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MAIN ARTICLE

Correlation between speech-evoked auditory brainstem responses and transient evoked otoacoustic emissions

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Abstract

Objective: To investigate the correlation between cochlear processing and brainstem processing.

Method: Transient evoked otoacoustic emissions and speech-evoked auditory brainstem responses were recorded in 40 ears of normal-hearing individuals aged 18 to 23 years. Correlation analyses compared transient evoked otoacoustic emission parameters with speech-evoked auditory brainstem response parameters.

Results: There was a significant correlation between speech-evoked auditory brainstem response wave V latency and transient evoked otoacoustic emission global emission strength; there were no other significant correlations between the two tests.

Conclusion: Tests for transient evoked otoacoustic emissions and speech-evoked auditory brainstem responses provide unique and functionally independent information about the integrity and sensitivity of the auditory system. Therefore, combining both tests will provide a more sensitive clinical battery with which to identify the location of different disorders (e.g. language-based learning impairments and hearing impairments).

Key words: Otoacoustic Emissions; Evoked Potentials; Auditory Brainstem Responses

Introduction

During recent years, one of the most exciting advances in our understanding of hearing has been the discovery of otoacoustic emissions (OAEs). Otoacoustic emissions refer to the acoustic energy signals generated by the cochlea in response to stimuli, which are detectable in the external auditory canal.[1] These acoustic signals are considered a byproduct of the physiological processes necessary for normal hearing, specifically the outer hair cell functions.[2] The recognition that the cochlea not only receives sound but also produces acoustic energy has been a major development in recent conceptions of cochlear function.

Transient evoked OAEs (TEOAEs) are a major subclass of evoked OAEs which can be recorded in response to brief acoustic stimuli. They are complex acoustic events which can be recorded in almost all individuals with normal hearing (i.e. in 96–100 per cent). They show a characteristic delay (i.e. latency) between the acoustic stimulus and the evoked emission. The origin of TEOAEs has been suggested to involve reflections from impedance discontinuities, either anatomical or as a result of wave-related mechanical interaction at the cochlea.[1,3,4] The detection of TEOAEs is considered to be a fast screening method for peripheral hearing loss.

Sound is encoded in multiple locations along the ascending auditory pathway from the cochlea to the auditory cortex, eventually leading to conscious perception. Speech is a complex acoustic signal rich in both spectral and temporal features, and, although not mandatory for survival, it is an essential part of everyday life. The cochlea performs the first analysis of complex sound stimuli according to their components. The cochlear nuclei, superior olivary complex and lateral lemniscus nuclei code different aspects of sound stimuli (i.e. frequency, intensity and timing) and transmit the processed information via six parallel paths into the medial nuclei of the inferior colliculi. Tonotopic organisation is preserved in all auditory nuclei and in the auditory cortices of both hemispheres.

Speech sounds consist of three fundamental components: pitch (a source characteristic conveyed by the fundamental frequency); formants (filter characteristics conveyed by the selective enhancement and attenuation of harmonics); and the timing of major acoustic landmarks. All of these aspects are important for speech perception.[5]

In the mature auditory system, the basal regions of the cochlea are maximally responsive to high frequencies, while the apical regions are maximally responsive

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to lower frequencies. This tonotopic organisation is preserved throughout the central auditory pathways, and is thought to help preserve spectral relations in the pattern of neural activity.[6,7]

Speech-evoked auditory brainstem responses (ABRs) are useful in many areas of research, and have clinical applications because of their high degree of reliability both within and between individuals. Thus, not only are the major morphological features of the ABR stable over time within an individual, the major peaks are also highly replicable between individuals, making deviations from the normal range easily identifiable and informative.[5,8–10]

Need for the study

The auditory nervous system connects the various sites of auditory processing, from the cochlea to the auditory cortex. Auditory processing at lower levels is likely to influence processing within higher auditory centres.

Some studies have reported deficient encoding of speech-evoked ABRs in children with learning disability, and weakened correlations have been found between the brainstem and the auditory cortex in such children.[11] It may be hypothesised that these children may have deficient encoding at any level of the auditory system.

Analysing cochlear and brainstem functions together, and in different clinical populations, may enable the development of a more sensitive clinical battery with which to identify the location of different disorders. It is also possible that the relationships between the cochlea and the brainstem can be enhanced through appropriate auditory training.[12] Certain aspects of speech-evoked ABRs (relating to harmonics, spectrotemporal data and the sound envelope boundary) are related to, or may vary in parallel with, aspects of cochlear function as measured by the strength and structure of distortion product OAEs.[13] As the acoustic signal is processed at the cochlear level and then transmitted to the higher auditory system, one might expect one-to-one correlation between test results obtained at the cochlea and at higher auditory levels.

The present study set out to investigate whether a relationship exists between cochlear functioning and auditory system functioning, despite their differences in acoustic signal processing. To the best of our knowledge, no previous study has assessed the correlation between cochlear processing and brainstem level processing, using speech-evoked ABR and TEOAE testing. We undertook such a study, within normal-hearing individuals. The information obtained from this study could be utilised for further research within clinical populations.

Aims

This study aimed to establish the relationship between TEOAEs and speech-evoked ABRs within normal-hearing individuals.

Method

Participants

Thirty-five individuals (40 ears) with ages ranging from 18 to 23 years participated in the study. All participants had normal hearing thresholds in both ears, as revealed by absolute pure tone thresholds of <15 dB HL in octaves frequency from 250 to 8000 Hz for air conduction and from 250 to 4000 Hz for bone conduction. Normal middle-ear function was established by tympanometry and reflexometry evaluations, and confirmed by otological examination. None of the participants had any neurological symptoms, as established by neurological history-taking. Speech in noise test results were normal, indicating normal auditory processing.

All subjects consented to participate in the study.

Procedure

All subjects underwent pure tone audiometry, tympanometry, reflexometry and speech in noise testing. Testing was performed in a sound-treated room with appropriate acoustic isolation and the maximum permissible ambient noise levels as specified by ANSI S3.1-1991.[14] Participants were placed in a reclining position with good neck support and were encouraged to close their eyes, relax and sleep during the recording process, so as to avoid artefacts related to muscle responses.

A two-channel clinical audiometer (Madsen OB922, V-2X; G N Otometrics, Taastrum, Denmark) was used for pure tone audiometry, calibrated as per ANSI S3.6-1996, with TDH-39 headphones housed in Mx-41/AR ear cushions (Telephonics, Farmingdale, New York, USA).[15] A Radioear B-71 bone vibrator (Radio ear, KIMMETRICS, 22050 Mohawak Drive, Smithsburg, MD 21783) was used to measure bone conduction threshold. The pure tone threshold was traced using a modified Hughson and Westlake procedure.[16] Tympanometry and reflexometry were performed with a calibrated middle-ear analyser (GSI Tympstar; GSI VIASYS Healthcare, Wisconsin, USA) using a 226 Hz probe tone. Reflexes for both the ipsilateral and contralateral ear were checked at 0.5, 1 and 2 kHz. Speech in noise testing was performed at the most comfortable level (i.e. 40 dB SL), at 0 dB signal-to-noise ratio.

Transient evoked otoacoustic emissions

Transient evoked OAEs (TEOAEs) were recorded using Capella OAE equipment (Madsen, V-2X, G N otometrics, Taastrum, Denmark). For each subject, the OAE probe was fitted with a foam tip and inserted into the external auditory canal, and the TEOAE calibration procedure was performed to obtaine a flat stimulus spectrum across the frequency range. We recorded OAEs evoked by non-linear clicks presented at 80 dB SPL. The two averaged TEOAE waveforms of each memory buffer, composed of 260 accepted

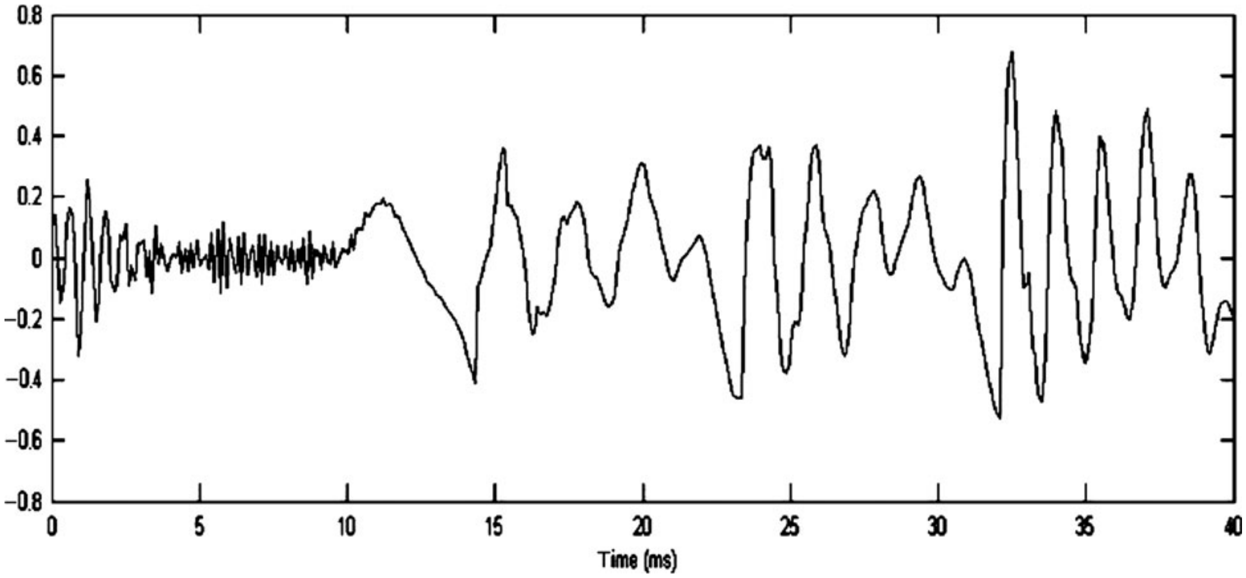

FIG. 1
Time domain waveform of the stimulus /da/.

click trains, were automatically cross-correlated. The equipment software used these cross-correlated waveforms to determine the reproducibility of the measured TEOAEs. A TEOAE was considered to be present if the reproducibility of the TEOAE was more than 80 per cent and the signal-to-noise ratio was at least 6 dB SPL criteria was taken (i.e. the difference between the amplitude of the response and the amplitude of the noise floor). The recorded TEOAE measurements were used to calculate the global signal-to-noise ratio, the signal-to-noise ratio at 1 kHz (the only TEOAE frequency that lies well within the high frequency range of speech-evoked ABRs) and the global emission strength.

Speech-evoked auditory brainstem responses

The speech-evoked frequency following response may be changed to speech evoked auditory brainstem response was recorded using a Biologic Navigator Pro evoked potential instrument (Natus Medical incorporated San Carlos, CA 94070 USA). A synthesised /da/ syllable was used as the test stimulus (available in the Biologic Navigator Pro system, using the BioMark protocol). The /da/ stimulus is a 40 millisecond, synthesised speech syllable produced using the Klatt synthesiser.[17] This stimulus contains broad spectral and fast temporal information (characteristic of stop consonants), together with spectrally rich formant transitions between the consonant and the steady-state vowel. The fundamental frequency rises in a linear fashion from 103 to 125 Hz, with voicing beginning at 5 milliseconds and an onset noise burst during the first 10 milliseconds. The first formant rises from 220 to 720 Hz, while the second formant decreases from 1700 to 1240 Hz over the duration of the stimulus. The third formant falls slightly from 2580 to 2500 Hz, while the fourth and fifth formants remain constant at 3600 and 4500 Hz, respectively. The time domain waveform of the stimulus used in the present study is shown in Figure 1.

Speech-evoked ABRs were recorded using a single channel. Each electrode site was cleaned with the help of skin preparatory gel. Electrodes were dipped in conductive paste and then placed on each recording site with the help of adherent paste. The non-inverting electrode was placed on the vertex, the inverting electrode on the test ear mastoid and the ground electrode on the non-test ear mastoid. The impedance at each electrode site was kept to within 5 kΩ, and that at the inter-electrode site to within 2 kΩ. The stimulus parameters and acquisition parameters used in the study are given in Table I.

For each ear, two waveforms were recorded for /da/; these were then added together using the ‘weighted add’ option in the Biologic EP instrument. This combined waveform was converted to American Standard Code for Information Interchange (ASCII) format using the ‘AEP to ASCII’ software function. ASCII format data were then analysed using the Brainstem Toolbox software developed at Northwestern University (School of communication 2240 Campus Drive Evanston IL 60208). This software runs on MATLAB® platform and can be used to calculate the FFT of the waveform and to analyze the Frequency following responses.

Data were analysed as described by Russo *et al.* and Wible *et al.*[8,18] The seven peaks of the response to /da/ (labelled wave V and peaks A, C, D, E, F and O) were identified. The frequency following response for frequency encoding was analysed using a Fourier analysis 11.4–40.6 millisecond time window. To increase the number of sampling points in the frequency domain, the time window was zero-padded to 4096 points

TABLE I
INVESTIGATION PARAMETERS

Parameter	Setting
Stimulus parameters	
Stimulus type	Speech stimulus (/da/)
Stimulus duration	40 msec
Stimulus rate	9.1/sec
Polarity	Alternating
Sweeps (*n*)	3000
Intensity	80 dB SPL
Transducer	ER-3 Ainsert receiver
Acquisition parameters	
Mode	Monaural stimulation
Electrode type	Disc electrode
Channels	Single channel
Analysis window	74.67 ms + 15 ms pre-stimulus time window
Filter settings	100–3000 Hz
Notch filter	On
Replicability	Twice for 3000 sweeps
Gain	1 00 000 times
Artefact rejection	23 μV

before performing a discrete Fourier transform. The average spectral amplitude was calculated for three frequency ranges: fundamental frequency (103–120 Hz), first formant (455–720 Hz) and higher frequencies (721–1154 Hz). The first formant of the stimulus ramped from 220 to 720 Hz over the 40 millisecond syllable. The first formant frequency range used for frequency following response analysis accounted for the time lag and the corresponding first formant frequency ramping between the onset of the stimulus and the periodic formant transition that elicited the frequency following response. The higher frequency range corresponded to the seventh to 11th harmonics of the fundamental frequency of the stimulus, a frequency range between the first and second formants. All the analysis for the frequency following response was computed using Brainstem Toolbox software.

These values were used to establish the correlation between speech-evoked ABR results and the TEOAE global signal-to-noise ratio, signal-to-noise ratio at 1 kHz and global emission strength.

Results

The present study aimed to correlate the speech-evoked ABR with the transient evoked OAE (TEOAE) amplitude. We calculated the mean, standard deviation and range for different parameters of speech-evoked ABR (both transient and sustained), as well as for TEOAE amplitude. Table II shows the mean, standard deviation and range data for speech-evoked ABR parameters.

It can be seen from Table II that the amplitude of the speech-evoked ABR fundamental frequency was greater than the mean amplitude calculated for the first formant and higher frequencies. It can also be seen that the periodicity between peaks D and E and peaks E and F is similar, indicating that the fundamental frequency is encoded efficiently in all subjects.

TABLE II
SPEECH-EVOKED ABR RESULTS

Parameter	Mean ± SD	Range
Wave V amplitude (μv)	0.06 ± 0.12	−0.32 to 0.29
F_0 amplitude (μv)	5.4 ± 2.28	0.84–8.95
F_1 amplitude (μv)	1.34 ± 0.59	0.42–2.49
HF amplitude (μv)	0.45 ± 0.16	0.20–0.89
Wave V latency (msec)	6.47 ± 0.34	5.64–7.39
Peak A latency (msec)	7.90 ± 2.37	6.59–18.76
Peak C latency (msec)	18.74 ± 1.38	16.43–22.85
Peak D latency (msec)	23.46 ± 2.40	21.83–31.16
Peak E latency (msec)	32.07 ± 3.22	22.99–40.49
Peak F latency (msec)	40.81 ± 3.27	38.74–49.24
Peak O latency (msec)	44.93 ± 11.39	0.05–49.97

ABR = auditory brainstem; SD = standard deviation; F_0 = fundamental frequency; F_1 = first formant; HF = higher frequencies

Table III shows the mean, standard deviation and range for the TEOAE global signal-to-noise ratio and global emission strength.

The Pearson product moment correlation coefficient was calculated to assess the correlation between the speech-evoked ABR parameters of interest (particularly the wave V amplitude and the amplitude at the fundamental frequency, first formant and higher frequencies) and the TEOAE parameters of interest (i.e. the global signal-to-noise ratio, signal-to-noise ratio at 1 kHz and global emission strength (absolute amplitude)). Table IV shows the Pearson product moment correlation coefficient for various combinations of these speech-evoked ABR and TEOAE parameters.

It can be seen from Table IV that there was no significant correlation between the ABR wave V amplitude, fundamental frequency amplitude, first formant amplitude and higher frequency amplitude, and the TEOAE global signal-to-noise ratio and global emission strength ($p > 0.05$). In addition, there was no significant correlation between the ABR higher frequency amplitude and the TEOAE signal-to-noise ratio at 1 kHz. However, there was a significant correlation between the TEOAE global signal-to-noise ratio (i.e. the difference between the amplitude of the response and the amplitude of the noise floor) and the TEOAE global emission strength (i.e. the overall absolute amplitude of the OAEs) ($p < 0.001$).

We also calculated the correlation between various speech-evoked ABR peak latencies and the TEOAE global emission strength. Table V shows the Pearson product moment correlation coefficient for these comparisons.

TABLE III
TEOAE RESULTS

Parameter	Mean ± SD	Range
Global SNR	14.13 ± 5.09	2–26.60
SNR at 1 kHz	12.99 ± 7.70	0.40–28.10
Global emission strength	15.23 ± 5.20	2.50–24.90

TEOAE = transient evoked otoacoustic emission; SD = standard deviation; SNR = signal-to-noise ratio

TABLE IV

CORRELATION BETWEEN SPEECH-EVOKED ABR AND TEOAE PARAMETERS

Comparison	r^*	p
Wave V ampl *vs* global SNR	−0.120	>0.05
Wave V ampl *vs* global ES	0.094	>0.05
F_0 ampl *vs* global SNR	−0.090	>0.05
F_0 ampl *vs* global ES	0.130	>0.05
F_1 ampl *vs* global SNR	−0.117	>0.05
F_1 ampl *vs* global ES	0.080	>0.05
HF ampl *vs* global SNR	−0.067	>0.05
HF ampl *vs* SNR at 1 kHz	−0.091	>0.05
HF ampl *vs* global ES	0.081	>0.05
Global SNR *vs* global ES	0.566	<0.001

*Pearson correlation coefficient. ABR = auditory brainstem response; TEOAE = transient evoked otoacoustic emission; ampl = amplitude; SNR = signal-to-noise ratio; ES = emission strength; F_0 = fundamental frequency; F_1 = first formant; HF = higher frequency

It can be seen from Table V that there was significant correlation only between the speech-evoked ABR wave V latency and the TEOAE global emission strength ($p < 0.001$). No other significant correlations were found. From these calculations, we infer that a correlation exists between the onset responses of speech-evoked ABRs and TEOAEs, but not between the sustained responses of speech-evoked ABRs and TEOAEs.

Discussion

The results in Table IV show that the speech-evoked ABR wave V, fundamental frequency, first formant and higher frequency amplitudes did not correlate with the transient evoked OAE (TEOAE) amplitude. This may be because the energy concentration at the fundamental frequency (103–120 Hz), first formant (455–720 Hz) and higher frequencies (721–1154 Hz) differed from that at the frequencies contributing to the TEOAE amplitude (i.e. 1, 1.5, 2, 3 and 4 kHz). The only TEOAE frequency which lay well within the speech-evoked ABR higher frequency range was 1 kHz. There was no significant correlation between the TEOAE signal-to-noise ratio at 1 kHz and the speech-evoked ABR higher frequency amplitude.

The only significant correlation identified in the study was between the speech-evoked ABR wave V latency and the TEOAE global emission strength. This could be because TEOAEs occur predominantly within the frequency region 500 Hz to 4 kHz, while the ABR wave V arises predominantly from the basal part of the cochlea.

TABLE V

CORRELATION BETWEEN SPEECH-EVOKED ABR LATENCIES AND TEOAE GLOBAL EMISSION STRENGTH

Comparison	r^*	p
Wave V latency *vs* GES	−0.37	<0.001
Peak A latency *vs* GES	−0.20	>0.05
Peak C latency *vs* GES	−0.18	>0.05
Peak D latency *vs* GES	−0.17	>0.05
Peak E latency *vs* GES	−0.07	>0.05
Peak F latency *vs* GES	−0.14	>0.05
Peak O latency *vs* GES	0.06	>0.05

*Pearson correlation coefficient. ABR = auditory brainstem response; TEOAE = transient evoked otoacoustic emission; GES = global emission strength

To our best knowledge, these specific relationships between TEOAE and speech-evoked ABR parameters have not previously been reported.

Anthony and colleagues conducted a retrospective study to assess the correlation between TEOAEs and ABRs (due to click stimuli) in a group of normal-hearing neonates and young children aged from approximately three weeks to four years.[19] These authors did not find any significant correlations between TEOAE and ABR variables.

Dhar *et al.* investigated the relationship between speech-evoked ABR and distortion product OAEs (DPOAEs) in normal-hearing adults, and found significant relationships between DPOAE strength and peak D, E and F latencies and harmonic measures (the average spectral energy was 455–720 Hz at the first formant and 721–1154 Hz at higher frequencies).[13] Distortion product OAE structure showed significant relationships with peak C and O latencies, but neither DPOAE strength nor structure was related to speech-evoked ABR pitch (fundamental frequency 103–120 Hz).

- **Otoacoustic emissions (OAEs) and speech-evoked auditory brainstem responses (ABRs) are objective indices of peripheral auditory physiology, and are used clinically to assess hearing function**
- **The relationship between these parameters is little known; this study aimed to assess any correlations**
- **There was significant correlation between ABR wave V latency and transient evoked OAE global emission strength; no other correlations were found**

These study findings suggest that, in order to maximise information derived from diagnostic testing, establishing a test protocol that includes both speech-evoked ABR and TEOAE testing would be efficacious, especially in patients with language disorders.

Conclusion

Certain aspects of speech-evoked ABRs are related to, or vary in parallel with, cochlear function as measured by transient evoked OAE global signal-to-noise ratio and global emission strength. The present study findings form a foundation for future research in clinical populations, such as patients with hearing loss, language-based learning impairments and speech-in-noise perception deficits.

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