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Research paper

Simultaneous suppression of tone burst-evoked otoacoustic emissions: Two and three-tone burst combinations

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ABSTRACT

Previous investigations have shown that components of a tone burst-evoked otoacoustic emission (TBOAE) evoked by a 1 kHz tone burst (TB_1) can be suppressed by the simultaneous presence of a 2 kHz tone burst (TB_2) or a pair of tone bursts at 2 and 3 kHz (TB_2 and TB_3 respectively). No previous study has measured this "simultaneous suppression of TBOAEs" for *both* TB_2 alone *and* TB_2 and TB_3 from the same ears, so that the effect of the additional presence of TB_3 on suppression caused by TB_2 is not known. In simple terms, three outcomes are possible; suppression increases, suppression is reduced or suppression is not affected. Comparison of previously reported simultaneous suppression data suggests TB_3 causes a reduction in suppression, though it is not clear if this is a genuine effect or simply reflects methodological and ear differences between studies. This issue has implications for previously proposed mechanisms of simultaneous suppression of TBOAEs and the interpretation of clinical data, and is clarified by the present study. Simultaneous suppression of TBOAEs was measured for TB_1 and TB_2 as well as TB_1, TB_2 and TB_3 at 50, 60 and 70 dB p.e. SPL from nine normal human ears. Results showed no significant difference between mean suppression obtained for the two and three-tone burst combinations, indicating the reduction of suppression inferred from comparison of previous data is likely a result of methodological and ear differences rather than a genuine effect.

1. Introduction

Transient-evoked otoacoustic emissions (TEOAEs) are complex multi-component signals emitted from the healthy cochlea and recorded in the ear canal in response to short duration acoustic stimuli (e.g. Probst et al., 1991; Shera, 2004; Withnell et al., 2008). Because their presence is reliant on the normal functioning of the physiological processes that enhance hearing sensitivity and selectivity, TEOAEs are widely used in the clinical setting as a non-invasive assessment of cochlear function (e.g. Robinette and Glattke, 2007). Clicks are commonly used as the evoking stimulus, producing click-evoked otoacoustic emissions, but tone bursts can also be used, producing tone burst-evoked otoacoustic emissions (TBOAEs).

A common clinical interpretation is that TEOAEs exhibit place-specificity. The presence of a response component (i.e. a component with amplitude clear of the noise floor) at frequency *f* is held to indicate normal physiological functioning at the basilar membrane (BM) place tuned to *f*. Where response component *f* is absent (i.e. when its amplitude is less than the noise floor) abnormal function at BM place *f* is assumed. This interpretation is likely incorrect for two reasons. First, at short latencies the TEOAE response at *f* is thought to arise from BM places basal to *f* (e.g. Yates and Withnell, 1999; Withnell et al., 2008; Moleti et al., 2013). Second, previous authors have demonstrated nonlinear interactions amongst TEOAE frequency components vitiate the principle of linear superposition. Specifically, the amplitude of a TBOAE recorded in response to a 1 kHz tone burst (TB_1) is reduced (suppressed) by the simultaneous presence of a single additional (equal level and phase) tone burst with centre frequencies at 1.5, 2 or 3 kHz (TB_2) (Yoshikawa et al., 2000; Killan et al., 2012, 2015) or a pair of additional tone bursts at 2 and 3 kHz (TB_2 and TB_3) (Xu et al.,

Abbreviations: BM, Basilar membrane; FFT, Fast Fourier transform; p.e. SPL, Peak-equivalent sound pressure level; TB, Tone burst; TBOAE, Tone burst-evoked otoacoustic emission; TEOAE, Transient-evoked otoacoustic emission

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1994; Killan and Kapadia, 2006). If the violation of linear superposition is significant, the conventional clinical interpretation of TEOAE place-specificity is not supported. Therefore, investigation of this simultaneous suppression phenomenon is important.

Collectively, findings from previous studies address a range of issues relating to simultaneous suppression of TBOAEs, including the effect of the frequency separation between TB_1 and TB_2 (referred to as Δf) (Yoshikawa et al., 2000; Killan et al., 2012, 2015), tone burst level (Xu et al., 1994; Killan and Kapadia, 2006; Killan et al., 2015) and averaging techniques (Killan and Kapadia, 2006). None of these studies have measured suppression for both a single additional tone burst (e.g. TB_2 at 2 kHz)[1] *and* a pair of additional tone bursts (e.g. TB_2 and TB_3 at 2 and 3 kHz respectively) from the same ears. Consequently, the extent to which the additional presence of TB_3 affects suppression caused by TB_2 alone is not known. In principle, there are three possibilities. First, comparison of data from two similar studies that separately tested simultaneous suppression caused by TB_2 alone (Killan et al., 2015) and TB_2 and TB_3 (Killan and Kapadia, 2006) suggests TB_3 causes a *reduction* in the amount of suppression caused by TB_2. Such behaviour is similar to the "release from masking" phenomenon described for the peripheral auditory system (e.g. Rutten and Kuper, 1982; Henry, 1987), however, it is unclear whether this is a genuine reduction, or simply reflects differences between the ears and methodologies used across studies. A reduction in suppression is also inconsistent with previously proposed mechanisms for simultaneous suppression of TBOAEs. These predict a second possible outcome where the additional presence of TB_3 causes an *increase* in suppression as a result of nonlinear interactions between response components generated at their characteristic BM place, or interference with the generation of short latency basal-source components (Yates and Withnell, 1999; Killan et al., 2012, 2015; Lewis and Goodman, 2015). Finally, the third possibility is that TB_3 has no effect on suppression.

To contribute to our understanding of simultaneous suppression of TBOAEs, the primary aim of this small-scale study was to explore the effect of TB_3 on the amount of suppression caused by TB_2 alone. To do this, TBOAEs were recorded from normal human ears in response to TB_1 presented in combination with TB_2, as well as TB_1 with TB_2 *and* TB_3, at a range of tone burst levels. In addition, observation of the effect of TB_3 is useful in defining the distance over which basal-source components in response to a 1 kHz tone burst arise. If TB_3 is shown to have no effect it can be argued that the BM region tuned to 3 kHz is not involved in the generation of components at 1 kHz (at least for the recording conditions described in this paper). Finally, the results presented within this paper could be used by future investigators to test predictions from their cochlear models.

2. Methods

2.1. Subjects

TBOAEs were recorded from a single ear (5 right, 4 left) from nine normally hearing adults (6 female, 3 male) aged between 18 and 33 years (median = 25 years). All ears tested had normal middle ear function as confirmed by tympanometry, repeatable TBOAEs at 50 dB p.e. SPL, i.e. the lowest tone burst level used in this study and did not exhibit synchronised spontaneous otoacoustic emissions as measured using the Otodynamics ILO 292 system (London, UK). Prior to testing, subjects gave informed consent in accordance with the requirements of the School of Healthcare Research Ethics Committee.

2.2. Instrumentation and stimuli

All TBOAE recordings were made using a custom-built system previously described by Killan et al. (2012). The synchronised input and output of a personal computer soundcard were controlled by purpose-written software. Stimuli were delivered to the ear canal via a custom-built amplifier and the earphone of an Otodynamics (London, UK) probe sealed into the ear canal with a soft plastic tip. The signal measured by the probe microphone was input to the soundcard (via a second amplifier) and was high-pass filtered (cut-off at 500 Hz with roll-off slope > 12 dB/octave). The input signal was sampled at a rate of 24 kHz and time-averaged within two separate buffers. This resulted in a pair of replicate recordings, each formed from 250 averages, which were stored on disk and analysed off-line.

Tone bursts (TB_1, TB_2 and TB_3) were cosine-windowed sinusoids (rise − fall = 2.5 ms; plateau = 0 ms) with centre frequencies 1, 2 and 3 kHz respectively, identical to those used by Killan and Kapadia (2006). Tone bursts were presented sequentially and simultaneously in two combinations: (i) TB_1 and TB_2; and (ii) TB_1, TB_2 and TB_3, which were the same combinations used separately by previous investigators. Simultaneous presentation was achieved via a complex stimulus resulting from the digital addition of the individual tone bursts. All tone bursts were presented using linear averaging at 50, 60 and 70 dB p.e. SPL (as calibrated within a passive 2 cm^3 cavity) and a rate of 50/s. Linear averaging was preferred to nonlinear averaging as it preserves linear and nonlinear components of the individual and complex responses. Preliminary testing indicated that stimuli at 50, 60 and 70 dB p.e. SPL corresponded to approximately 35, 45 and 55 dB sensation level respectively, and as such the response characteristic of the cochlea is assumed to be nonlinear (e.g. Kim et al., 1980; Nuttall and Dolan, 1996; Patuzzi, 1996; Rhode and Recio, 2000; Ren, 2002; Gorga et al., 2007).

2.3. Procedure

For each subject, TBOAE recordings were made during a single recording session lasting approximately one hour. Subjects were comfortably seated in a sound-attenuated room, and instructed to remain quiet and still throughout recordings. The probe was sealed in the ear canal with a soft plastic tip and was taped in position for the duration of testing. In order to minimise potential order effects, the presentation order of individual and complex tone bursts was randomised across tone burst level.

2.4. Analysis

At each tone burst level, a mean response waveform was calculated for all individual tone bursts and the two complex stimuli. Two "composite" response waveforms were then generated by summing the mean response waveforms of TB_1 and TB_2 and the mean waveforms of TB_1, TB_2 and TB_3. Thus, for each subject and at each tone burst level, there was a two-tone burst and a three-tone burst composite (i.e. the predicted linear response) and complex (i.e. the simultaneous response) waveform. In order to minimise the influence of linearly scaling stimulus ringing components, the first 8 ms (post-stimulus onset) of each composite and complex waveform was discarded from subsequent analysis. Removal of such a substantial portion of the waveform is not unusual when recording TBOAEs (e.g. Rutten, 1980; Prieve et al., 1996;

[1] The convention for numbering tone bursts (i.e. TB_1 and TB_2) was used by Killan et al. (2012). It is used here for simplicity when describing the present and previous studies, and is extended to include TB_3. In the present use, the subscript number also refers to the centre frequency (in kHz) of the tone bursts.