

# Otoacoustic emissions as a screening test for hearing impairment in children

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## Abstract

**Transient evoked otoacoustic emissions (TEOAEs) are low amplitude sound waves produced by the healthy cochlea. They can be recorded with a microphone in the external ear. TEOAEs are abolished by hearing losses of 30 dB or more. The feasibility of using TEOAEs as a screening test for hearing loss in children was studied. TEOAE recordings were attempted in 56 children attending an audiology clinic. Recordings were possible from both ears in 52 children; of these 104 ears, 32 had hearing deficits of 30 dB or more. Hearing status was compared with the results of six TEOAE screening criteria. All criteria had a sensitivity of 1.00. Four standard TEOAE criteria yielded specificities of 0.46-0.58. Two new criteria derived from analysis of limited frequencies from the TEOAE waveform gave specificities of 0.76 and 0.82. It can be concluded that, when appropriate pass/fail criteria are employed, TEOAEs are a feasible screening test in children.**

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Otoacoustic emissions are soundwaves of very low amplitude that are produced by the inner ear.<sup>1</sup> Emissions can occur spontaneously, but in clinical practice they are usually elicited in response to a brief auditory stimulus. These transient evoked otoacoustic emissions (TEOAEs) can be recorded from virtually all normal ears and are abolished in virtually all ears with a significant degree of hearing loss.<sup>1-3</sup> This characteristic 'all or nothing' response, combined with the simplicity of the test procedure, led to the proposal that TEOAEs could be used as a simple and effective screening test for hearing impairment.<sup>2,3</sup> In fact, several reports exist of successful applications of the technique for both high risk<sup>4,5</sup> and universal<sup>6</sup> neonatal screening.

TEOAEs could also be used to quickly identify or exclude hearing loss in older children. In this way, health professionals such as paediatricians, audiologists, general practitioners, and health visitors could perform or obtain a rapid TEOAE test in order to identify those children who require a more detailed, diagnostic audiological assessment. Several situations have been identified in which TEOAE screening may be of value in this context. Populations that could be screened include children, such as those with severe

learning difficulties, who are difficult to assess by conventional means.<sup>7</sup> Another potential group consists of those children who have a particularly high risk of hearing impairment after meningitis<sup>8,9</sup> or the use of ototoxic drugs.<sup>3,8</sup> It has also been proposed that TEOAEs could be used for universal preschool screening.<sup>10</sup> To date, however, only two short reports have been published on the clinical use of TEOAE screening in children.<sup>9,10</sup>

Two major difficulties have been identified in the use of TEOAEs in older children. The first is that some children will not tolerate the test procedure.<sup>7,9</sup> The second is that, despite the excellent sensitivity of the test, there may be an unacceptably high number of false positive results.<sup>11</sup> This problem of low specificity is mainly due to the fact that the sound of the TEOAE signal is often obscured by other noise.<sup>11</sup> Noise can be both external (in the test environment) and internal (from activities such as swallowing and breathing by the child).

The effect of noise is demonstrated in the figure which shows TEOAE recordings obtained from two normally hearing children with the commercially available ILO88 device. The left hand panel of (i) demonstrates a clear TEOAE as evidenced by high amplitude waveforms with excellent correlation between the two averaged responses (A and B). The existence of a high quality TEOAE is confirmed by the presence of a clear signal showing above the noise in the power analysis panel. The recording would be classified as a pass by all current screening criteria. In contrast, the normally hearing ear in figure (ii) would fail. While the trace does show visible waves, there is poor correlation between the two averaged waveforms and the power analysis shows only noise across most of the auditory frequencies. As all current objective screening criteria are derived from an analysis of the whole TEOAE waveform, the presence of noise leads to the recording being classified as a fail. Inspection of (ii) does suggest, however, the presence of an emission in the mid-auditory frequencies as shown by the black peak between 2.0 and 3.0 kHz on the power analysis. This appearance suggested to us that the specificity of the TEOAE test could be improved by developing pass/fail criteria that are derived from the analysis of a limited part of the TEOAE waveform.

The aims of this study were therefore to determine the feasibility of obtaining TEOAE recordings in older children and to assess novel, limited frequency pass/fail criteria in an attempt to improve the specificity of the test.

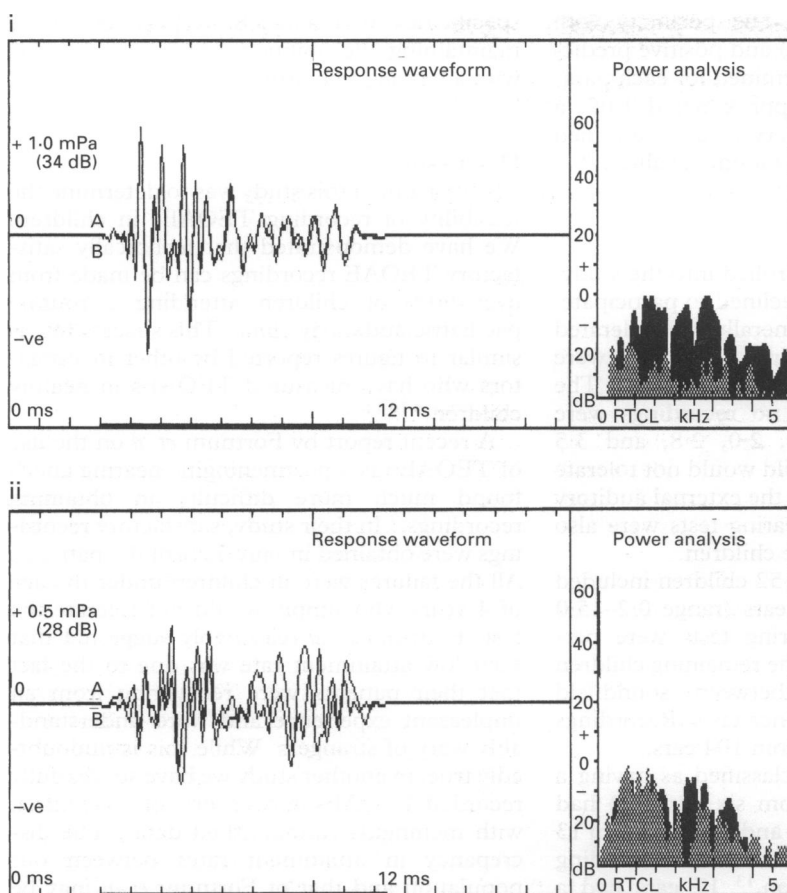
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*TEOAE recordings from children with normal hearing using the ILO88 device. (i) Recorded in quiet conditions, (ii) from a noisier child. Left hand panel (response waveform) shows two averaged emissions (A and B) superimposed. The two averages are compiled from the responses to alternate stimuli. Averages of large amplitude with close correlation between A and B, as in figure (i) confirm the presence of an emission. Less marked correlation, as in figure (ii) suggests absence of emission or contamination by noise. Right hand panel (power analysis) shows strength of waveform across auditory frequencies (0–5 kHz). TEOAE signal appears black, noise is hatched.*

## Methods

Children attending audiology clinics at the department of child health in Bath were invited to participate. Approval had been granted by the local research ethics committee and informed consent was obtained from all parents and/or children. Standard hearing tests were first performed in a sound treated room by an experienced paediatric audiologist (TJW). The tests employed were appropriate to the child's age and consisted of closed field assessments wherever possible. Soundfield tests, in which responses were elicited from loudspeakers, were used for the remaining patients. Children received tympanometry and otoscopy at the discretion of the audiologist.

Upon completion of the standard assessment, children were moved to another clinic room (not sound treated) where TEOAEs were recorded by another investigator (MPR) who was unaware of the child's hearing status. TEOAEs were recorded with the commercially available ILO88 System (Otodynamics Ltd)<sup>11</sup> with version 3.94 software, using guidelines for clinical usage as described by the originators of the device.<sup>12</sup> A brief description of the procedure follows.

Firstly the procedure was explained to parents and children, with the technique being demonstrated initially on toy animals in the case of anxious participants. Care was taken to reassure or, if necessary, to distract the child before inserting the ear probe containing the miniature loudspeaker and microphone. The influence of noise was limited by calming the

child, ensuring a good fit for the probe in the ear canal, and using the low frequency cut off filter in the system software. The QuickScreen programme was used in order to shorten the test and further decrease low frequency noise contamination.<sup>6</sup> The programme delivers a 0.1 ms broadband click stimulus to the loudspeaker at 80 clicks/second. Peak stimulus intensity was adjusted to 85 dB sound pressure level (SPL). Alternate responses from the microphone are averaged between 3.0 and 12.5 ms after the stimulus and displayed as two averages (A and B in the figure). The noise rejection level was set as low as was judged prudent by the operator (always <50 dB SPL), and the test was terminated when 260 responses of intensity below this level had been obtained. In certain cases, when the child was becoming impatient and a visually convincing TEOAE was seen on the display, the test was terminated at an earlier stage ( $\geq 100$  responses). In all other situations the test was either continued or abandoned.

## ANALYSIS

Ears were classified as having a hearing loss if the results of conventional closed field testing revealed an auditory threshold  $\geq 30$  dB hearing level (HL) at any frequency between 0.5 and 4.0 kHz. For soundfield tests the equivalent threshold was 40 dB (A). The severity of any hearing loss was graded according to the World Health Organisation (WHO) system.<sup>13</sup> Ears with hearing loss were further classified into sensorineural and conductive impairments on the basis of bone conduction, tympanometry, otoscopy, and the results of previous investigations (including auditory brainstem responses). All children with sensorineural hearing loss had already been identified and investigated by the department.

TEOAE recordings were accepted as being technically satisfactory if the following conditions were met: (i) clear stimulus lasting  $\leq 2$  ms with peak intensity 82–88 dB SPL, (ii) noise rejection level <50 dB SPL, and (iii) 260 responses recorded below this level (except in the cases detailed above). For each accepted recording, values were obtained for six screening parameters, all of which are readily obtainable from the ILO88 device. These included four previously utilised criteria: (a) waveform correlation,<sup>11 12</sup> (b) weighted response level,<sup>14</sup> (c) corrected response level,<sup>14</sup> (d) Rhode Island screening criterion<sup>6</sup> (pass=signal to noise ratio  $\geq 3$  dB at three distinct frequencies between 1.0 and 4.0 kHz).

In addition two new parameters were obtained from a subsection of the ILO88 analysis which divides the power analysis into five frequency bandwidths. In each recording, values were taken from the frequency that gave the highest figures for: (e) bandwidth waveform reproducibility and (f) bandwidth signal to noise ratio.

For each parameter, with the exception of (d) which is fixed, a critical value was determined that would yield a sensitivity of 1.00; that is all ears with hearing loss would have a

value less than this figure. The specificity (with 95% confidence intervals) and positive predictive value were then determined for each parameter.<sup>15</sup> As sensitivity approximated 1.00, a lower 95% confidence interval was determined for this figure using exact binomial values.<sup>16</sup>

### Results

Fifty six children were enrolled into the study. No parents or children declined to participate. The TEOAE test was generally well tolerated and technically satisfactory recordings were obtained from both ears of 52 children. The four children in whom no recordings were obtained were aged 0.9, 2.0, 2.8, and 3.5 years. In each case the child would not tolerate the probe being placed in the external auditory meatus. Conventional hearing tests were also impossible in two of these children.

The median age of the 52 children included in the analysis was 4.0 years (range 0.2–15.0 years). Closed field hearing tests were performed on 40 children. The remaining children were equally divided between soundfield behavioural and performance tests. Recordings were therefore available from 104 ears.

Thirty two ears were classified as having a hearing loss; 10 ears (from six patients) had sensorineural impairment and 22 ears (from 13 patients) had a conductive loss. According to the WHO classification,<sup>13</sup> 17 ears had a mild or moderate loss (averaged threshold 26–55 dB), six ears had a moderately severe or severe loss (56–91 dB), and four ears had a profound hearing loss (>91 dB). The remaining five ears had average hearing thresholds of less than 26 dB but did have a raised threshold at a single auditory frequency. In fact, a total of 10 ears from six children had hearing losses limited to either high or low frequencies. Six ears, including four with a sensorineural hearing loss, showed an impairment limited to the 4 and 8 kHz frequencies. Four ears with a conductive defect had hearing loss limited to the 0.5 kHz frequency. In all of these 10 ears the auditory threshold at the affected frequency lay between 40 and 60 dB HL.

The median TEOAE test time was 100 seconds/ear (range 25–330 seconds). The critical value, specificity, and positive predictive value for each of the test parameters are shown in the table. In each case a sensitivity of 1.00 was obtained (lower 95% confidence interval 0.90). It can be seen that the first four parameters, (a) to (d), have specificity values of between 0.46 and 0.58. The two new parameters, (e) and (f), have noticeably higher

specificities (0.76 and 0.82 respectively) while maintaining the ability to detect all the ears with a hearing impairment.

### Discussion

The first aim of this study was to determine the feasibility of recording TEOAEs in children. We have demonstrated that technically satisfactory TEOAE recordings can be made from over 90% of children attending a routine paediatric audiology clinic. This success rate is similar to figures reported by other investigators who have measured TEOAEs in healthy children.<sup>8 10 11</sup>

A recent report by Fortnum *et al* on the use of TEOAEs as a postmeningitis hearing check found much more difficulty in obtaining recordings.<sup>9</sup> In their study, satisfactory recordings were obtained in only 53% of the patients. All the failures were in children under the age of 4 years who simply would not tolerate the test. Fortnum *et al* reasonably suggested that their low attainment rate was due to the fact that their patients were recovering from an unpleasant experience and were understandably wary of strangers. While this is undoubtedly true, in another study we have successfully recorded TEOAEs in over 90% of 70 children with meningitis (unpublished data). The discrepancy in attainment rates between our population and that of Fortnum *et al* may be further explained by other differences between the two studies. For instance, the equipment used in our research differs from that of Fortnum *et al*. We also believe that the extensive paediatric experience of the investigators in our study was of considerable importance in gaining the cooperation of the children who were to be tested.

The second aim of this study was to determine the specificity of the ILO88 device and to optimise potential objective screening criteria. Most early reports of TEOAE experiments relied upon subjective interpretation of the waveform by experienced researchers in order to verify the existence of a true emission.<sup>1 3 4</sup> If the technique is to be used widely as a screening procedure, it is clear that objective criteria are needed. Several such criteria have been used in neonatal<sup>5 6</sup> and childhood<sup>9 10</sup> screening programmes, and others have been proposed in more experimental work.<sup>11 14</sup> The only previous clinical study in which any of these criteria have been compared was that of Nozza and Sabo.<sup>10</sup> In this study schoolchildren were screened by three different TEOAE parameters and results were compared with those of audiometry, tympanometry, and otoscopy. It was found that specificities of around 0.8 were attainable. The investigators were unable to obtain reliable sensitivity values as only two of the 61 participants had a confirmed hearing loss.

In our study we have been able to compare a larger number of screening criteria. Also, as we have studied a larger number of children with hearing loss, our sensitivity values and, indirectly, our specificity values are more accurate. In this study we have compared

Critical value, specificity (with 95% confidence intervals, CI), and positive predictive value (PPV) is shown for each TEOAE parameter

TEOAE parameter	Critical value	Specificity (95% CI)	PPV
(a) Waveform correlation	50%	0.47 (0.38 to 0.56)	0.46
(b) Weighted response level	2 dB	0.58 (0.49 to 0.67)	0.52
(c) Corrected response level	0 dB	0.54 (0.45 to 0.65)	0.49
(d) Rhode Island	N/A*	0.46 (0.37 to 0.55)	0.45
(e) Bandwidth waveform reproducibility	60%	0.76 (0.69 to 0.83)	0.65
(f) Bandwidth signal to noise ratio	3 dB	0.82 (0.77 to 0.87)	0.71

Parameters are defined in text. Sensitivity 1.00 for all parameters.

\*Not applicable (see text).

specificities between different TEOAE parameters with sensitivities fixed at 1.00. We justify this approach on the grounds that the implications of a false negative screening result are clearly more serious than those of a false positive when screening for hearing impairment in young children. We have found that standard TEOAE parameters, (a) to (d) in the table, yielded specificities of around 0.5 when used as screening criteria in children. They would produce an unacceptably high number of false positive results in clinical practice. In all of these cases the false positive result was due to the presence of noise in the recording.

Our new screening criteria, (e) and (f) in the table, produced markedly superior specificity values. The values obtained are similar to those quoted for TEOAE screening in neonates.<sup>4-6</sup> They are also comparable with specificity values reported for other hearing tests in young children, such as the distraction test.<sup>4,17</sup> The performance of our limited frequency screening criteria is not wholly unprecedented. Others have mentioned some success with criteria based on analysis of certain sections of the TEOAE waveform. Bray and Kemp found that analysis limited to a fixed frequency range reduced the influence of noise and improved the specificity of the original ILO88 device.<sup>11</sup> Also, the large Rhode Island screening programme<sup>6</sup> contained a 'partial pass' category that is, in fact, identical to criterion (f) in the table. This partial pass category successfully identified all infants with sensorineural hearing loss and produced less false positives than the major pass/fail criterion.

It appears that the use of limited frequency criteria has enabled us to minimise the effect of noise on TEOAE screening, and hence to improve the specificity of the test. Further improvements in specificity can be expected with other refinements to the technique. For example, it is known that the influence of noise can be reduced by recording a greater number of responses.<sup>12</sup> In our experience this is rarely practical in young children because most will only tolerate the test for a limited time. Machines are now being developed, however, that can analyse TEOAE responses in half the time taken by our equipment.<sup>18</sup> This will certainly be of considerable benefit in the future of childhood screening.

There is a potential cause of false negative results with the use of limited frequency screening criteria. This arises from the fact that ears with isolated low or high frequency hearing losses may produce emissions at other frequencies.<sup>3,7,12</sup> Children with such a hearing loss could therefore pass a single frequency screening test because of the presence of emissions at other frequencies. It is precisely because of this concern that hearing loss in our study was defined as threshold  $\geq 30$  dB HL at any auditory frequency. Accordingly, the critical value for each of the screening criteria variables was set at a figure that would cause any ears with such a partial hearing loss to fail the test. In fact, 10 ears from six children had hearing loss limited to either high or low

frequencies. As expected, these 10 ears were successfully identified by all six screening criteria. In fact, on visual inspection of their TEOAE recordings, two ears with high frequency hearing loss did appear to have weak emissions present at the lower auditory frequencies. These emissions were not strong enough, however, to pass either of the limited frequency criteria. This finding suggests that, while ears with a partial hearing loss may indeed produce TEOAEs at certain frequencies, the emissions produced will be too weak to cause an affected ear to pass the test.

While we recognise that more data are needed, particularly from children with partial hearing loss, we believe that our limited frequency criteria are both safe and effective. In our current research into postmeningitic hearing loss we are now routinely using just one such criterion (pass=bandwidth signal to noise ratio  $\geq 3$  dB).

In summary, we have demonstrated that TEOAEs can be recorded in children of all ages using the commercially available ILO88 device. We have also shown that, largely because of contaminating noise, standard screening criteria lack sufficient specificity for clinical use. However, our limited frequency criteria produce markedly improved specificities while maintaining excellent sensitivity.

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