms amplitude of the vibration of a point on the basilar membrane will increase when either the MLS rate or the MLS click amplitude is increased.

Ryan and Kemp (1996) explored the relationship between rate-suppression and I/O nonlinearity by recording high-rate OAEs over a range of click amplitudes and presentation rates using click trains apparently similar to MLSs. In an attempt to unify I/O nonlinearity and rate-suppression, they presented the resulting OAE amplitudes as a function of input power level (IPL), defined as the rms power of the stimulus over the duration of the recording epoch. The rationale for this approach can be explained with reference to the K–L model. First it is assumed that the degree of nonlinearity observed depends on the rms amplitude of the basilar membrane vibration, which is given by a bandpass filtered version of the input. This vibration amplitude can most easily be increased by an increase in the click amplitude, thereby revealing I/O nonlinearity. However, it can also be increased by reducing the interstimulus intervals, provided the interval is less than the ring-down time of the linear filter element in the model (representing the tuned basilar membrane response). In fact, the rms amplitude of filter output is proportional to the rms amplitude of the acoustic input stimulus, assuming a constant shape of input signal power spectrum.

We can formally state these arguments as a hypothesis, termed here the input power hypothesis, which runs as follows. If the IPL is increased from some baseline level, then the degree of nonlinearity observed in the OAE (relative to this baseline condition) will depend on the increase in IPL, regardless of whether this is achieved by an increase in click amplitude (for conventional CEOAEs or MLS OAEs) or in click presentation rate (for MLS OAEs). On this hypothesis, rate-suppression is simply a manifestation of the underlying compressively nonlinear amplitude dependence of the cochlear amplifier.

As will be demonstrated in Section 3 below, one consequence of the input power hypothesis is that the rate-suppression of an MLS OAE in dB is proportional to the logarithm of the mean click presentation rate, and also proportional to $1 - m$, where m is the I/O slope in dB/dB. That the input level hypothesis holds true for the K–L model with an MLS input signal is confirmed by the simulations of rate-suppression given by Kapadia and Lutman (2001) in which the instantaneous compressive nonlinearity was implemented as a power law with a constant I/O slope of m dB/dB. Re-analyzing the results presented in their Fig. 6 reveals that the simulated rate-suppression in dB is in agreement with above predictions: it is approximately proportional to the logarithm of the mean click presentation rate, and to $1 - m$.

An anomalous point in their data at a rate of 250 clicks/s (their Fig. 6) illustrates a limitation of the hypothesis. It only holds when the shape of the power spectrum in the region of the passband of the linear filter is unchanged by changes in rate, as otherwise the input power to the nonlinearity element (which is the output power of the filter element) is no longer proportional to the input power to the linear filter. The spectrum of the MLS signal is not perfectly white, but rather contains additional spectral lines whose location is rate dependent, which thus complicates the interpretation at low rates.

Ryan and Kemp (1996) appear to present data that might be used to test the input power hypothesis. However, it appears that they used click trains that were either MLSs of very low order (orders 2 and 3) or that were not true MLSs (such as a train of 6 clicks). Furthermore they used a limited range of mean click presentation rates (50–300 clicks/s) which produce only small degrees of rate-suppression. Thus, a direct test of the input power hypothesis is not possible. The only relevant result they report is that the I/O slope was approximately 0.25 dB/dB, while at a constant click amplitude, rate-suppression increased with IPL at 0.5 dB/dB. This result is not consistent with the input power hypothesis which, given $m = 0.25$ dB/dB, would predict that the rate-suppression would increase with IPL at 0.75 dB/dB.

Hine et al. (2001) compared I/O functions for conventional CEOAE data at 40 clicks/s with those for MLS OAEs at a mean rate of 2500 clicks/s. Rather than using the click amplitude, these I/O functions were constructed on an abscissa of the sensation level of the click train, which more closely corresponds its input power level. However, the form of normalisation used does not allow the input power hypothesis to be tested directly.

The primary aim of the present study is to directly compare measured results with the input power hypothesis. MLS OAEs have been measured over a wide range of click amplitudes and mean click presentation rates (40–2000 clicks/s). Also, the effect of varying the I/O slope, m, is examined by considering portions of the response at two different latencies.

The input power hypothesis stated above can be extended to cover not just the rms amplitude of the OAE defined over a portion of the waveform, but also to each instantaneous point in waveform. The rationale for this arises from the finding that the general morphology of the OAE waveform is similar for MLS OAEs and CEOAEs from a given ear (Hine and Thornton, 1997), and that this morphology shows only a small variation with changes either in stimulus level or stimulus rate. Typically, the small changes in morphology that are observed with changes in stimulus IPL arise from the differences in the degree of suppression seen at short and long latencies, rather than from any shift in the location of the peaks or troughs in the waveform. This result is also consistent with predictions from the K–L model, where the OAE waveform shows suppression without any phase shift in the carrier wave (Kapadia and Lutman, 2001). Thus, a secondary aim of this study is to compare the entire waveforms of CEOAEs and MLS OAEs at equal IPLs, which, under this extended hypothesis, should appear similar.

2. Method

2.1. MLS

An MLS is a quasi-random binary sequence comprising $2^n - 1$ elements in total, of which 2^{n-1} equal -1, and $2^{n-1} - 1$ equal $+1$. The MLS is converted into a sequence of stimuli in which each element equalling -1 is converted into a click and each element equalling $+1$ is converted into a silence. Additional silences are then inserted between elements to achieve the required stimulus rate (i.e., click presentation rate) for a given DAC sample rate, which in this study is 30,000 samples/s. The parameter n is termed the order of the MLS. In this study, the order of the MLS is 12, thus giving a train of 2048 clicks and 2047 silences in each MLS epoch.

For any nonlinear system stimulated using MLS, the recovered deconvolved record is the same duration as the MLS excitation signal, and comprises a main response, termed here the "first-order kernel", occurring at the start of the record, together with a series of higher-order kernels arising from the nonlinearity in the system (Shi and Hecox, 1991; Thornton, 1997). The location of the higher-order kernels in the deconvolved record depends on the taps of the shift register used to generate the MLS (Davies, 1966). In order to prevent significant contamination of the first-order kernel by any of the higher-order kernels, both the order of the MLS, and the generative taps were carefully chosen. Note that the MLSs used here are far longer than those used by Ryan and Kemp (1996), where significant overlap between kernels was probable. Note also that Kapadia and Lutman (2001) used high-order MLS signals in their simulations, and considered only the first-order kernel. Thus, the experimental results presented here can be compared directly with predictions from the K–L model.

In specifying the click rate of an MLS, it is common for authors to quote the maximum click presentation rate, defined as the reciprocal of the minimum interclick interval in the MLS click train (e.g., Hine and Thornton, 1997) rather than the mean rate. This is because the maximum rate is independent of the order of the MLS, for a given rate of presentation of the MLS elements. However, since the IPL depends on the mean rather than the maximum rate, the mean rate will be quoted in the present paper. The ratio of the mean to the maximum rate is approximately one half, but its exact value depends on the length of the MLS used.

2.2. Subjects

Eighteen ears (10 female, 8 male) from 12 normally hearing volunteers aged 21–37 years were included in the study. Both ears were tested in six subjects. In the remaining six subjects, only one ear was tested either due to failure to meet the inclusion criteria, or to limitations of time. Ears were balanced for side (9 right, 9 left). For inclusion in the study, ears had to show no abnormality or wax occlusion on otoscopy, and to be within normal limits for tympanometry (middle-ear pressure range −100 to +50 daPa, middle-ear compliance range 0.3–1.5 ml) and pure-tone audiometry (hearing threshold level $\leqslant$20 dB at 0.25, 0.5, 1, 2, 4 and 8 kHz). Subjects were seated comfortably in a sound-treated booth, asked to remain as still as possible, and asked to swallow as infrequently as was comfortable during recording.

All the experiments were performed in accordance with the guidelines of the declaration of Helsinki, and were approved by the Southampton and South West Hants Local Research Ethics Committee.

2.3. Equipment

CEOAE and MLS OAE recordings were made using an in-house system comprising a PC containing a DSP board connected via a fibre–optic link to a remote converter module. This was connected to an Otodynamics general purpose transient evoked OAE probe (SGS-type). The remote converter module comprised a 24-bit DAC, an attenuator, a 24-bit ADC, and a sample rate generator. The ADC used a delta–sigma converter employing 256-times oversampling, thus obviating the need for antialiasing filters. The digital output signal was generated in the DSP with a sample rate of 30 kHz by converting each stimulus element of the chosen MLS into a rectangular pulse three samples wide, thus giving electrical click pulses of 90 μs duration. The output signal was played out under the timing of the sample rate generator and delivered to the probe earphone while the probe microphone signal was acquired synchronously by the ADC. To improve the signal-to-noise ratio through synchronous averaging, a number of MLS epochs were presented contiguously. To eliminate starting transients, the first MLS was preceded by the last 30 ms of one MLS. The recorded microphone signal was deconvolved "on-the-fly" (Thornton et al., 1994) allowing artefact rejection and signal averaging to be performed in real-time on the section of the deconvolved record of interest.

The probe microphone was calibrated at 1 kHz by sealing it into the half-inch adaptor in the top of a Bruel and Kjaer Type 4230 sound level calibrator. The earphone click level was calibrated with the probe inserted into a 2 cc reference cavity, by measuring the peak-to-peak acoustic pressure using the probe microphone.

2.4. Stimuli and procedures

2.4.1. Conventional CEOAEs and MLS OAEs

MLS OAEs were recorded at five mean stimulus rates: 100, 250, 500, 1000, and 2501 clicks/s, while conventional CEOAEs were recorded at 40 clicks/s, thus giving six rate conditions in total. For each rate, six different stimulus peak levels were used: 45–70 dB peSPL in 5 dB steps, giving a total of 36 different stimulus conditions. Two replicates were recorded consecutively in each condition.

The order of presentation of the 36 conditions was as follows. Recording began at the highest stimulus peak level (i.e., 70 dB peSPL), and the six rate conditions were completed at this level. In order to minimize possible order effects, the order of presentation of the six rate conditions was randomized across ears according to a six-by-six Latin-square carry over design. The stimulus peak level was then reduced by 5 dB, and the six rate conditions repeated. This pattern was repeated, reducing the stimulus level by 5 dB each time until all 36 conditions had been recorded.

In each recording condition, initially a pre-defined minimum number of epochs were acquired. Thereafter, averaging was continued until either the OAE signal quality, as measured by the F_{SP} criterion (Elberling and Don, 1984; Lutman and Shephard, 1990), exceeded 20, or until a pre-defined maximum number of epochs had been presented. The pre-defined minimum and maximum numbers of epochs depended on the click rate. Recording typically lasted for 60–120 s in each condition, and took approximately 1 h and 20 min to complete both replicates of all 36 conditions.

Pilot studies had suggested that the F_{SP} is an unreliable quality estimator when only a small number of epochs was acquired. Since the available recording time in each condition was limited, this became an important consideration in those MLS conditions at low rates, where the duration of each epoch was long. For example, when using the MLS of order 12 at 100 clicks/s mean rate, each epoch comprised 2048 clicks and lasted 20.48 s. Therefore, in the subsequent data analysis, the replicate waveform cross-correlation was used as the quality estimator, instead of the F_{SP}. However, due to software restrictions, the replicate cross-correlation was unavailable as a stopping criterion, and thus, despite its unreliability, the F_{SP} criterion was still used as one of the stopping criteria during MLS recordings. The choice of relatively high values for both the minimum number of acquired epochs and the F_{SP} stopping criterion ensured an acceptable compromise between the acquisition time and the quality of the recordings.

2.4.2. Spontaneous OAEs (SOAEs)

Some authors have suggested there may be complex influences of SOAEs on CEOAEs, which might lead to marked differences between the nonlinear behaviour of ears with strong SOAEs and that of ears without any SOAEs (e.g., Zwicker, 1983; Probst et al., 1986; Gobsch and Tietze, 1993; Tavartkiladze et al., 1997; Kulawiec and Orlando, 1995; Kapadia and Lutman, 2000b). It has also been reported that noise-evoked OAEs appear to differ from conventional click-evoked OAEs where strong SOAEs are evident (Maat et al., 2000; Harte and Elliott, 2005). Therefore, the decision was made prior to the experimental phase to exclude ears with detectable SOAEs from the analysis.

To record any SOAEs present, the microphone signal in the absence of any stimulus was recorded without signal averaging, for off-line processing. For each ear, four recordings were made in total, two before and two after the recordings of the evoked OAEs. Each recording lasted 7.4 s.

3. Analysis of results

3.1. Input power level

The input power level (IPL) is defined here in terms of the rms amplitude of the acoustical input, calculated over a 25 ms time window. The duration of the time window is not critical to the analysis, and was chosen for convenience to correspond to the reciprocal of the lowest click presentation rate (i.e., 40 clicks/s). The IPL is proportional to the number of clicks occurring within the 25 ms window.

For convenience, the IPL is calculated relative to the baseline condition defined as that with a click presentation rate of 40 clicks/s, and a peak level of 45 dB peSPL. This gives the IPL, in dB re baseline, as

$$\mathrm{IPL} = 10\log_{10}\left(\frac{p^2_{\mathrm{pk-pk}}R}{p^2_{\mathrm{pk-pk0}}R_0}\right) \tag{1}$$

where $p_{\mathrm{pk-pk}}$ is the peak-to-peak amplitude of the click in Pa, R is the mean click presentation rate in clicks/s, and $p_{\mathrm{pk-pk0}}$ and R_0 are the peak-to-peak amplitude and mean presentation rate respectively in the baseline condition. Eq. (1) becomes

$$\mathrm{IPL} = L_{\text{click-pe}} - 45 + 10\log_{10}(R/40) \tag{2}$$

where $L_{\text{click-pe}}$ is the peak-equivalent sound pressure level of the click stimulus measured in the 2 cc reference coupler. The peak-equivalent sound pressure level of the click stimulus is (from its definition) given by

$$L_{\text{click-pe}} = 20\log_{10}\{p_{\mathrm{pk-pk}}/(2\sqrt{2})\} \tag{3}$$

where factor of $2\sqrt{2}$ is included because the peak-equivalent sound pressure level is defined in terms of the rms amplitude of an equivalent sine wave.

3.2. OAE response per unit click

The usual way in which CEOAEs and MLS OAEs are presented does not facilitate the direct comparison of I/O nonlinearity with rate-suppression. This is because while I/O nonlinearity appears as a less-than-linear growth, rate-suppression appears as an apparent reduction in the MLS OAE (i.e., deconvolved) response amplitude, despite the fact that the total energy in the raw (undeconvolved) response may well have increased.

In order to overcome this, the OAE response per *unit* click is defined here for both CEOAEs and MLS OAEs. For a linear system, this response would be independent of the input, while for a compressively nonlinear system this response will reduce with increases in the input power level. The OAE response per unit click, $y_{\mathrm{OAE}}(t)$, is defined by

$$y_{\mathrm{OAE}}(t) \equiv \frac{p_{\mathrm{OAE}}(t)}{p_{\mathrm{pk-pk}}} \times 2\sqrt{2} \tag{4}$$

where $p_{\mathrm{OAE}}(t)$ is the instantaneous OAE pressure in μPa (either the CEOAE recording in conventional recordings, or MLS OAE deconvolved response for MLS recordings), and $p_{\mathrm{pk-pk}}$ is the peak-to-peak amplitude of the click, as measured in the 2 cc cavity. The factor of $2\sqrt{2}$ is included for compatibility with the definition of peak-equivalent sound pressure level in Eq. (3).

The nonlinear system described by Kapadia and Lutman (2001) for which the nonlinearity is characterised by the parameter m (the I/O slope in dB/dB), shows a gradient of $m - 1$ when the rms amplitude of y_{OAE} is converted to dB and plotted against IPL, both when IPL increases due to increases in click amplitude (i.e., I/O nonlinearity) and when IPL increases due to increases in click presentation rate (i.e., rate-suppression).

3.3. RMS amplitude of CEOAE and MLS OAE responses

In order to examine the effect of different I/O slopes, the OAE rms amplitude in two different time windows was calculated: 6–9 ms, and 9–13 ms post-stimulus. An unbiased estimate of the rms amplitude was obtained from the two replicates in each condition using

$$\langle p_{\mathrm{OAE}}^2\rangle = \frac{1}{\Delta T}\int_{T_1}^{T_2}\left[\frac{A(t)+B(t)}{2}\right]^2 \mathrm{d}t - \frac{1}{\Delta T}\int_{T_1}^{T_2}\left[\frac{A(t)-B(t)}{2}\right]^2 \mathrm{d}t,$$
$$\Delta T \equiv T_2 - T_1 \tag{5}$$

where $\langle p_{\mathrm{OAE}}^2\rangle$ is the mean-square amplitude of the OAE in μPa, $A(t)$ and $B(t)$ are the two replicate response waveforms, and T_1 and T_2 are the start and end times of the window. The OAE rms amplitude per unit click, expressed in decibels, is then calculated from

$$L_{\mathrm{OAE/click}} \equiv 20\log_{10}\sqrt{\langle p_{\mathrm{OAE}}^2\rangle} - L_{\text{click-pe}} \tag{6}$$

3.4. Predictions of the input-power hypothesis

The input power hypothesis states that, regardless of the form of the input signal, the nonlinearity in the OAE arises from compressive growth of the form:

$$\frac{p_{\mathrm{OUT}}}{p_{\mathrm{OUT0}}} = \left(\frac{p_{\mathrm{IN}}}{p_{\mathrm{IN0}}}\right)^m \tag{7}$$

where p_{IN} and p_{OUT} are the stimulus input and OAE output rms pressures, respectively; m is the slope of the I/O curve; and the subscripts ending in "0" denote the baseline conditions. Note that p_{OUT} here refers to the raw, undeconvolved OAE output. In order to allow a direct comparison of the rate-suppression of MLS OAEs with CEOAE I/O nonlinearity, it is convenient to normalise Eq. (7) to give the output per unit input:

$$\left(\frac{p_{\mathrm{OUT}}}{p_{\mathrm{IN}}}\right)\Big/\left(\frac{p_{\mathrm{OUT0}}}{p_{\mathrm{IN0}}}\right) = \left(\frac{p_{\mathrm{IN0}}}{p_{\mathrm{IN}}}\right)\left(\frac{p_{\mathrm{IN}}}{p_{\mathrm{IN0}}}\right)^m = \left(\frac{p_{\mathrm{IN}}}{p_{\mathrm{IN0}}}\right)^{m-1} \tag{8}$$

As in Eq. (1), for both conventional click trains and MLS stimuli, the input rms pressure is given by

$$\left(\frac{p_{\mathrm{IN}}}{p_{\mathrm{IN0}}}\right) = \left(\frac{p_{\text{pk–pk}}\sqrt{R}}{p_{\text{pk–pk0}}\sqrt{R_0}}\right) \tag{9}$$

where the symbols on the right-hand side have the same meanings as in Eq. (1). For conventional CEOAEs, p_{OUT} is simply the rms amplitude of the OAE given in Eq. (5). However, for MLS OAEs, the rms amplitude of the OAE given in Eq. (5) refers to the deconvolved response, which is the derived response for a single click, assuming linear superposition. The normalisation in Eq. (8) ensures that for both CEOAEs and MLS OAEs, the left-hand side of Eq. (8) is given by

$$\left(\frac{p_{\mathrm{OUT}}}{p_{\mathrm{IN}}}\right)\Big/\left(\frac{p_{\mathrm{OUT0}}}{p_{\mathrm{IN0}}}\right) = \left(\frac{\sqrt{\langle p_{\mathrm{OAE}}^2\rangle}}{p_{\text{pk–pk}}}\right)\Big/\left(\frac{\sqrt{\langle p_{\mathrm{OAE0}}^2\rangle}}{p_{\text{pk–pk0}}}\right) \tag{10}$$

where p_{OAE} has the same meaning as in Eq. (5). Note that the rate R does not appear in Eq. (10), despite its appearance in Eq. (9), because in the case of MLS OAEs the deconvolution yields the response for single click. Combining Eqs. (7), (9) and (10), gives the prediction from the input power hypothesis that

$$\frac{\sqrt{\langle p_{\mathrm{OAE}}^2\rangle}}{\sqrt{\langle p_{\mathrm{OAE0}}^2\rangle}} = \left(\frac{p_{\text{pk–pk}}\sqrt{R}}{p_{\text{pk–pk0}}\sqrt{R_0}}\right)^{m-1} \tag{11}$$

Converting Eq. (11) into decibels, and using the definition of OAE rms amplitude per unit click in Eq. (6) gives, after re-arrangement:

$$\begin{aligned} L_{\mathrm{OAE/click}} - L_{\mathrm{OAE/click0}} &= (m-1)(L_{\text{click-pe}} - L_{\text{click-pe0}}) \\ &= (m-1)(\mathrm{IPL} - \mathrm{IPL}_0) \end{aligned} \tag{12}$$

where IPL is given in Eqs. (1) and (2). Thus, for $m < 1$, the OAE response per unit click reduces with increasing IPL.

Under the input power hypothesis, Eq. (12) holds both for conventional CEOAEs and for MLS OAEs under changes in IPL, whether these occur due to changes in click level or in click presentation rate. Eq. (12) is used in the analysis to provide two estimates of the degree of nonlinearity, m: the first from changes in conventional CEOAEs under changes in click level, and the second from changes in MLS OAEs under changes in mean rate, R.

3.5. Averaging across ears

$L_{\mathrm{OAE/click}}$ was averaged across ears for each condition. Since both ears were measured for six of the 12 subjects, not all of the 18 data points for one condition were statistically independent. Thus, where independence was required, as in hypothesis testing, averaging was performed over left and right ears separately. However, where the intention was only to indicate average trends, independence is not required and averaging has been performed across all ears. Prior to averaging, some ears were excluded from the average as described in Section 3.6.

3.6. Excluded data

Two exclusion criteria were set *a priori*: the presence of detectable SOAEs, as defined in Section 3.7, and poor signal quality, as estimated by the replicate cross-correlation. The SOAE criterion led to three ears (two left, one right) being excluded.

An OAE response which did not have a replicate whole waveform cross-correlation of 50% or better across the relevant time window was deemed "unsatisfactory". An ear showing one or more unsatisfactory responses in any of the conditions that were required for a particular analysis

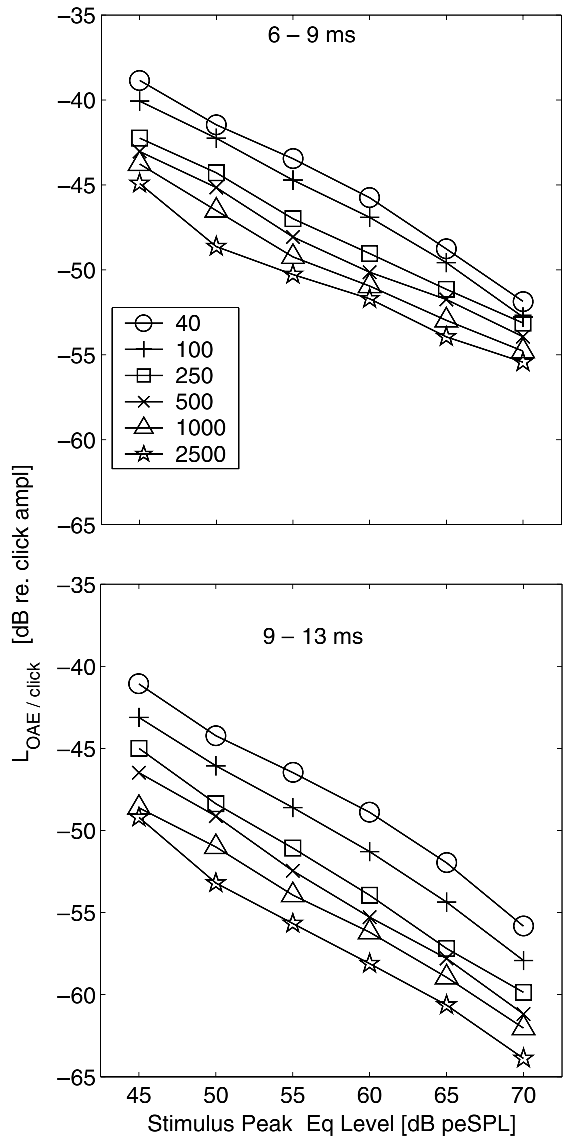

Fig. 1. I/O nonlinearity at constant click presentation rates, averaged over 13 ears for the 6–9 ms window (upper panel) and 9–13 ms window (lower panel). The OAE rms amplitude is expressed relative to the click amplitude. The legend refers to the mean click rate. The 40 clicks/s condition refers to a conventional click train (i.e., constant interclick intervals), while the five higher rates refer to MLS click trains.

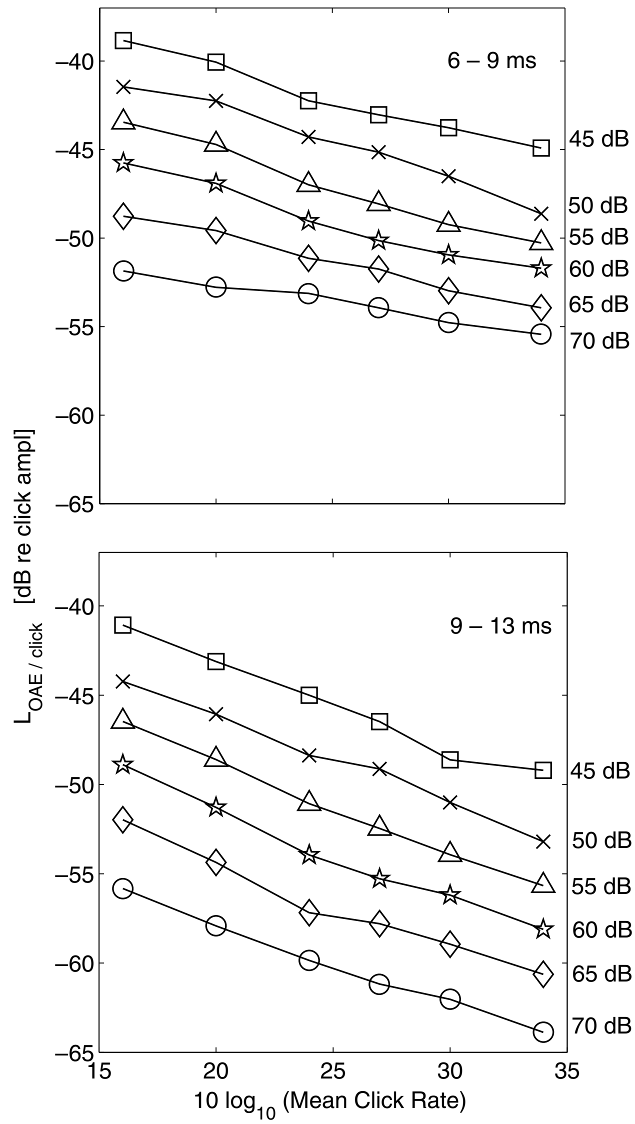

Fig. 2. Rate-suppression at constant click amplitudes, averaged over 13 ears for the 6–9 ms window (upper panel) and 9–13 ms window (lower panel). The OAE rms amplitude is expressed relative to the click amplitude. The legend refers to the peak equivalent level of the click.

was excluded altogether. This led to two ears being excluded where all 36 conditions were considered together (Figs. 1–3). Where only 24 of the conditions were used in an analysis (Fig. 5, Table 1), no ears were excluded on the signal quality criterion.

3.7. Presence of SOAEs

For each ear, each of the four non-stimulus ear canal recordings was split into 37 contiguous segments of 200-ms duration, noisy segments rejected, and the power spectrum calculated by Welch's method of segment averaging, thus giving a 5-Hz spectral resolution. The power spectra from the first and second recordings were then averaged together to give the power spectrum (termed here the pre-session power spectrum) prior to the CEOAE recording. Similarly the post-session power spectrum was defined as the average of the third and fourth recordings. SOAEs were defined as narrow spectral lines (10-Hz bandwidth or less) that exceeded the neighbouring background level by at least 5 dB in the average power spectrum in both the pre- and post-session power spectrum.

Three of the 18 ears were identified as having detectable SOAEs, and were excluded from the across-ear averages of OAE amplitudes. This surprisingly low prevalence of SOAEs (see, for example, Probst et al., 1991) was matched

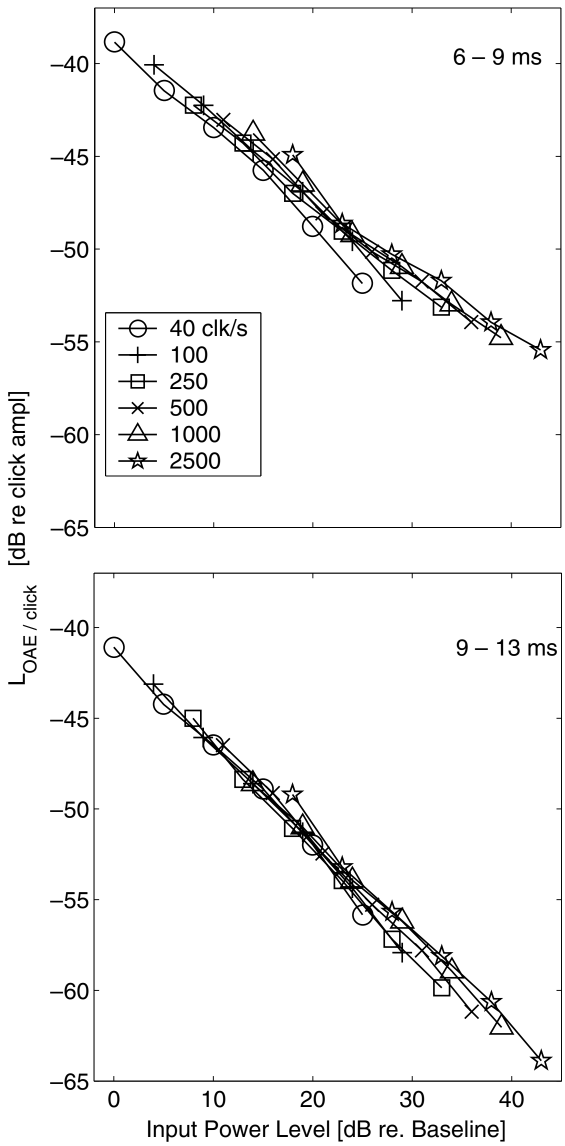

Fig. 3. Suppression as a function of IPL along lines of constant click rate, averaged over 13 ears for the 6–9 ms window (upper panel) and 9–13 ms window (lower panel). The OAE rms amplitude is expressed relative to the click amplitude. The legend refers to the mean click rate. The 40 clicks/s condition refers to a conventional click train (i.e., constant interclick intervals), while the five higher rates refer to MLS click trains.

Table 1
Estimates of the degree of nonlinearity, m, from the regression lines in Fig. 5

Ear	Time window (ms)	m	
		I/O nonlinearity	Rate-suppression
Left	6–9	0.50	0.62
	9–13	0.44	0.55
Right	6–9	0.47	0.68
	9–13	0.42	0.52

by a lower-than-expected amplitude of CEOAEs suggesting that, by chance, the sample had particularly weak CEOAEs and SOAEs.

4. Results and discussion

Compressive I/O nonlinearity shows itself in the ear-averaged data in Fig. 1 as a downward slope of $L_{\mathrm{OAE/click}}$ versus click amplitude, along lines of constant click rate. In the 9–13 ms window, the data show an approximately linear trend, with little variation of slope with rate. The 6–9 ms data are similar, though there appears to be some variation of slope with click rate. Notwithstanding this slight variation, the simplifying assumption made in the K–L model, that the slope, $m - 1$, is independent of click level and rate, appears to be a reasonable one for the measured data. The data vary somewhat from those presented by Hine and Thornton (1997), where a greater variation in the degree of nonlinearity with both level and rate is seen. One difference between the sample in this study and that in Hine and Thornton is the exclusion of ears showing strong SOAEs, but it is unknown whether this could account for the differences reported.

Rate-suppression is seen in Fig. 2, in which the same data as in Fig. 1 are plotted, but as functions of mean click rate along lines of constant click amplitude. Approximately in accordance with the input power hypothesis, $L_{\mathrm{OAE/click}}$ decreases linearly with the logarithm of the mean click rate. A further prediction from the hypothesis is that when plotted against IPL, the $L_{\mathrm{OAE/click}}$ will collapse onto a single line, irrespective of whether IPL is increased through click amplitude or click rate, provided that the typical inter-click intervals are significantly shorter than the ring-down time (or "memory") of the bandpass filter element.

Recent simulations from the K–L model suggest that suppression versus rate function obeys the input-power hypothesis provided the rate is high enough that the mean interstimulus interval is less than the filter ring-down time (Cooper, 2006). The filter ring-down time can be estimated from previous experimental studies of two-click interactions, which reported that a single preceding suppressor click starts to noticeably influence the amplitude of the CEOAE evoked by a subsequent click when the two clicks are separated by less than around 10–12 ms (Kemp and Chum, 1980; Kapadia and Lutman, 2000b). Assuming the K–L model, and taking the ring-down time to be 12 ms leads to the prediction that some degree of rate-suppression should start to become apparent with MLS stimulation once the mean click rate exceeded around 40 clicks/s (giving a *minimum* interstimulus interval of 12.5 ms) but that the input-power hypothesis would not fully apply until the mean click rate exceeds around 80 clicks/s (giving a *mean* interstimulus interval of 12.5 ms). Thus, for rates at and above 80 clicks/s, the suppression versus rate function is expected to be a straight line (as is approximately seen in Fig. 2), and to obey the input-power hypothesis.

In Fig. 3, the measured data do not collapse precisely onto a single line, but do cluster closely around it. The 9–13 ms data appear to follow the model predictions more closely than do the 6–9 ms data, where there is a systematic tendency for the data at high rates to show less nonlinearity than would be predicted based on their IPL. Fig. 4, which presents data for the 9–13 ms window from six individual ears typical of the sample, indicates that the trends for the mean data are also seen in each individual ear.

The degree of nonlinearity was quantified by fitting a straight line to the data for both I/O nonlinearity and rate-suppression over similar regions of the IPL, as shown in Fig. 5. The data for the baseline point itself has been excluded from the regression lines for characterising both I/O nonlinearity and rate-suppression. This was to ensure that no two regression lines shared the same data point, and thus that all the regression lines were independent of each other. It also ensures that the fit to the rate-suppression data is at a high enough rate for the input-power hypothesis to apply. Left and right ears were analysed separately to ensure independence of sample points.

From the straight-line fits in Fig. 5, four values of $m - 1$, and hence, m, have been estimated for left and right ears, and are presented in Table 1.

In agreement with previously reported findings (e.g., Rutten, 1980), I/O nonlinearity increases with the latency of the time-window. In accordance with the model predictions, rate-suppression shows the same trend of an increasing degree of nonlinearity with increasing latency. However, there are slight deviations from the predictions as the degree of nonlinearity for a given time window differs slightly in I/O nonlinearity from that seen in rate-suppression. For both time-windows, the value of m obtained from the rate-suppression data is less than that from the I/O data (Table 1). The statistical significance of this difference was calculated using paired t tests for the 6–9 ms window and 9–13 ms window, with left and right ears tested

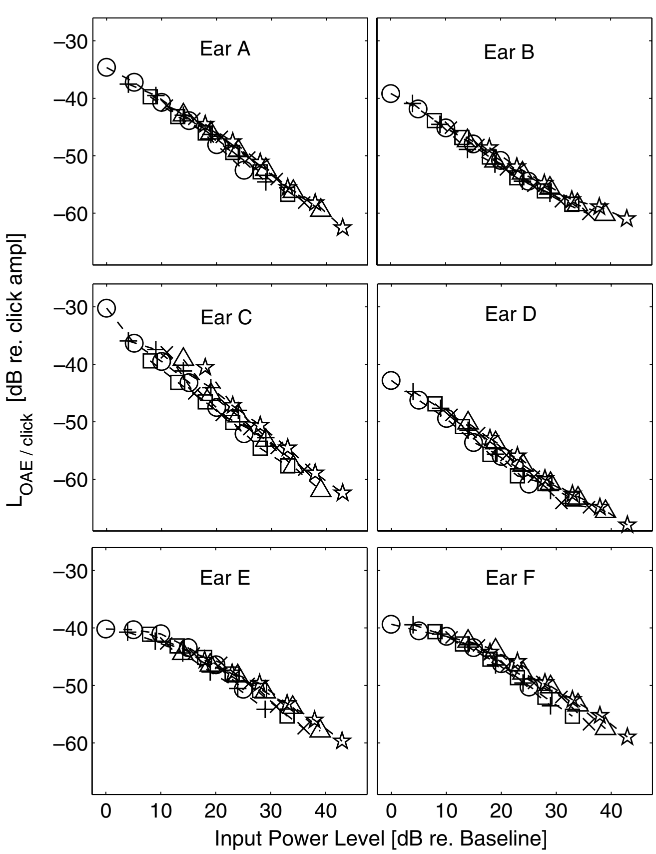

Fig. 4. Suppression as a function of IPL along lines of constant click rate for six typical ears for the 9–13 ms window. The OAE rms amplitude is expressed relative to the click amplitude. The legend refers to the mean click rate. The 40 clicks/s condition refers to a conventional click train (i.e., constant interclick intervals), while the five higher rates refer to MLS click trains.

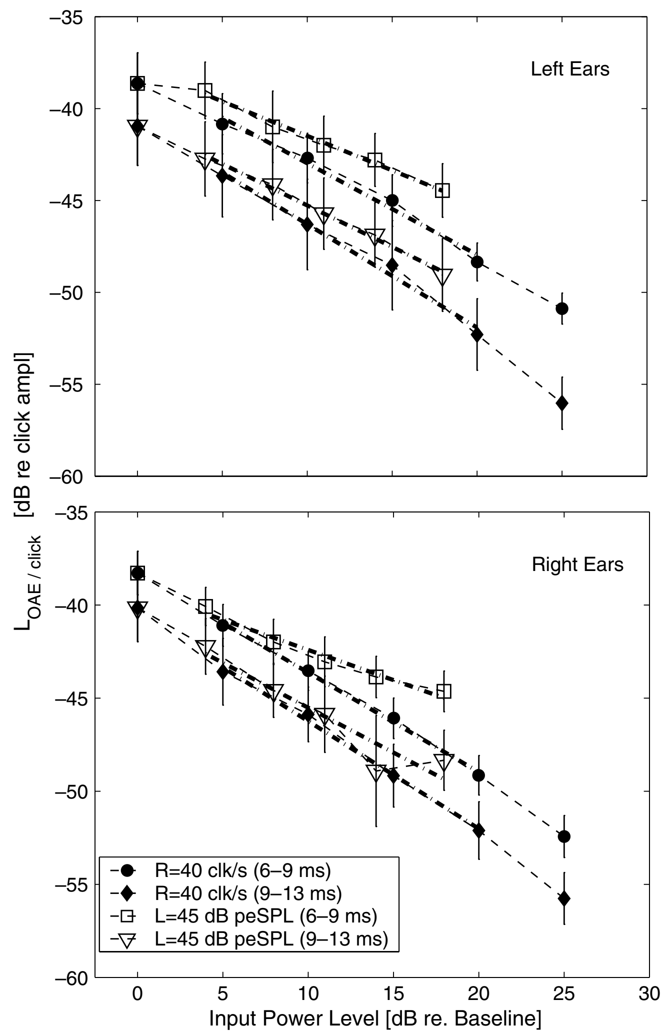

Fig. 5. Linear regression lines of OAE amplitude on IPL for the data averaged over seven left ears (upper panel) and eight right ears (lower panel). For each panel, four regression lines (thick chain) are computed over a range of IPL of approximately 15 dB. For the 6–9 ms data, regression lines are calculated for increasing click amplitude at a constant click rate of 40 clicks/s (filled circles) and for increasing rate at a constant click amplitude (open squares). Similarly, for the 9–13 ms data, the regression line is shown for increasing click amplitude at a constant click rate of 40 clicks/s (filled diamonds) and for increasing rate at a constant click amplitude (open triangles). Error bars indicate one standard error of the mean.

separately in order to avoid correlations between sample points when the left and right ears were from the same subject. For the 6–9 ms window, the difference was significant at the 5% level for both left ears (df = 6) and right ears (df = 7). For the 9–13 ms window, the difference was significant for left ears, but not for right ears.

Despite this tendency for the input power hypothesis to somewhat overestimate the rate-suppression that will occur for a given I/O nonlinearity, the degree of overestimation is far lower than that reported by Ryan and Kemp (1996). The cause of the small overestimation is unknown, but could arise from a number of the simplifications present in the K–L model that underpin the input power hypothesis. Note, for example, that the intermediate variable in the K–L model (the output from the linear filter, which is the input to the static nonlinearity) has no direct physiological correlate. The pattern of vibration of basilar membrane due to an acoustic stimulus is thought to be influenced by the arrayed outer-hair cells which, through positive feedback, interact nonlinearly with each other, leading to complex level dependencies in both the shape and speed of propagation of the travelling wave (Patuzzi, 1996). Thus, this pattern of vibration cannot simply be predicted, even approximately, from a simple two-element model. Multiple reflections within the cochlea (Talmadge and Tubis, 1993) may further complicate this vibration pattern.

The dependence of the degree of nonlinearity, m, on the latency of the analysis window is seen both in rate-suppression and I/O nonlinearity. Note also that there are several possible mechanisms for this dependence. It is speculated here that at least four mechanisms may be important: First, the degree of nonlinearity may be frequency dependent and thus also latency dependent. Second, there may be nonlinear temporal interactions between components such that later components are suppressed by earlier ones. Third, longer latencies contain more energy from multiple-reflection components, which become increasingly nonlinear with each additional nonlinear reflection (see, for example, the terms in the reflection coefficient in the power series expansion given by Shera and Zweig, 1993). Finally, increases in level are known to lead to a reduction in latency and thus a net shift in energy from longer to shorter latencies, giving the appearance of enhanced nonlinearity in a fixed long latency window, and reduced nonlinearity in a fixed short latency window (Neely et al., 1988; Norton and Neely, 1987). Whatever mechanisms are responsible for the dependence of m on latency, it appears that a similar dependence is seen whether m is derived from increases in rate or increases in level, as predicted by the input-power hypothesis.

One possible reason why the input-power hypothesis not hold perfectly for MLS stimulation is that the spectrum of the MLS stimulus is not entirely uniform with frequency, but instead comprises a uniform spectrum plus additional spikes situated at a frequency equal to the maximum click rate. Note that this is true for the variant of MLS used in this study in which each "−1 element" in the sequence elicits a single brief unipolar click. The properties of this variant of MLS are discussed and compared to other MLS-variants by Shi and Hecox (1991). A consequence of this is that an increase in rate not only increases the uniform level of the spectrum, but also cause a shift in some of the stimulus energy to higher frequencies. Since the generation of the OAE is sensitive to the frequency of the stimulation, this may influence the amplitude of the resulting OAE.

As well as comparing the OAE rms amplitudes, the entire OAE waveforms were compared. On the input power hypothesis, the entire OAE waveforms should appear similar when obtained at equal IPL, and when the response is expressed per unit click, as obtained by Eq. (4). From Eq. (3), we see that an increase in mean click rate from 40 to 2500 clicks/s causes an increase in IPL of 17.96 dB assuming a time-window of 25 ms as before. To compare the effect of a stimulus level increase with a rate increase giving a similar change in IPL, the OAE waveform at $R = 40$ clicks/s; $L = 70$ dB peSPL was compared with that at $R = 2500$ clicks/s; $L = 55$ dB peSPL. This comparison is shown in Fig. 6, where the waveforms of the OAE response per unit click for the two conditions are overlaid for six typical ears (ears A–F) without SOAEs and for one ear (ear Q) with strong SOAEs. For the six ears (A–F) without SOAEs, waveforms at similar IPLs closely resemble each other across the 5–20 ms window in agreement with the input power hypothesis. However, in the ear with a strong SOAE, a corresponding synchronised SOAE (SSOAE) is clearly seen in the conventional CEOAE, but is absent from the MLS OAE, contradicting the hypothesis and suggesting that the model breaks down in the presence of SOAEs.

Instead of using MLS stimuli, some authors have also recorded OAEs using Gaussian white noise evoking stimuli, combined with signal processing techniques that recover an estimate of the click-evoked response (Maat et al., 2000; Harte and Elliott, 2005). If the input power hypothesis holds for these noise-evoked OAEs, this would imply that the amplitude and morphology of the waveform of noise-evoked OAEs could be predicted from the conventional CEOAE at the same IPL. Whether or not this is the case cannot be determined from the results published to date. If it does turn out to be the case, then, for the purposes of evoking OAEs, the MLS stimulus can be thought of as simply a broadband noise stimulus whose IPL is determined by both the click amplitude and the presentation rate.

Interestingly, in studies of Gaussian noise-evoked OAEs, SSOAEs that were clearly seen in conventional OAE recordings were less prominent in the noise-evoked OAEs (Maat et al., 2000; Harte and Elliott, 2005). These results suggest that the input power hypothesis cannot hold for noise-evoked OAEs in the presence of strong SOAEs, in agreement with the results for MLS OAEs shown (Fig. 6).

As pointed out by Hine et al. (2001), the subjective loudness of the MLS click train at a mean rate of 2500 clicks/s

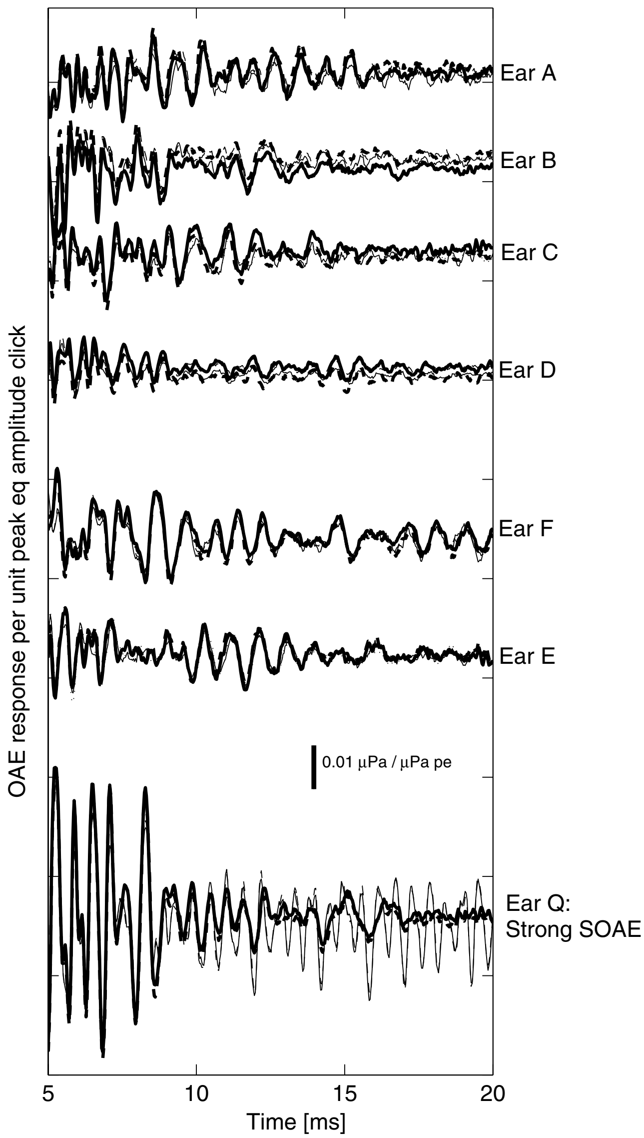

Fig. 6. Comparison of a conventional OAE waveforms with a high-rate MLS OAE waveform at a similar IPL. The OAE waveform is expressed as the response per unit click amplitude. OAEs from seven ears are shown, ears A–F had no detectable SOAEs, while ear Q had a strong SOAE corresponding to the SSOAE seen in the conventional OAE waveform. Two replicates of conventional OAE (thin solid and thin dashed lines) and two replicates of the MLS OAE (thick solid and thick dashed) are shown. The IPLs are made similar by overlaying the 40 clicks/s, $L = 70$ dB peSPL condition on top of the 2500 clicks/s, $L = 55$ dB peSPL condition.

is higher than that of a conventional click train at a rate of 40 clicks/s. In fact the difference in the detection threshold of the two click trains is around 15 dB (Hine et al., 2001; Fig. 5), which is similar to the difference in IPLs of 17.96 dB. However, the data presented by Hine et al. (2001) in which OAE amplitudes are compared on the basis of equal sensation levels cannot be used directly to test the input power hypothesis since this further requires that the comparison be made for the OAE response amplitude per unit click.

It is also important to note that the increase in subjective loudness that accompanies an increase in click presentation rate means that the maximum comfortable click amplitude (expressed in dB peSPL) is lower for high rate MLS recordings than for conventional recordings. The IPL of a click train is similar to its sound pressure level measured in dB SPL (with the "fast" time constant) and probably gives a better predictor of the subjective loudness of a click train than does the peak equivalent SPL. As pointed out by Rife and Vanderkoy (1989), this limits the maximum improvement in signal-to-noise ratio that can be achieved by increasing the click presentation rate.

5. Conclusion

Following Ryan and Kemp (1996), a simple phenomenological model, termed the input power hypothesis, has been proposed which predicts that the degree of nonlinear suppression exhibited by an MLS OAE is determined by only two quantities: the input power level of the stimulus, and the slope of the I/O growth function of the conventional CEOAE. On this hypothesis, the nonlinear phenomenon described as rate-suppression is simply a manifestation of the underlying compressively nonlinear amplitude dependence of the cochlear amplifier, as suggested by Kapadia and Lutman (2001).

Measurements of MLS OAE rate-suppression curves averaged over 15 ears are broadly in agreement with the predictions from the input power hypothesis. This suggests that it is not the rate of the MLS stimulation that is important in determining the nonlinear behaviour, but rather the rms amplitude.

There are small, but probably real, discrepancies between model predictions and measured results, in that the model slightly overestimates the degree of nonlinear suppression induced by high rate MLS click trains. Possible reasons for this discrepancy are discussed. One suggested reason is the rate-dependence of the shape of spectrum of the MLS stimulus. There is also some suggestion in the data that the predictions do not hold for ears showing significant SOAEs.

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References

Cooper, H.E., 2006. Modelling the properties of transient-evoked otoacoustic emissions at very high stimulus rates. MSc Dissertation, Institute of Sound and Vibration Research, University of Southampton, United Kingdom.

Davies, W.D.T., 1966. Generation and properties of maximum length sequences. Control 10, 302–304.

Elberling, C., Don, M., 1984. Quality estimation of averaged auditory brainstem responses. Scand. Audiol. 13, 187–197.

Gobsch, H., Tietze, G., 1993. Interrelation of spontaneous and evoked otoacoustic emissions. Hear. Res. 69, 176–181.

Harte, J.M., Elliott, S.J., 2005. Using the short-time correlation coefficient to compare transient- and derived, noise-evoked otoacoustic emission temporal waveforms. J. Acoust. Soc. Am. 117, 2989–2998.

Hine, J.E., Thornton, A.R.D., 1997. Transient evoked otoacoustic emissions recorded using maximum length sequences as a function of stimulus rate and level. Ear Hear. 18, 121–128.

Hine, J.E., Thornton, A.R.D., Brookes, G.B., 1997. Effect of olivocochlear bundle section on evoked otoacoustic emissions recorded using maximum length sequences. Hear. Res. 108, 28–36.

Hine, J.E., Ho, C.T., Slaven, A., Thornton, A.R.D., 2001. Comparison of transient evoked otoacoustic emission thresholds recorded conventionally and using maximum length sequences. Hear. Res. 156, 104–114.

Johannesen, P.T., Rassmussen, A.N., Osterhammel, P.A., 1998. Instrumentation for transient evoked otoacoustic emissions elicited by maximum length sequences. Scand. Audiol. 27, 37–42.

Kapadia, S., Lutman, M.E., 2000a. Nonlinear temporal interactions in click-evoked otoacoustic emissions: I. Assumed model and polarity–symmetry. Hear. Res. 146, 89–100.

Kapadia, S., Lutman, M.E., 2000b. Nonlinear temporal interactions in click-evoked otoacoustic emissions: II. Experimental data. Hear. Res. 146, 101–120.

Kapadia, S., Lutman, M.E., 2001. Static input–output non-linearity as the source of non-linear effects in maximum length sequence click-evoked OAEs. Br. J. Audiol. 35, 103–112.

Kemp, D.T., 1978. Stimulated acoustic emissions from within the human auditory system. J. Acoust. Soc. Am. 64, 1386–1391.

Kemp, D.T., Chum, R., 1980. Properties of the generator of stimulated acoustic emissions. Hear. Res. 2, 213–232.

Kulawiec, J.T., Orlando, M.S., 1995. The contribution of spontaneous otoacoustic emissions to the click evoked otoacoustic emissions. Ear Hear. 16, 515–520.

Lina-Granade, G., Liogier, X., Collet, L., 1997. Contralateral suppression and stimulus rate effects on evoked otoacoustic emissions. Hear. Res. 107, 92–93.

Lutman, M.E., Shephard, S., 1990. Quality estimation of click-evoked oto-acoustic emissions. Scand. Audiol. 19, 3–7.

Maat, B., Wit, H.P., van Dijk, P., 2000. Noise-evoked otoacoustic emissions in humans. J. Acoust. Soc. Am. 108, 2272–2280.

Neely, S.T., Norton, S.J., Gorga, M.P., Jesteadt, W., 1988. Latency of auditory brain-stem responses and otoacoustic emissions using tone-burst stimuli. J. Acoust. Soc. Am. 82, 652–656.

Norton, S.J., Neely, S.T., 1987. Tone-burst-evoked otoacoustic emissions from normal-hearing subjects. J. Acoust. Soc. Am. 81, 1860–1872.

Patuzzi, R., 1996. Cochlear micromechanics and macromechanics. In: Dallos, P., Popper, A.N., Fay, R.R. (Eds.), The Cochlea. Springer-Verlag, New York, pp. 186–257.

Picton, T.W., Kellett, A.F.C., Vezsenyi, M., Rabinovitch, D.E., 1993. Otoacoustic emissions recorded at rapid stimulus rates. Ear. Hear. 14, 299–314.

Probst, R., Coats, A.C., Martin, G.K., Lonsbury-Martin, B.L., 1986. Spontaneous, click-, and toneburst-evoked otoacoustic emissions from normal ears. Hear. Res. 21, 261–275.

Probst, R., Lonsbury-Martin, B.L., Martin, G.K., 1991. A review of otoacoustic emissions. J. Acoust. Soc. Am. 89, 2027–2067.

Rassmussen, A.N., Osterhammel, F.A., Johannesen, P.T., Borgkvist, B., 1998. Neonatal hearing screening using otoacoustic emissions elicited by maximum length sequences. Br. J. Audiol. 32, 355–366.

Rife, D.G., Vanderkoy, J., 1989. Transfer function measurement with maximum length sequences. J. Audio. Eng. Soc. 37, 419–444.

Rutten, W.L., 1980. Evoked acoustic emissions from within normal and abnormal human ears: comparison with audiometric and electrocochleographic findings. Hear. Res. 2, 263–271.

Ryan, S., Kemp, D.T., 1996. The influence of evoking stimulus level on the neural suppression of transient evoked otoacoustic emissions. Hear. Res. 94, 140–147.

Shera, C.A., Zweig, G., 1993. Noninvasive measurement of the cochlear traveling-wave ratio. J. Acoust. Soc. Am. 93, 3333–3352.

Shi, Y., Hecox, K.E., 1991. Non-linear system identification by m-pulse sequences: application to brainstem auditory evoked responses. IEEE Trans. Boomed. Eng. 38, 834–845.

Talmadge, C.L., Tubis, A., 1993. On modelling the connection between spontaneous and evoked otoacoustic emissions. In: Duifhuis, H., Horst, J.W., van Dijk, P., van Netten, S.M. (Eds.), Biophysics of Hair-Cell Sensory Systems. World Scientific, Singapore, pp. 25–32.

Tavartkiladze, G.A., Frolenkov, G.I., Kruglov, A.V., Artamasov, S.V., 1994. Ipsilateral suppression effects on transient evoked otoacoustic emissions. Br. J. Audiol. 28, 193–204.

Tavartkiladze, G.A., Frolenkov, G.I., Kruglov, A.V., Artamasov, S.V., 1997. Ipsilateral suppression of transient evoked otoacoustic emissions. In: Robinette, M.S., Glattke, T.J. (Eds.), Otoacoustic Emissions: Clinical Applications. Thieme, New York, pp. 110–129.

Thornton, A.R.D., 1993a. High rate otoacoustic emissions. J. Acoust. Soc. Am. 94, 132–136.

Thornton, A.R.D., 1993b. Click-evoked otoacoustic emissions: new techniques and applications. Br. J. Audiol. 27, 109–115.

Thornton, A.R.D., 1994. Contralateral and ipsilateral 'suppression' of evoked otoacoustic emissions at high stimulation rates. Br. J. Audiol. 28, 227–234.

Thornton, A.R., 1997. Maximum length sequences and Volterra series in the analysis of transient evoked otoacoustic emissions. Br. J. Audiol. 31, 493–498.

Thornton, A.R.D., Slaven, A., 1994. The effect of stimulus rate on the contralateral suppression of transient evoked otoacoustic emissions. Scand. Audiol. 24, 83–90.

Thornton, A.R.D., Folkard, T.J., Chambers, J.D., 1994. Technical aspects of recording evoked otoacoustic emissions using maximum length sequences. Scand. Audiol. 23, 225–231.

Zwicker, E., 1983. Delayed evoked oto-acoustic emissions and their suppression by Gaussian-shaped pressure impulses. Hear. Res. 11, 359–371.