Original Article

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TEOAE recording protocols revised: data from adult subjects

Revision de protocolos de registro de TEOAE: informacion de sujetos adultos

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Abstract
The objective of this study was the experimental re-evaluation of the current clinical transiently evoked otoacoustic emission (TEOAE) protocols, based on linear and non-linear protocol paradigms from a population of 42 adult subjects serving as a normative database. The linear and non-linear TEOAE responses were elicited by clicks with average intensities of 72 and 84 dB p.e. SPL respectively. An initial comparison between non-processed non-linear and linear recordings, at early recording segments from 3.2 to 5.2 ms, showed that the responses had highly similar contours and no statistically significant mean differences. The stimulus-induced artefact in the linear TEOAE responses was suppressed by post-processing the data with a window function (3.8–13.8 ms) and by a high-pass filter at 830 Hz. A repeated-measures model was used to evaluate the differences between post-processed linear and non-linear responses across clinical variables of interest (such as TEOAE response, noise, correlation, and signal-to-noise ratios (SNRs) at 1.0–5.0 kHz). The data indicated that the linear recordings demonstrate significantly lower levels of noise (and thus superior SNRs) and higher values of reproducibility. Normative adult scoring criteria were calculated from free distribution tolerance intervals for the TEOAE correlation and the SNRs at 2.0 and 3.0 kHz.

Sumario
El objetivo de este estudio fue la re-evaluación experimental de los protocolos actuales de medición de emisiones otoacústicas evocadas por transientes (TEOAE), basados en paradigmas de protocolo lineal o no lineal, obtenidos en una población de 42 sujetos adultos que sirvieron como base de datos normativa. Las respuestas lineales y no lineales de TEOAE fueron generadas por medio de *clicks* con intensidades promedio de 72 y 84 dB pe SPL, respectivamente. Una comparación inicial entre los registros lineales y los no lineales-no procesados, en segmentos tempranos de registro de 3.2 a 5.2 ms, mostraron que las respuestas tenían contornos muy similares y que no había ninguna diferencia promedio estadísticamente significativa. El artefacto inducido por el estímulo en la respuesta de las TEOAE lineales fue suprimido por procesamiento ulterior de la información, con una función de ventana (3.8–13-8 ms) y por un filtro de pasa-alto a 830 Hz. Se utilizó un modelo de medidas repetidas para evaluar las diferencias entre las respuestas lineales y las no lineales, procesadas ulteriormente, considerando variables clínicas de interés (tales como respuesta de TEOAE, ruido, correlación y tasas de señal-ruido (SNR) a 1.0–5.0 kHz). Los resultados indicaron que los registros lineales poseían niveles de ruido significativamente menores (y por lo tanto SNR mayores) y mayores valores de reproducibilidad. Los criterios normativos de puntuación para adultos se calcularon a partir de intervalos de tolerancia de distribución libre, para la correlación de las TEOAE y de las SNR a 2.9 y 3.0 kHz.

Introduction

Traditionally, the transient evoked otoacoustic emission (TEOAE) responses can be evoked by two types of train stimuli: (1) by a set of four clicks of equal magnitude (referred to as the linear protocol); or (2) by three clicks of positive polarity followed by a fourth click of an inverse polarity with a relative magnitude 9.5 dB higher than the corresponding positive clicks (referred to as the non-linear or the derived non-linear protocol). Under the hypothesis that the TEOAE recordings originate from saturated cochlear generators, it is assumed that the non-linear protocol removes stimulus artefacts of a linear nature which can be misinterpreted as TEOAE responses (Kemp et al, 1986, 1990). Despite the lack of sufficient research on the statistical verification of the functional premises of the non-linear protocol (i.e. how much the induced linear artefacts at stimulus levels >80 dB SPL are suppressed), it is generally accepted that the non-linear ILO protocol is a practical compromise to maximize the reliability of a TEOAE recording, and this protocol is used to assess the integrity of the cochlear function of neonatal and adult subjects.

The fact that the non-linear protocol contains the word 'non-linear' has created considerable confusion in the OAE clinical community. Over the years, after the introduction of this methodology by Kemp et al (1986, 1990), two questionable assumptions have been generated: (1) the non-linear protocol

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captures the non-linear cochlear responses due to the non-linearity of its stimulation paradigm—this statement is not true, because the utilized clicks are linear; and (2) the 'non-linear protocol' 'ensures' the capture of the non-linear TEOAE responses, because the high-intensity click stimuli saturate the cochlea. The TEOAEs are of non-linear origin, due to the non-linear operation of the cochlear amplifier and mainly of the outer hair cells of the organ of Corti (Kim, 1986; Zwicker, 1986; Leeuw & Dreschler, 1998; Thorton et al, 2001; Zinn et al, 2000), but not all segments of the cochlear amplifier saturate at the same stimulus intensity (Patuzzi, 1987; Shera & Guinan, 1999). For example, the regions related to TEOAE frequencies <1.0 kHz saturate even with mid-intensity stimuli of approximately 60 dB SPL (Grandori et al, 1994), and in many cases (neonatal subjects and children), even high-intensity stimuli (>80 dB SPL) do not fully saturate the cochlea. In this context, it should be clarified that both linear and non-linear TEOAE protocols can efficiently capture the non-linear responses (TEOAEs) of the cochlear amplifier.

This issue of 'OAE capturing efficiency' has been an interesting argument among the signal-processing OAE community during the last 10 years (Lutman, 1993; Lutman et al, 1994; Grandori & Ravazzani, 1993; Grandori et al, 1994; Berlin et al, 1995; Hatzopoulos et al, 1999, 2000a; Tognola et al, 2001; Von Specht et al, 2001). Recently, the impetus from the spread of TEOAE neonatal screening technology has prepared the ground for further TEOAE protocol redesign and re-evaluation. This goal is also one of the main objectives of the European Concerted Action on Otoacoustic Emissions (AHEAD-II (AHEAD, 2002)), aiming at the optimization of the current TEOAE recording methods (i.e. an improvement of the signal-to-noise ratio (SNR), referred to as the quality of the TEOAE recording). The optimized protocols are expected to offer improvements in two areas: (1) an improvement in the amplitude and the SNR of the TEOAE response; and (2) a decrease of the TEOAE acquisition time, a requirement imposed by the neonatal hearing screening programmes.

A way to minimize the TEOAE time-recording requirements is based on the fact that the characteristics of the final TEOAE response depend on the number of averaged sweeps (or acquisition frames), which for an adult subject varies from 100 to 260. In this context, it has been proposed to drive the cochlea with a higher stimulus rate, in order to capture TEOAE responses in less time. This is the basis of the maximum length sequence (MLS) protocol using linear clicks and stimulation rates up to 5 kHz (Thornton, 1993; Thornton et al, 2001). This protocol has not yet been implemented commercially, because it requires significant changes in the current TEOAE instrumentation. An alternative approach (used in the popular neonatal protocol QuickScreen) is to decrease the value of the interstimulus interval. The latter, by default, is approximately 20 ms and corresponds to a stimulation rate of 50 stimuli/s. In this context, the use of a shorter 12.5-ms TEOAE response window increases the stimulation rate from 50 to 80 repetitions/s. The processing of information derived from smaller TEOAE response windows, such as the one mentioned above, offers an additional advantage. If the response window is shortened, the average noise level, which is usually higher at the later segments of the TEOAE response, decreases, and the resulting waveform presents higher SNRs (Kemp et al, 1990; Hatzopoulos et al, 1995; Whitehead et al, 1995, Fitzgerald & Prieve, 1997). Despite these two positive aspects, the TEOAE window processing proposals suffer from the same disadvantages as the traditional non-linear recordings (low SNR), which are caused by the effect of the fourth click in the stimulus train (Kemp et al, 1986).

The alternative solution to a non-linear TEOAE protocol is based on trains of click stimuli with the same polarity. Such protocols were used before the commercial introduction of the ILO non-linear method, but TEOAE recordings evoked by such schemes were prone to stimulus-induced artefacts, generated by reflections of the acoustical energy from the walls of the acoustical meatus and the tympanic membrane (Kemp et al, 1986; Johnsen et al, 1988). For the recordings evoked by a non-linear protocol, the stimulus artefact is cancelled out by subtracting properly scaled TEOAE responses evoked by different-intensity click stimuli of the opposite polarity. The stimulus artefact of the linear response can be suppressed, by applying a window function that zeros the initial portion of the response that is corrupted by the artefact. In physical terms, the linear artefact is not cancelled out, but its contribution to the TEOAE response is severely attenuated by the weighting effect of the window function on the TEOAE response. TEOAE recordings evoked by a linear protocol are expected to present higher SNRs, because the stimulus train lacks the differencing (subtracting) action of the fourth click, which reduces the signal strength and increases the high-frequency noise. A possible drawback of a windowed linear protocol might be the exclusion of an initial segment of the TEOAE response, which is assumed to contain unique higher-frequency components. This assumption is not valid according to a number of studies (Cheng, 1993; 1995; Hatzopoulos et al, 2000a) that have evaluated the structure of the TEOAE recordings with time–frequency (TF) techniques. Data from the TF analyses have demonstrated that the high TEOAE frequency components (>5 kHz) are still detectable at TEOAE latencies ≥4.0 ms.

A forthcoming application of otoacoustic emissions is the possible 'auditory description' of carriers of genetic syndromes such as the Usher syndrome. When recording TEOAEs from these cases, it is very often necessary to attain a high quality of TEOAE response. In this context, we have considered resolving the 'quality issue' by using a linear TEOAE protocol. Data from a previous study (Hatzopoulos et al, 2000c) that compared TEOAE responses from neonatal subjects evoked by different protocols have suggested that properly scaled linear click stimuli (maximum intensity of 72–75 dB SPL) generate responses which, when windowed from 3.5 to 12.5 ms, present superior characteristics (higher SNR estimates and higher TEOAE correlation) than those evoked by a non-linear or a Quickscreen protocol. In a number of trial sessions with suspected Usher II syndrome carriers, it was noticed that responses evoked by a linear TEOAE protocol resulted in higher SNRs than those evoked by the standard non-linear protocol. These trial sessions were based on data extrapolated (post-windowing of the responses from 4.0 to 19.5 ms) from the previously mentioned study on neonates (Hatzopoulos et al, 2000c).

The present study was designed to answer the questions which arose during the previously mentioned trial sessions and provide a new approach to TEOAE data acquisition for emerging TEOAE clinical applications. The objectives of the study were the following: (1) the identification of the limits of the window function, which can be applied to the linear TEOAE responses, preserving the frequency content of the data and suppressing, as much as possible, stimulus artefacts; (2) the definition of any significant differences between the means of the linear and non-linear TEOAE responses; and (3) the definition of scoring criteria regarding normal TEOAE responses, which can be extrapolated for use in other clinical applications (contralateral stimulation, ototoxicity monitoring, carriers of other genetic syndromes, etc). The last objective was sought because, despite the long history of applying TEOAEs to assess the hearing status of adult subjects, there are very few references in the literature (Gorga et al, 1993; Prieve et al, 1993) indicating which criteria to use for the TEOAE hearing evaluation.

To reach the project objectives, we first estimated the extent of the stimulus artefact in the linear recordings. Based on this information, we estimated a new window, whose efficiency was evaluated from TEOAE recording simulations in 2-cc and 5-cc cavities and ears with severe sensorineural hearing losses. After post-processing of the data, we compared the non-linear and linear responses in terms of various clinical parameters of interest. Finally, we estimated scoring criteria (minimal normative responses) for the linear recordings. We have postulated that a post-windowed linear TEOAE response will be characterized by lower noise and higher SNRs than the corresponding non-linear response, a feature that is very useful in the successful application of discriminant models to a population of probable carriers. To simplify the terminology throughout the text, the data evoked by a linear/non-linear protocol are called linear or non-linear recordings respectively.

Materials and methods

Subjects

Forty-two healthy adults (age 26±3.2 years) participated in the study. The hearing normality of each subject was assessed with otoscopy, pure-tone audiometry (thresholds better than or equal to 20 dB HL at 0.5–4.0 kHz), and tympanometry. All subjects had a normal medical history, and none was under any particular medication. Otoacoustic emissions were recorded from the best ear, and for the cases where both left and right hearing thresholds were similar, an ear was randomly selected.

TEOAE recordings (from both linear and non-linear protocols) were also acquired from four patients with severe sensorineural loss (SNHL), showing mean threshold levels higher than 60 dB HL at 2.0 and 4.0 kHz. The data from these recordings were not analysed statistically, but were used as validators of the duration of the stimulus artefact in the linear recordings.

Recordings

The recording sessions were conducted in an acoustically isolated room using the ILO-292 apparatus (software version 5.60). The linear recordings were elicited by clicks of 72 dB SPL (–12 dB ILO), and the non-linear recordings by clicks of 84 dB SPL (0 dB ILO). Each recording was the average of 260 sweeps. The level of acceptable noise was set to be <3.4 mPa (or approximately 44.6 dB SPL). For all recordings, the default ILO window (2.5–19.5 ms) was used.

POST-PROCESSING OF LINEAR RECORDINGS

Prior to the comparison of the linear and non-linear data sets, the linear recordings were post-processed by a filtering and a windowing routine. According to a previous study (Hatzopoulos et al, 2000b), the frequency content of TEOAEs for frequencies below 900 Hz is very low. Since these frequencies are often associated with the stimulus artefact, a bandpass filter attenuating frequencies below 830 Hz and above 4800 Hz was applied to the data. The digital filter is incorporated in the ILO software. For the windowing of linear recordings, a 3.8–13.8-ms window function was used with a rise and fall time of 0.64 ms. The low limit of the window function was defined according to the results in 'Presence of stimulus artefact in the linear recordings'. The upper limit of the window function (13.8 ms) was defined according to the results of a previous study on adult subjects (Hatzopoulos et al, 2000a). The window function was defined by the ILO software, and is similar to the cosine tapered window used in the default non-linear protocol.

POST-PROCESSING OF NON-LINEAR RECORDINGS

For the statistical comparisons of the data, we generated two data sets from the available non-linear recordings. In the first set, called non-linear default (coded as D), the data used were as recorded by the ILO-292 windowed with the ILO default window function (applied from 2.5 to 19.5 ms). For the second set of data (coded as N), the recordings were post-windowed with the same window function as applied to the linear recordings (3.8–13.8 ms). Both non-linear data sets were filtered with the same bandpass filter as used for the linear recordings.

Statistical methods

The collected linear and non-linear recordings were compared in terms of nine parameters—TEOAE response, noise, corrected TEOAE response (Welzl-Muller & Stephan, 1994), SNR ratio in the bands 1.0–5.0 kHz, and signal reproducibility (correlation)—which are routinely used in clinical practice (Dircxx et al, 1996). For all statistical analyses, we used a mainframe SAS package.

In order to evaluate the presence of an artefact in the first millisecond of the linear TEOAE response, we sampled all acquired responses every 0.2 ms in the interval from 3.2 to 5.2 ms (11 data points). We expected that the presence of a linear artefact at an interval=x (where x=from 3.2 to 5.2 ms) would manifest as a significant difference between the means of the tested data sets. We modelled the difference between the linear and non-linear response values (TEOAE amplitude) over time using the following repeated-measures model:

$$D(ij)=mu+T(i)+E(ij)$$

where $D(ij)$ is the amplitude difference between the linear and non-linear measurement for subject j at time I, mu is the overall amplitude mean, $T(i)$ is the effect of time i, and $E(ij)$ is the error associated with response $D(ij)$.

The SAS procedure 'proc mixed' was used to fit the model. Several within-subject covariance structures, including the compound symmetry and the autoregressive of order 1 structures, were considered, but unstructured covariance gave the best fit as determined by the AIC and BIC measures (see Appendix for details).

For each of the nine parameters described above, we used the following repeated-measures model to evaluate differences in means among the three TEOAE protocols:

$$Y(ij)=mu+P(i)+E(ij)$$

where $Y(ij)$ is the response of subject j to protocol i (linear, non-linear, or non-linear default), mu is the overall mean, $P(i)$ is the effect of protocol i, and $E(ij)$ is the random error associated with the observation.

The SAS procedure 'proc mixed' was used to fit each model. As with the previous model, several within-subject covariance structures were considered, but for each parameter the compound symmetrical covariance structure gave the best fit as determined by the AIC and BIC measures (see Appendix for details). To evaluate significant differences in response means for the different protocols, each overall F-test significant at the 0.05 level was followed by Tukey–Kramer simultaneous pairwise comparisons, with an experiment-wise 0.05 significance level.

For the calculation of the scoring criteria, we used a free-distribution approach, because the TEOAE variables were not normally distributed. The scoring criteria provide us with a minimum estimate of normal performance, which is the lower tolerance bound of the estimated tolerance interval (for every tested variable). To obtain scoring pass–fail criteria, we calculated one-sided distribution-free tolerance intervals. These intervals ensure that, for a user-specified confidence M, and a user-specified population proportion p, we can be M% confident that the computed interval will contain at least a percentage p of measurements for the entire population. We present these intervals for $M=90\%$ and $M=95\%$, and values of p between 89% and 94%. Additional details of the free-distribution method can be found in previous publications (Hatzopoulos et al, 1999, 2000a).

Results

Presence of stimulus artefact in the linear recordings

The results from the repeated-measures model indicated that there are no statistically significant differences between the mean linear and the non-linear responses evaluated in the TEOAE recording segment from 3.2 to 5.2 ms. Five subjects presented a number of outliers, but when these were removed and the data were re-fitted, the results were substantially the same. These findings verify the visual inspection of the linear data set, and a representative case is shown in Figure 1. The similarity between the non-linear and linear trace contours demonstrates that, in the initial part of the TEOAE response, the differences between the linear and non-linear recordings are minimal. Following the findings of the repeated-measures model, the value of 3.8 ms was selected to represent the lower limit of the post-processing window function. This choice was followed in order to preserve the highest possible TEOAE signal bandwidth. The upper limit of the window function was set to 13.8 ms, according to previous data (Hatzopoulos et al, 2000a), indicating that a windowed response limited to this upper value would contain more than 90% of the original energy.

TEOAE simulations and data from ears with severe hearing losses

The artefact-suppression efficiency of the window defined in the previous section was tested on simulated TEOAEs, in 2-cc and 5-cc cavities, and on ears presenting severe SNHLs. Figure 2 shows typical post-processed data from a simulated TEOAE linear recording, in a 2-cc and a 5-cc cavity, elicited by a stimulus of 74 dB SPL. The post-processing of the data completely suppressed the induced artefact. Twenty simulated responses were collected for each cavity. A t-test statistic suggested that the mean of the processed responses was significantly different from the mean of unprocessed linear responses at 1.0, 2.0, 3.0 and 4.0 kHz $p<0.003$ and $p<0.001$ for the 2-cc and 5-cc cavities, respectively).

As expected, the linear recordings from the tested SNHL ears showed a lack of emissions. The first millisecond of the TEOAE

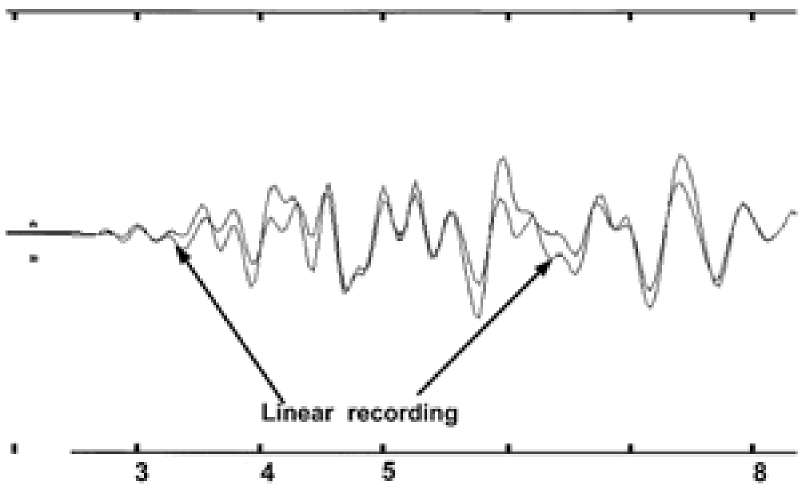

Figure 1. The trace contours (TEOAE amplitudes) depict the linear and non-linear TEOAE responses from subject Bar_Lin_R. To compare the recordings, we have used the 'compare' feature of the ILO software. To reveal the details of the response in the first 8 ms, we have expanded the time scale using the 'Expand Response' option from the View menu of the ILO software. The contours of the two recordings are very similar, and at a time 5.5 ms the traces overlap completely. The arrows indicate the trace of the linear response.

response were corrupted by a low-frequency artefact. After the post-processing (i.e. filtering and windowing), the artefact was totally suppressed, and the average amplitude of the TEOAE response was within levels of random noise. A typical example of an SNHL recording evoked by a click stimulus of 72 dB SPL is shown in Figure 3. Figure 3A shows the response prior to any processing, and Figure 3B shows the processed result. The stimulus artefact manifests as a low-frequency waveform (Figure 3A) spanning at least 4.2 ms (this was the largest value observed in all tested SNHL ears). The TEOAE response in Figure 3B shows that the artefact has been suppressed/eliminated. The amplitude of the TEOAE response in Figure 3B remains below a value of 60 mPa, in accordance with the hearing status of the tested ear (i.e. absence of emissions).

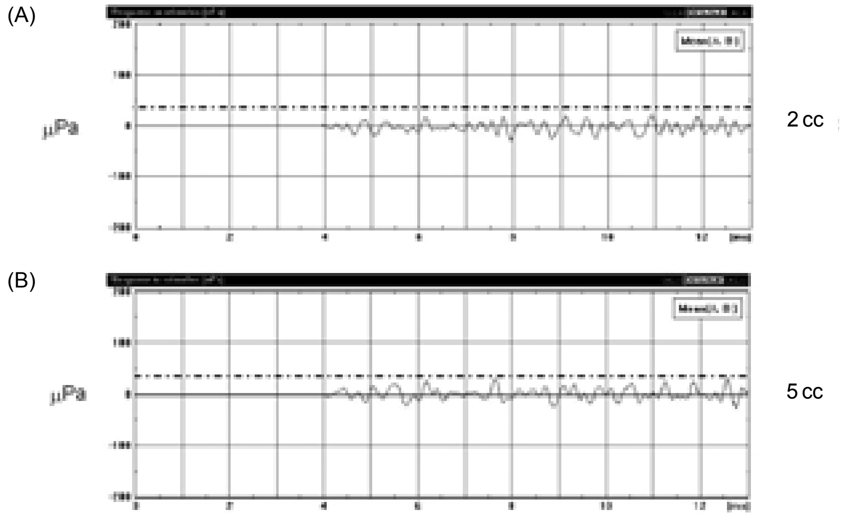

Figure 2. Results of simulating TEOAE recordings in two coupler cavities, in order to evaluate the efficiency of the post-processing applied to linear TEOAE responses. (A) The processed TEOAE response recorded in a cavity of 2 cc and elicited by a stimulus of 74 dB SPL. (B) The processed TEOAE response recorded in a cavity of 5 cc, and elicited by the same amplitude stimulus as in (A). Both recordings were high-pass filtered at 830 Hz (second-order filter, provided on-line by the ILO software) and windowed by a 3.80–13.8-ms window with a 0.6-ms rise-time. The *y*-axis scale has been set to ±200 mPa to be compatible with the data of Figure 3. The *x*-axis in both panels shows time (0–13) in ms.

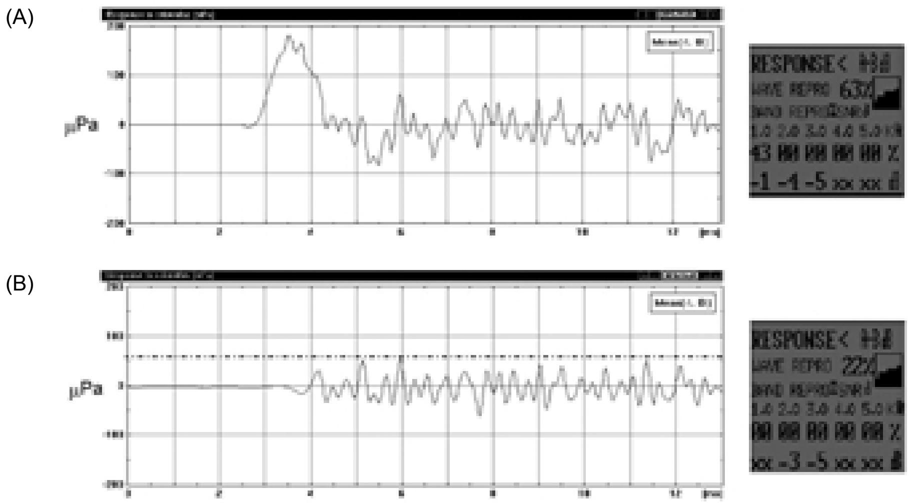

Figure 3. Results of using a linear protocol to capture the TEOAE responses from an ear showing large threshold shifts (>45 dB HL at 2.0 and 4.0 kHz) due to sensorineural hearing losses. (A) The unprocessed response. (B) The processed TEOAE recording. The latter was high-pass filtered at 830 Hz (second-order filter, provided by the ILO software) and windowed by a 3.80–13.8-ms window with a 0.6-ms rise-time. In (B), no traces of the artefact are visible. The smaller panels, taken from the ILO software display, show the SNRs at 1.0–5.0 kHz. The top ILO panel shows that the spectral energy of the artefact is concentrated at the lower frequencies, <1.0 kHz. The dotted line in (B) indicates an amplitude of 60 mPa. In both (A) and (B), the units of the *y*-axes are mPa, and those of the *x*-axes are ms (0–13).

Comparison between linear and non-linear responses
The results from the repeated-measures model indicated that for all tested parameters, except the TEOAE response and noise, the mean linear recording values were significantly larger than the values from the two non-linear data sets. As expected, the mean non-linear recording values for the TEOAE response were larger, due to the difference in the stimulus intensity (84 versus 72 dB SPL for the non-linear and linear protocols respectively). The significant differences for the TEOAE noise variable verify the assumptions regarding the noising effects of the fourth click in the non-linear stimulus train. The distributions of noise in the linear and non-linear responses are shown in Figure 4. The results from the linear–non-linear data comparisons are summarized in Table 1.

Scoring criteria
For the scoring criteria, we considered mainly the SNRs and the correlation estimate, which is traditionally used to indicate the quality of the TEOAE response (or the absence of noise in the TEOAE recording). We used two levels of confidence, at 95% and 90%. The various option scenarios are presented in Table 2. The most advantageous choice of variables (bold type in Table 2) can be summarized as follows: (1) we are 90% confident that at least 91% of the tested population's TEOAE linear recording values will present an SNR at 2 kHz ≥13 dB; (2) we are 90% confident that at least 91% of the tested population's TEOAE linear recording values will present an SNR at 3 kHz ≥11 dB; and (3) we are also 90% confident that at least 91% of the population's TEOAE linear recording values will present a correlation value ≥91%. For the scoring criteria, the values of SNR at 1.0 kHz were very low (close to zero or negative), and for this reason they are not reported in Table 2.

Discussion

The objective of this study was to evaluate the possibility of clinically assessing otoacoustic emission responses, from adult subjects, evoked by a linear protocol. In previous papers (Hatzopoulos et al, 2000b,c), we have shown that TEOAE responses from neonatal subjects can be acquired with a protocol using mid-level linear click stimuli, when a 10-ms window function (from 3.5 to 13.5 ms) is applied to the data. The combined use of mid-level stimuli, high-pass filtering and windowing effectively suppress the stimulus artefacts found in the first millisecond of the recording. The present study was designed to verify the findings from the previous studies on neonates and the trial sessions with suspected Usher syndrome carriers.

The comparison of linear and non-linear responses in the interval from 3.2 to 5.2 ms (prior to any post-processing of the data) suggested that the linear and non-linear recordings were similar, due to lack of any significant differences between their means. Based on this result, we have defined a window function from 3.8 to 13.8 ms which we have applied to all linear TEOAE recordings. The fact that the linear and non-linear responses are so similar (see the response contours in Figure 1) is surprising, considering that the non-linear protocol was invented in order to suppress stimulus artefacts. Prior to the analysis of the data, we postulated that the outcome of the analyses could be interpreted as follows: (1) the linear responses are not contaminated by an artefact; or (2) the non-linear responses contain linear components in the early segments of the recording. After the completion of the analyses, we concluded that both assumptions are probably correct. An earlier study by Grandori et al (1994), using the growth patterns of TEOAE input–output curves, presented evidence showing that the non-linear responses

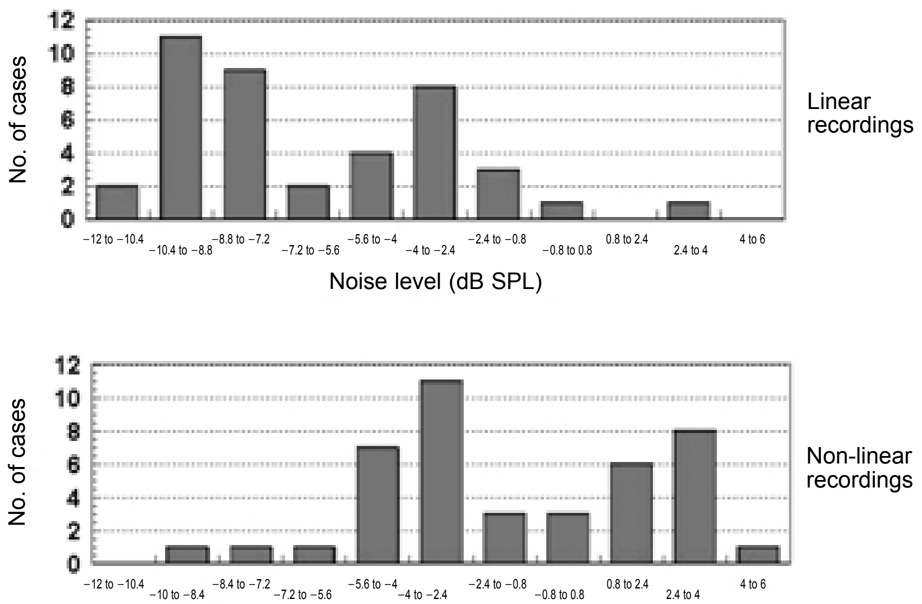

Figure 4. Distribution histograms of the noise (A–B) level in the linear and the non-linear TEOAE recordings. Larger negative values indicate lower levels of noise that correspond to higher values of signal strength, since the noise is approximated by the difference between the two recorded traces. The *y*-axis indicates the number of cases per noise level. The *x*-axis indicates the noise-level interval.

Table 1. Results from the comparison between post-processed responses from linear and non-linear TEOAE protocols

Variable	*Interpretation*
Response	$D > N > L$
A–B (Noise)	$D > N > L$
Corrected signal	$L > N > D$
Correlation %	$L > N > D$
SN_1 kHz	$L > N > D$
SN_2 kHz	$L > N > D$
SN_3 kHz	$L > N, D$
SN_4 kHz	$L > N, D$
SN_5 kHz	$L > N, D$

L= linear post-windowed data from 3.8 to 13.8 ms.
N= non-linear post-windowed data from 3.8 to 13.8 ms.
D= non-linear post-windowed data from 2.5 to 19.5 ms.

The first column indicates the TEOAE variable and the second shows the relationship between the means. For the majority of variables, the means for the linear recordings are significantly larger than those for non-linear recordings. The symbol '>' is used to indicate the order in terms of magnitude between the means.

Table 2. The normative adult scoring criteria for a confidence range (M) of 90–95% and a probability (p) of 89–94%

Confidence (M)	*Probability (p)*	*Scoring criteria*
95%	93%	SNR 2.0 kHz ≥ 13 dB SNR 3.0 kHz ≥ 10 dB SNR 4.0 kHz ≥ 0 dB Correlation ≥ 90%
	89%	SNR 2.0 kHz ≥ 13 dB SNR 3.0 kHz ≥ 11 dB SNR 4.0 kHz ≥ 5 dB Correlation ≥ 91%
90%	94%	SNR 2.0 kHz ≥ 13 dB SNR 3.0 kHz ≥ 10 dB SNR 4.0 kHz ≥ 0 dB Correlation ≥ 90%
	91%	**SNR 2.0 kHz ≥ 13 dB** **SNR 3.0 kHz ≥ 11 dB** **SNR 4.0 kHz ≥ 5 dB** **Correlation ≥ 91%**

The best option (bold type) corresponds to a combination of M=90% and p=91%, showing that the minimum SNRs from normal-hearing adults should be 13, 11 and 5 dB at 2.0, 3.0 and 4.0 kHz. To extend the scoring criteria to more frequencies, a larger normal-hearing population is necessary.

contain linear components. In addition, we were informed that in the linear protocol the stimulus sequence changes polarity every 10 clicks. This feature was introduced in the early design of the ILO in order to avoid saturation of the preamplifier circuits. As far as we know, the reverse polarity option is always on during the ILO data acquisition. Undoubtedly, this ILO instrumentation feature contributes to the similarity between the linear and the non-linear responses.

The lower limit of the window function was set at 3.8 ms, despite the fact that the repeated-measures model indicated no significant differences at time=3.2, 3.4 and 3.6 ms. In our opinion, this choice represents a compromise for the suppression of the artefact and the preservation of the highest possible signal bandwidth. The definition of the 3.8–13.8-ms window is a procedural improvement over older data suggesting response windows starting from 5.0 ms (Osterhammel et al, 1996; Grandori et al, 1994) or 6.0 ms (Lutman, 1993). By shifting the lower bound of the window function to a lower value, we are more confident that we can capture a wider bandwidth of the TEOAE response. It is worth mentioning, that for adult subjects, the later TEOAE recording segments do not contribute significantly to the overall TEOAE response in terms of frequency components and signal energy (Grandori et al, 1994; Hatzopoulos et al, 2000a). A response averaged over a shorter window (3.8–13.8 ms) benefits from the absence of the noisier segments of the TEOAE recording (later segments >10 ms), so it presents higher SNRs than those obtained from recordings processed with previously proposed processing schemes. It should be noted that, with the ILO-292 system, it is possible to perform the processing of the TEOAE linear responses (i.e. filtering and windowing) during the data acquisition stage, by changing a number of default values of the ILO software.

The proposed linear protocol can be further optimized by shortening the interstimulus interval, which may decrease the required TEOAE acquisition time. From the earlier versions of the ILO hardware/software (ILO-92, software v. 4.20), it was possible to select a user-defined interstimulus interval of 13.5 ms, thus increasing the stimulation rate from 50 to 74 stimuli/s. The increase of the stimulation rate and the shortening of the recording time might prove very useful in cases when children or difficult subjects are being examined. In using a 13.5-ms response window, the user does not consider a 0.3-ms (13.8–13.5-ms) TEOAE segment. Data from previous studies on TF analyses (Cheng, 1995; Hatzopoulos et al, 2000c) suggest that this omission should not significantly change the resulting TEOAE waveforms.

While the use of a smaller window (3.8–13.8 ms) results in superior SNRs, there are clinical cases where such an approach might create difficulties in interpreting the TEOAE data. In subjects undergoing a contralateral TEOAE suppression procedure, Berlin et al (1993) have shown that the suppression effect is maximized within the 8–18-ms TEOAE recording segment. In this context, a linear protocol might provide more robust TEOAE responses, but the response window should be modified to include data from the later TEOAE segments (e.g. 3.8–18.8 ms). However, further studies have to be completed to find whether the use of a smaller window (and thus faster rate) can give reliable results in screening for medial olivocochlear function in children and infants, where a short acquisition time is a requirement.

Data from the comparison of TEOAE protocols suggest that a linear response, evoked by a mid-intensity click stimulus and properly windowed (3.8–13.8 ms), is characterized by higher reproducibility (correlation) and a higher set of SNRs than the corresponding non-linear response. These results are in agreement with the theoretical premise of the non-linear protocol, which is expected to generate moderate SNRs as a compensation for the artefact suppression (Grandori &

Ravazzani, 1993; Fitzgerald & Prieve, 1997). The data from Table 1 show significant differences between the two protocols in all the analysed parameters. These differences favour the linear protocol for all tested variables, except in the case of TEOAE response.

The estimated scoring criteria were based on a confidence level $M=90\%$, which implies a 10% margin of error. The authors postulate that an initial population selection (normal versus hearing-impaired subjects) is possible by applying the obtained criteria at 2.0, 3.0 or 4.0 kHz. The shortcoming of this estimation is that it applies to only three frequencies, used mainly in neonatal screening practices. It might be more advantageous to use in clinical practice a single and more global criterion, based on the value of the TEOAE correlation (>91%), which reflects the contribution to the final TEOAE response of all the important TEOAE frequency components. The proposed adult TEOAE criteria can be useful for a general clinical practice, but it might not produce good separation results when applied on populations (i.e. carriers of an X genetic syndrome) that overlap with the rest of the normal population. To increase the effectiveness of the scoring criteria, it is necessary to obtain additional information on the TEOAE characteristics of the X-syndrome' carriers. This implies the collection and evaluation of a larger sample, which might permit a higher level of confidence M.

One of the necessary requirements for the successful application of the linear protocol is the condition that the stimulus intensity should not exceed the mean value of 74+2 dB SPL (data derived from the 2-cc cavity simulations). To control the efficiency of the window function, it is mandatory to control the intensity of the stimulus energy reaching the tympanic membrane. Given a good probe fit with no leakage effects (attenuation of the low-frequency or the high-frequency TEOAE components), this can be achieved by manipulating the ILO stimulus level to an approximate level of 72.0–74.0 dB SPL, an indication that is available to the ILO user prior the collection of data. The reader should be aware that the stimulus artefact associated with the linear protocol actually depends on the positional relationship between the TEOAE probe and the tympanic membrane. The greater the distance between the two, the larger the latency of the stimulus artefact (the reflection energy takes more time to reach the transducer microphone of the probe). In this context, a larger distance between the probe microphone and the tympanic membrane (caused in many instances by erroneous placement of the probe) will result in a temporal prolongation of the stimulus artefact; that is, the ringing will last longer in terms of milliseconds. Such an effect was not observed in any of the normal subjects who participated in this study. In our clinical practice, when the probe fitting results in excessive stimulus ringing, we have found it very useful to use the smaller adult ILO probe (like the neonatal version but brown in colour), which offers superior fitting and less ringing in the spectrum of the TEOAE stimulus. Incorrect positioning of the ILO probe might result in ringing stimulus waveforms with spectral peaks around 4 kHz in adult subjects, which will probably generate artefacts longer than 2.5 ms. The data from this study suggest that the combination of high-pass filtering and windowing significantly attenuates the artefacts (for practical purposes, the artefact vanishes), but in such cases it is recommended to use lower-intensity click stimuli (i.e. 70 dB SPL) to ensure the absence of any linear artefacts in the sampling window.

The data from the ears with SNHL indicate that a low-frequency linear artefact is present in the unprocessed recording, but is completely suppressed after the application of the proposed post-processing scheme. None of the tested SNHL ears generated responses which could be placed in or above the estimated 10th normative percentile of TEOAE correlation and SNR at 2.0, 3.0 and 4.0 kHz.

The findings of this study can be summarized as follows :

1. Linear recordings evoked by mid-intensity (72 dB p.e. SPL) click stimuli and post-windowed from 3.8 to 13.8 ms present better SNRs, lower levels of noise and higher values of correlation than the corresponding non-linear recordings.
2. Post-windowed linear recordings evoked by mid-intensity stimuli present amplitude contour patterns very similar to those from the corresponding non-linear responses in the early recording segments (3.2–5.2 ms). A repeated-measures model verified that there were no statistical mean differences between linear and non-linear recordings in these early segments. The authors have considered this finding as evidence of the lack of stimulus artefacts in the linear response.
3. It is possible to construct scoring criteria for adult subjects using the SNRs at 2.0 kHz (≥13 dB) and 3.0 kHz (≥11 dB). In the set of scoring criteria variables, one can include the TEOAE correlation (≥91%), since it relates to the quality of the TEOAE recording.

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Notes

The TEOAE visualization software used in the present study (see Figures 2 and 3) was developed by a scientific collaboration between the technical University of Warsaw, Poland and the Department of Audiology of Ferrara University, Italy. The viewer uses the data already stored by the ILO software in the dta ILO files. The program can be downloaded for free, from the Otoacoustic Emissions Portal site, address: http//www.otoemmisions.org

Appendix: The repeated-measures model

The selection of an appropriate within-subject covariance structure in the repeated-measures models was aided by comparing observed and theoretical covariance matrices, and by the use of the AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) model fit criteria. Both criteria are essentially the negative of the log likelihood value of the fitted model penalized by the number of parameters estimated, with BIC providing a heavier penalty than AIC. Models giving smaller values of the criteria are preferred.

References

AHEAD. 1995. *Newsletter of the European Concerted Action on Otoacoustic Emissions*, No. 7, 1–4.

Berlin, C.I., Hood, L.J., Hurley, A.E., Wen, H. & Kemp, D.T. 1995. Binaural noise suppresses linear click-evoked otoacoustic emissions more than ipsilateral or contralateral noise. *Hear Res*, 87, 96–103.

Berlin, C.I., Hood, L.J., Wen, H., Szabo, P., Cecola, R.P., et al. 1993. Contralateral suppression of non-linear click-evoked otoacoustic emissions. *Hear Res*, 71, 1–11.

Cheng, J. 1993. *Time Frequency Signal Representation of Transient Evoked Otoacoustic Emissions via Smoothed Pseudo-Wigner Distribution*. Report TA129. Stockholm: Karolinska Institute of Technical Audiology.

Cheng, J. 1995. Time frequency analysis of transient evoked otoacoustic emissions via smoothed pseudo-Wigner distribution. *Scand Audiol*, 24, 91–96.

Dircxx, J.J.J., Daemers, K., Somers, Th., Offeciers, F.E. & Govaerts, P.J. 1996. Numerical assessment of TEOAE screening results: currently used criteria and their effect on TEOAE prevalence figures. *Acta Otolaryngol (Stockh)*, 116, 672–679.

Fitzgerald, T.S. & Prieve, B. 1997. COAE thresholds: 1. Effects of equal amplitude versus subtraction methods. *J Speech Lang Hear Res*, 40, 1164–1176.

Gorga, M.P., Neely, S.T., Bergman, B.M., Beauchaine, K.L., Kaminski, J.R., et al. 1993. A comparison of transient-evoked and distortion product otoacoustic emissions in normal-hearing and hearing-impaired subjects. *J Acoust Soc Am*, 94(5), 2639–2648.

Grandori, F. & Ravazzani, P. 1993. Non-linearities of click-evoked otoacoustic emissions and the derived non-linear technique. *Br J Audiol*, 27(2), 97–102.

Grandori, F., Ravazzani, P., Tognola, G. & Hatzopoulos, S. 1994. Derived nonlinear versus linear click-evoked otoacoustic emissions. *In:* F. Grandori, L. Collet, D. Kemp, G. Salomon, K. Shorn, et al (eds.) *Advances in Otoacoustic Emission*, Vol I. Milan: Casa editrice Stefanoni, pp. 48–64.

Hatzopoulos, S., Cheng, J., Grzanka,A. & Martini, A. 2000b. Time–frequency analyses of TEOAE recordings from normal and SNHL cases. *Audiology*, 39, 1–12.

Hatzopoulos, S., Martini, M., Cheng, J, Grzanka, A. & Morlet, T. (2000a). Optimization of the TEOAE recording protocols. A linear protocol derived from parameters of a time–frequency analysis. A pilot study from neonatal subjects. *Scand Audiol*, 29, 21–27.

Hatzopoulos, S., Mazzoli, M. & Martini, A. 1995. Identification of hearing loss using TEOAE-based descriptors: preliminary results. *Audiology*, 34, 248–259.

Hatzopoulos, S., Petrucelli, J., Pelosi, G. & Martin, A. 1999. An optimized neonatal TEOAE screening protocol based on linear stimulus sequences. *Acta Otolaryngol* (*Stock*), 119(2), 135–139.

Hatzopoulos, S., Tsakanikos, M., Grzanka, A., Ratynska, J. & Martini, A. 2000c. A comparison of neonatal TEOAE responses recorded with linear and QuickScreen protocols. *Audiology*, 39, 70–79.

Johnsen, N.J., Bagi, P., Parbo, J. & Elberling, C. 1988. Evoked acoustic emissions from the human ear. IV. Final results in 100 neonates. *Scand Audiol*, 17(1), 27–34.

Kemp, D.T., Bray, P.B., Alexander, L. & Brown, A.M. 1986. Acoustic emission cochleography—practical aspects. *Scand Audiol Suppl*, 25, 71–94.

Kemp, D.T., Ryan, S. & Bray, P. 1990. Otoacoustic emission analysis and interpretation for clinical purposes. *In:* F. Grandori, G. Ciafrone & D.T. Kemp (eds.) *Cochlear Mechanisms and Otoacoustic Emissions*. Bern: Karger, pp. 77–98.

Kim, D.O. 1986. Active and nonlinear cochlear biomechanics and the role of outer-hair-cell subsystem in the mammalian auditory system. *Hear Res*, 22, 105–114.

Leeuw, A.R. & Dreschler, W.A. 1998. The relation between otoacoustic emissions and the broadening of the auditory filter for higher levels. *Hear Res*, 126(1–2), 1–10.

Lutman, M.E. 1993. Reliable identification of click-evoked otoacoustic emissions using signal-processing techniques. *Br J Audiol*, 27(2), 103–108.

Lutman, M.E., Jennings, K., Davis, A.C., Houston, H.G. & Meredith, R. 1994. Coloration of click-evoked otoacoustic emissions by characteristics of the recording apparatus. *In:* F. Grandori, L. Collet, D. Kemp, G. Salomon, K. Shorn, et al (eds.) *Advances in Otoacoustic Emission*, Vol. I. Milan: Casa editrice Stefanoni, pp. 36–47.

Osterhammel, P.A., Rasmussen, A.N., Olsen, S. & Nielsen, L.H. 1996. The influence of spontaneous otoacoustic emissions on the amplitude of transient-evoked emissions. *Scand Audiol*, 25, 187–192.

Patuzzi, R.B. 1987. A model of the generation of the cochlear microphonic with nonlinear hair cell transduction and nonlinear basilar membrane mechanics. *Hear Res*, 30, 73–82.

Prieve, B.A., Gorga, M.P., Schmidt, A., Neely, S., Peters, J., et al. 1993. Analysis of transient-evoked otoacoustic emissions in normal-hearing and hearing-impaired ears. *J Acoust Soc Am*, 93, 3308–3319.

Shera, C.A. & Guinan, J.J. Jr. 1999. Evoked otoacoustic emissions arise by two fundamentally different mechanisms: a taxonomy for mammalian OAEs. *J Acoust Soc Am*, 105(2 Pt 1), 782–798.

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

Thornton, A.R., Shin, K., Gottesman, E. & Hine, J. 2001. Temporal non-linearities of the cochlear amplifier revealed by maximum length sequence stimulation. *Clin Neurophysiol*, 112, 768–777.

Tognola, G., Ravazzani, P., Molini, E., Ricci, G., Alunni, N., et al. 2001. ‘Linear’ and ‘derived’ otoacoustic emissions in newborns: a comparative study. *Ear Hear*, 22, 182–190.

Welzl-Muller, K. & Stephan, K. 1994. Confirmation of transiently evoked otoacoustic emissions based on user-independent criteria. *Audiology*, 33, 28–36.

Whitehead, M.L., Jimenez, A.M., Stagner, B.B., McCoy, M.J., Lonsbury-Martin, B.L., et al. 1995. Time-windowing of click-evoked-otoacoustic emissions to increase signal-to-noise-ratio. *Ear Hear*, 16, 599–611.

Von Specht, H., Ganz, M., Pethe, J., Leuschner, S. & Pytel, J. 2001. Linear versus non-linear recordings of transiently-evoked otoacoustic emissions—methodological considerations. *Scand Audiol Suppl*, 52, 116–118.

Zinn, C., Maier, H., Zenner, H. & Gummer, A.W. 2000. Evidence for active, nonlinear, negative feedback in the vibration response of the apical region of the in-vivo guinea-pig cochlea. *Hear Res*, 142, 159–183.

Zwicker, E. 1986. ‘Otoacoustic’ emissions in a nonlinear cochlear hardware model with feedback. *J Acoust Soc Am*, 80, 154–162.