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Original Article

Time-Frequency Properties of Neonatal Transiently Evoked Otoacoustic Emissions Measured in Three Different Acquisition Modes

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OBJECTIVE: The purpose of this study was to investigate transiently evoked otoacoustic emissions recorded from the cochleas of neonates using three acquisition protocols: non-linear; linear; and QuickScreen. In the non-linear mode, a series of four clicks was used, with three clicks at the same level and polarity and a fourth at three times greater amplitude and inverted polarity. In the linear protocol, all stimuli were presented at the same level and polarity. Both modes used a 20 ms recording window, but the third QuickScreen screening mode used the non-linear click sequence and a shorter 12 ms window.

MATERIALS and METHODS: All responses were processed off-line with time-frequency algorithms, with the linear transiently evoked otoacoustic emissions additionally processed to eliminate linear artifacts in the initial few milliseconds of signal.

RESULTS: Short windows contained only a fraction of the transiently evoked otoacoustic emission, distorting its time-frequency structure. Analysis of the response level and signal to noise ratio suggested that recordings elicited by a linear protocol had an advantage in terms of signal to noise ratio.

CONCLUSION: The results indicate that screening protocols that use recording windows with a reduced length, such as QuickScreen, can only be used to detect the presence or absence of otoacoustic emission. Removing the stimulus artifact from linear transiently evoked otoacoustic emission responses improves response level and signal to noise ratio compared with the standard non-linear protocol.

KEY WORDS: Otoacoustic emission, TEOAE, linear protocol, non-linear protocol, QuickScreen, newborns

INTRODUCTION

Previous studies [1-4] have shown that transiently evoked otoacoustic emissions (TEOAEs) elicited from the cochlea by a sequence of identical clicks, a 'linear' mode, exhibit stimulus artifacts in the first few milliseconds of the post-stimulus time window. Kemp et al. [1] therefore devised a 'non-linear' mode to cancel these artifacts. This mode is currently considered the standard TEOAE acquisition paradigm. The non-linear protocol averages responses in a way that linear components of the signal, in particular, reflections from the tympanic membrane are cancelled and the signal contains only non-linear components, which neatly reflect the nonlinear properties of the otoacoustic emissions. In the non-linear mode, TEOAE responses are elicited by a series of four clicks delivered to the ear canal, with three clicks at the same level and polarity and the fourth at three times greater amplitude and inverted polarity. The recording window is typically 20 ms, allowing 50 stimuli per second to be delivered. Despite these advantages, the non-linear mode has notable shortcomings, such as the lower level of otoacoustic emissions (OAEs) produced and the partial elimination of high frequency components that are present in the first few milliseconds of the response [4, 5].

Another modification introduced by Kemp and Ryan [6] is the so-called QuickScreen protocol, which has become the most common method of measuring TEOAEs in neonates. It is based on the non-linear protocol but uses an abbreviated recording window (2.5-12 ms), which means a shorter recording time, its main advantage. A drawback, however, is that the low frequency response of the TEOAE suffers [4].

Recently, a new procedure for cancelling linear artifacts was introduced [7]. This work showed that the linear artifacts were contained mainly in a time window of 0-5 ms and in a frequency range of 0-2200 Hz. This part of the response can be easily and reliably removed using a simple combination of windowing and filtering, or more advanced time-frequency analysis techniques, leaving the high frequency TEOAE response intact. The above study was based on TEOAE responses from adult ears, but in clinical practice TEOAEs are of most interest in the case of newborns and young children. Therefore, the challenge is to apply the same procedure

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of artifact removal on TEOAE responses from newborn subjects. The aim of this study was to record TEOAEs from neonatal ears using each of the three stimulation protocols and compare their characteristics using time-frequency decomposition algorithms.

MATERIALS and METHODS

Transiently evoked otoacoustic emissions from 40 full-term neonates (19 males, 21 females) were measured in low-noise ambient conditions by an ILO-292 apparatus (Otodynamics Ltd, Hatfield, UK) running software version 5.6. The probe used in the measurements was calibrated using the manufacturer-supplied calibration cavity. Only one ear of each newborn was randomly picked for data acquisition (18 right and 22 left). The neonates were also tested otoscopically to exclude any external ear abnormalities (e.g., excessive wax, collapse of the meatal canal). Middle ear function was evaluated using impedance audiometry, as middle ear status may significantly influence OAE properties [8]. The families provided a consent for the hearing screening of the infants and the anonymity of the data. Transiently evoked otoacoustic emissions from 40 full-term neonates.

Standard non-linear, linear, and screening (called QuickScreen in ILO equipment) TEOAE protocols were used to collect data (average stimulus of 80 peak dB SPL, 260 repetitions). In analysing the data, the following windows (i.e., TEOAE recording lengths) were considered: (i) non-linear protocol 2.5-20 ms; (ii) linear protocol 2.5-20 ms; and (iii) QuickScreen protocol 2.5-12.5 ms. The TEOAEs recorded in the linear protocol were subject to additional windowing of 0-5 ms and filtering of 0-2200 Hz according to the procedure described in the Methods section.

All TEOAE recordings were evaluated using standard TEOAE parameters: response level and signal to noise ratio (SNR, the difference between the response and noise levels expressed in dB). The SNR is related to another common TEOAE parameter, reproducibility, which is calculated as follows: reproducibility=$[1+(SNR)^{-2}]^{-1}$ [9]. Of particular interest were the time-frequency parameters latency and duration, and their estimation is described in the Methods section. Values of all these parameters were estimated at half-octave band intervals (1.0, 1.4, 2.0, 2.8, and 4.0 kHz).

The OAE signals were subject to time-frequency analysis using the matching pursuit (MP) method introduced by Mallat and Zhang [10]. The MP algorithm relies on adaptive decomposition of the signal into discrete waveforms, called atoms, from a large and redundant set of functions called a dictionary. The method has proved to be a reliable tool to extract time-frequency properties of TEOAE components [11]. Here, a slightly modified method was used that accounts for the asymmetrical character of some of the components [12]. The modified MP method allowed the decomposition of the TEOAE signals into waveforms of defined frequency, latency, duration, and amplitude. The latency is the time taken from onset of the stimulus to the maximum point in the waveform envelope, and the duration parameter is defined as half the width of the waveform envelope.

The latency of OAEs has been of considerable interest in the literature for some time [13, 14]. It has proved to be an important descriptor not only for the theory of OAEs and cochlear mechanics [15, 16], but also as a clinical parameter, since some pathologies cause shifts in latency [17, 18]. The duration of OAE components is a more recent parameter: its usefulness is not as direct but it can be a valuable tool to assess features of OAEs in addition to their type and latency. For example, evoked components generally have a short duration, while spontaneous or long-lasting components have a much increased duration [19]. High frequency OAE components usually have short durations and low frequency components have longer ones [11].

In the case of TEOAEs recorded with the linear protocol, additional processing was applied. In line with the procedure proposed by Jedrzejczak et al. [7], the signal in the range of 0-5 ms and 0-2200 Hz was filtered out. This was done using the MP method, which makes it possible to algebraically subtract unwanted components from the original signal. For those that do not have access to advanced processing methods such as MP, there is an equivalent method. First, the linear TEOAE signal should be filtered below 2.2 kHz (a second-order Butterworth filter should be adequate). Next, a windowing from 2.5-5 ms using a cosine window should be applied. Last, this derived signal should be subtracted from the linear TEOAE recording. It has been shown on adult subjects that such processing removes linear artifacts and leaves the high frequency response largely unaffected.

Statistical Analysis

For all parameters, the statistical significance of the mean difference between groups was evaluated using the Wilcoxon rank sum test (all evaluations were made in Matlab). This is the equivalent of Student's *t*-test when the populations involved do not have normal distributions. As a criterion of significance, a 95% confidence level ($p<0.05$) was chosen.

RESULTS

In order to objectively compare properties of TEOAEs recorded under different protocols, time-frequency analysis was applied to each recording. The parameters of interest were latency and duration of each frequency component. Figure 1 shows the average time-frequency parameters of TEOAE signals recorded under the non-linear, linear, and QuickScreen protocols. It can be seen that the time progressions of the linear and non-linear protocols were very similar. The latency began at about 5 ms for the 4 kHz components and extended to around 11 ms for 1 kHz components. The differences between the linear and non-linear protocols were not significant. The latency values for QuickScreen were slightly different compared with those for the other two protocols: it can be observed that average values of latency and time span were smaller at lower frequencies and greater at higher frequencies. The differences were statistically significant, and were the effect of the shorter acquisition window used in the QuickScreen protocol. Only values in the range from 1.4-2.8 kHz were similar to those of the other two protocols. In the case of duration, the differences were smaller, but it can be seen that the average duration of QuickScreen responses was about 1 ms shorter, especially at lower frequencies. In summary, the time-frequency parameters derived from the QuickScreen protocol were generally significantly different at the lowest and highest frequencies compared with those of the non-linear and linear protocols ($p<0.05$). On the other hand, there was no statistically significant difference between the non-linear and linear protocols.

Figure 2 shows the average response levels and SNRs. These parameters are especially important because most OAE screening criteria are based on them. The results indicated that all modes provided

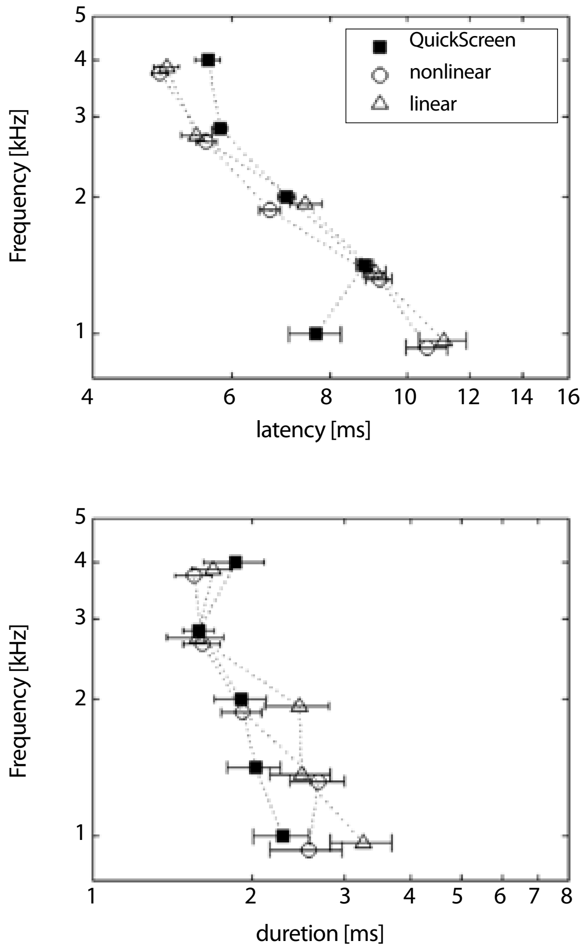

Figure 1. Average latency and duration (all parameters taken from MP analysis) in half-octave frequency bands for TEOAEs measured in different protocols (nonlinear, linear, QuickScreen). The whiskers indicate standard errors

MP: matching pursuit; TEOAEs: transiently evoked otoacoustic emissions

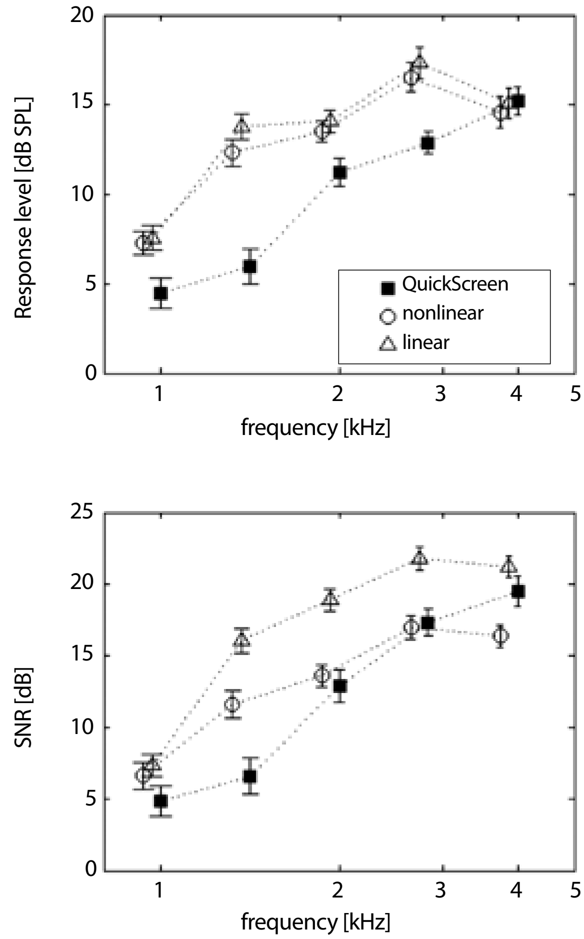

Figure 2. Average half-octave response level and SNR for TEOAEs measured in different protocols (nonlinear, linear, QuickScreen). The whiskers indicate standard errors

SNR: signal to noise rotio; TEOAEs: transiently evoked otoacoustic emissions

quite a low level of response at 1 kHz. However, response levels were significantly better with the linear and non-linear modes than with QuickScreen at frequencies from 1-2.8 kHz. QuickScreen provided similar response levels to the other two protocols only at 4 kHz. In the case of SNR, there was an apparent advantage of the linear mode over both the non-linear and QuickScreen modes. The difference was especially prominent between 1.4 and 2.8 kHz, reaching around 5 dB.

DISCUSSION

The objective of the present study was to compare three available modes of TEOAE recording: the non-linear; linear; and screening (QuickScreen) modes. In contrast to previous work in which the initial 6 ms of the TEOAE linear signal was discarded in order to avoid stimulus artifacts [2, 20], here an alternative method was used. Only the range 0-5 ms in time and 0-2200 Hz in frequency was windowed and filtered, while for frequencies above 2200 Hz, only the initial 2.5 ms were windowed. The effect of this change was preservation of the high frequency response when using the linear protocol [7].

The time-frequency analysis revealed that TEOAEs measured using protocols with recording windows of reduced length (12 ms, i.e., QuickScreen) had significantly different properties in comparison with full-length recordings (20 ms). Additionally, it was shown that when the method of artifact reduction was applied to the linear mode TEOAE recordings, the time-frequency properties of the data were similar to the responses elicited by the non-linear protocol. The TEOAE latency-frequency dependence for newborn ears studied here was found to have similar characteristics to those of adults [7]. In terms of latency-frequency properties, there seemed to be no maturational effects [21], which are found with response level [22].

Analysis of the standard TEOAE parameters, response level, and SNR suggested that recordings elicited by the linear protocol had an advantage in terms of SNR. This finding is important, as SNR is commonly used in automated algorithms to distinguish a genuine TEOAE response from noise [23]. Looked at another way, high values of SNR mean that the averaging process requires fewer samples, leading to shorter measurement times.

Some papers already exist that demonstrate the advantages of the linear mode [3-5, 20], and this work further strengthens them. Moreover, the present investigation shows general agreement between the properties of the linear and non-linear modes, and the higher SNR of the linear mode.

In conclusion, the results of time-frequency analysis have shown that TEOAEs measured using protocols with recording windows of reduced length (i.e., QuickScreen) are distorted compared with measurements with standard windows. This indicates they should only be used in quickly detecting the presence of an OAE. For more sophisticated clinical analyses, the standard 20 ms TEOAE recording window is more appropriate.

The linear mode appears to be a promising alternative to the commonly used non-linear mode. This is especially the case when the new method to filter out artifacts is applied. The high frequency part of a TEOAE is preserved and the response at both high and low frequencies shows high values of level and SNR.

Ethics Committe Approval: This study does not need ethics committee approval, nevertheless it was performed according to Helsinki Declaration.

Informed Consent: Written informed consent was obtained from patients who participated in this study.

Peer-review: Externally peer-reviewed.

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