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Repeatability of Transient-Evoked Otoacoustic Emissions in Young Adults

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Background: The aim of this study was to evaluate the repeatability and variability of TEOAE characteristics in hearing screening tests performed under practical conditions on normal subjects.

Material/Methods: A group of 11 young, normal-hearing subjects aged 19–24 years was tested. They were examined otologically and audiotologically prior to the tests and no ear pathologies were found. Responses were acquired with a commercially available instrument (Integrity, Vivosonic Inc.) using a standardized OAE protocol. The TEOAE tests were repeated 3 times in each subject at random intervals within 24 h. The analyzed parameters of interest were: (i) whole wave reproducibility (WWR) and; (ii) signal-to-noise ratio (SNR).

Results: WWR and SNR did not differ significantly among the 3 measurement sessions. In most cases the differences in WWR among measurements were around 1–2% and for SNRs they were 1–4 dB SNRs and were highest in the 1–2 kHz range. TEOAE-based tests can be useful tools for hearing screening.

Conclusions: The tests can give reliable results provided that adequate procedures are used and low-noise conditions are ensured. The tests are best complemented with other examinations to widen the range of ear pathologies able to be detected.

MeSH Keywords: **Audiology • Biomedical Technology • Otoacoustic Emissions, Spontaneous**

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Background

Clinical testing of otoacoustic emissions (OAEs) is frequently done to provide objective, non-invasive assessment of cochlear function [1–3]. The tests are primarily used for newborn hearing screening [4–6], but they can also be used for hearing screening of schoolchildren [7,8]. Because of their high sensitivity, TEOAE examinations can be used, among other things, to monitor cochlear maturation [9,10] as a diagnostic tool in the course of therapy with ototoxic drugs [11], and for early detection of noise-related hearing impairments [12–16]. For example [14], it was shown that TEOAE amplitude and reproducibility decrease significantly in young people who frequently visit discotheques. The relationship between alteration in otoacoustic emission and occurrence of tinnitus has recently been studied [18].

The spectral content of transiently evoked otoacoustic emissions (TEOAEs) is most prominent in the 1–4 kHz range. In newborns, the dominant frequencies are 2–4 kHz and in adults they are 1–2 kHz. They are usually absent when hearing loss extends beyond 30 dB HL [2].

TEOAEs are characterized by high inter-subject variability related to differing distributions of their characteristic components [18,19]. In large groups of data, there are also some significant differences between ears, with right ears having slightly higher amplitude [20]. TEOAEs also have good intra-subject stability [21–23]. It is also known that measurement repeatability is affected by factors such as stimulation parameters, characteristics of the test devices, and state of the middle ear, as well as subject-generated noise and environmental factors.

To date, repeatability of TEOAEs has been evaluated mainly using the ILO system (Otodynamics Ltd., Hatfield, UK) [21–24]. This system is often considered a reference because it was created in partnership with the discoverer of OAEs. Nowadays, however, there are many other systems used clinically, but there is little data in the literature on their performance.

Because TEOAE tests can be used not just for newborn hearing screening but also for screening of pre-schoolers, schoolchildren, and older students, we were prompted to assess the repeatability of measurements performed using the Integrity device from Vivosonic (Toronto, Canada). TEOAE-based hearing screening tests usually record a reproducibility parameter together with the signal-to-noise ratio (SNR) as an indicator of the signal's strength [1]. Reproducibility is measured as the percentage correlation between 2 buffers containing subaverages. SNR is evaluated as the difference (in dB) between the response and the noise level. In the present investigation, we

assessed the variability of these quantities observed in TEOAE measurements in young adult students.

The purpose of this study was to evaluate the repeatability and variability of TEOAEs in tests performed under practical conditions of hearing screening.

Material and Methods

Measurements were conducted in a group of 11 young normal-hearing adults (8 females, 3 males, 22 ears). The subjects were aged 19–24 years (average 22 years). Hearing tests included pure tone audiometry, impedance audiometry, and measurement of TEOAEs. Impedance audiometry is essential in OAE-related studies because middle ear status may significantly affect OAE properties [25].

Audiometric hearing for air conduction was tested over the range of 250–8000 Hz with an AC5 audiometer (Interacoustics, Denmark), and impedance audiometry was performed with an AZ26 impedance meter (Interacoustics, Denmark).

TEOAEs were recorded by the Integrity device (ver. 4.7, Vivosonic Inc., Toronto, Canada). The recorded TEOAE signal was evoked by a 100- μ s click with amplitude of approximately 80 dB SPL. The intensity of the stimulus was automatically compensated depending on the volume of the external ear canal.

The TEOAE tests were carried out in an audiometric booth and repeated 3 times for each subject for both ears. The first measurement was performed in the morning, the second 2–4 h later, and the third in the morning of the next day. Intervals between first and last measurements were no longer than 1 day. Analyses were performed separately for each ear.

The analyzed TEOAE parameters were:

- Whole-wave reproducibility (WWR), expressed in percents, for the frequency range of 0.5–4.5 kHz.
- Signal-to-noise ratio (SNR) determined in ± 500 Hz bands around 1, 2, 3, and 4 kHz.
- Absolute values of differences between all TEOAE parameters obtained over the 3 consecutive measurements and designated as D1, D2, and D3:
 - D1 – difference between measurements #1 and #2.
 - D2 – difference between measurements #1 and #3.
 - D3 – difference between measurements #2 and #3.

For statistical analysis, one-way ANOVA was used, and we used its non-parametric equivalent (Friedman test) where the distributions of the data were not normal. As a criterion of significance, a 95% confidence level ($p < 0.05$) was chosen.

Figure 1. Average values of TEOAE signal (open symbols) and background noise level (filled symbols) obtained for 4 frequency bands from 3 sequential TEOAE measurements (test 1, 2, 3). Whiskers indicate standard deviations.

Figure 2. Individual values of whole wave reproducibility (WWR) over 3 consecutive TEOAE measurements. Data for each subject are separated with vertical lines.

Table 1. Whole wave reproducibility (WWR): means, standard deviations, and minimum and maximum values (in%) obtained from three individual TEOAE measurements. Means did not differ significantly between consecutive measurements.

Test #	Mean	SD	Minimum	Maximum
1	96.38	3.88	85.34	99.85
2	95.67	4.83	82.08	99.56
3	95.19	4.88	82.99	99.59

Table 2. Median, mean values, and maximum differences between WWRs (%) determined in individual TEOAE measurements. Mean differences did not differ significantly between consecutive measurements.

Difference	Median value	Mean value	Minimum	Maximum
D1	0.53	1.06	0.00	4.2
D2	1.08	1.85	0.00	14.1
D3	0.60	1.49	0.00	9.9

Results

Figure 1 shows the average response and noise levels in consecutive measurements for 4 frequency bands. The largest response was at 1 kHz and the smallest at 4 kHz, and background noise followed a similar trend. On average, the response exceeded the noise by 20 dB. Both response and noise levels were relatively stable over the span of the 3 tests, and statistical analysis did not show any significant differences.

Individual values of whole-wave reproducibility (WWR) over 3 consecutive TEOAE measurements are shown in Figure 2. The subjects are sorted from highest to lowest average response level. It can be seen that generally the ears with highest response level

also had the highest WWR. However, there are some exceptions, such as ears 9 and 10. Mean values of WWRs obtained over 3 individual TEOAE measurements are shown in Table 1. There were no significant differences between consecutive measurements (although there were significant differences between ears). All measurements showed reproducibility above 80%, and 95% on average. In terms of inter-subjective variability of WWR, Figure 2 shows differences between individual subjects (e.g., in ears #1, 2, 12, and 19 the variability was small, while in ears #10, 13, 21, and 22 it was quite high). Nevertheless, the differences in WWR were usually less than 1%, as shown in Table 2 and Figure 3.

Both Table 2 and Figure 3 illustrate an irregular distribution of the differences and appreciable variability. Nevertheless, statistical

Figure 3. Histograms of absolute values of differences between WWRs determined from 3 consecutive TEOAE measurements. D1, D2, and D3 are the differences between measurements #1 and #2, #2 and #3, and #3 and #1, respectively.

analysis shows that the means do not differ significantly. In some cases the differences between the WWR values appeared only in the second decimal place, and in fact the minimum difference found between 2 measurements was zero (e.g., in Figure 2, where 2 of the symbols for ear 7 overlap). The subjects that showed the greatest inter-aural WWR differences (ears 19/20 and 21/22) did not have any abnormalities in audiometric results, with both ears having thresholds equal to or better than 10 dB HL.

The SNR was evaluated over 4 frequency bands (1, 2, 3, and 4 kHz), and the results for individual ears are shown in Figure 4.

Figure 4. Individual SNR values at 4 frequencies obtained from 3 consecutive TEOAE measurements. Dashed line denotes the acceptability criterion of SNR=6 dB, dotted line denotes criterion of 3 dB.

In the same way as for WWR, usually the ears with larger response levels also had higher SNRs, although there were some appreciable differences between ears. The most common

Table 3. Signal to noise ratios (SNRs). Means, standard deviations, and range of SNRs (in dB) obtained in consecutive TEOAE measurements. Means did not differ significantly between consecutive measurements.

Frequency	Measurement #	Mean value	S.D.	Minimum	Maximum
1 kHz	1	20.9	5.2	14.0	34.1
	2	19.3	5.8	8.4	28.5
	3	19.0	5.2	9.4	31.5
2 kHz	1	22.4	7.0	6.9	34.8
	2	21.6	7.0	7.1	32.5
	3	21.4	6.1	5.9	31.0
3 kHz	1	18.8	7.3	2.3	33.8
	2	19.1	6.8	2.5	31.2
	3	20.2	6.8	6.2	31.7
4 kHz	1	13.7	7.1	-2.0	30.4
	2	14.5	6.8	4.0	27.9
	3	15.3	7.1	5.1	28.3

Figure 5. Histograms of absolute values of differences between SNRs determined in consecutive TEOAE measurements for the 4 frequency bands.

criterion for the presence of TEOAEs used in screening is SNR >3 or 6 dB [26,27], and these criteria are shown in Figure 4. At a frequency of 1 kHz, both criteria were satisfied in all measurements for all ears. The 3 dB criterion was satisfied in all measurements for 1 and 2 kHz, and in all ears except one for

3 and 4 kHz. Generally, there were only a few individual measurements where both criteria failed to be satisfied.

Mean values, standard deviations, and minimum/maximum values of SNR obtained in consecutive measurements for

Table 4. Differences in SNR between the three measurements for each frequency band. Medians, means, standard deviations, and minimum and maximum values are shown. Mean values of differences between SNRs did not differ significantly between consecutive measurements.

Frequency	Median value	Mean value	Minimum	Maximum
1 kHz	2.60	2.60	0.00	10.10
2 kHz	2.45	2.45	0.00	9.70
3 kHz	2.45	2.45	0.00	10.80
4 kHz	2.40	2.40	0.00	11.10

individual frequency bands (Table 3) confirm that the most stable (smallest SD) SNR values appear at 1 kHz, where SD slightly exceeds 5 dB, while SNRs at 3 and 4 kHz exhibit slightly higher variability. Statistical analysis did not reveal any significant differences between mean SNR values obtained in consecutive measurements, at any of the frequencies. Over the course of 3 measurements, the highest average SNR was observed at 2 kHz, and the lowest at 4 kHz. For 1 and 3 kHz, the SNRs were similar.

Histograms of absolute values of differences between SNRs determined in consecutive TEOAE measurements (Figure 5) reveal that, at each frequency, most of the differences are contained in the interval 0–4 dB. Medians, means, standard deviations, and minimum and maximum values of these differences for each frequency band are shown in Table 4. Only in isolated cases did the observed differences exceed 10 dB. Again, the differences between SNRs were not statistically significant.

Discussion

The main purpose of this study was to evaluate the repeatability of TEOAEs measured in young adults. The results of analyses have shown that most of the test result variations can be explained by the individual characteristics of subjects/tested ear.

For a given person, WWR was approximately stable over consecutive measurements (with a tolerance of 1–2%). However, there was a large intersubject variability between individual values of WWR. Generally, results from the 2 ears of the same person were similar – both ears had similar WWR and a similar spread of results (e.g. ears 1–6), although the average magnitude of TEOAE from the right ear was slightly higher. There were also some exceptions, especially with ears 19 and 20, which differed from the usual pattern of small changes between the results of consecutive measurements, with one ear showing a 10% variation in WWR. There was no loss in the audiogram of the ear with the low WWR, and it is possible that the variability may, in part, be due to experimental

factors such as the repeatability of the way in which the probe microphone was placed in the ear canal. Measurements obtained in a comparative study between the results of TEOAE in newborns and adults [25] showed that the intersubject variability in the case of infants was 15.6% and intrasubject variability was 4.2%. In adults, the results were lower, at 9.9% and 2.6%. Other researchers [21,26] have also demonstrated that TEOAEs are characterized by high reliability across measurements in individuals with normal hearing, particularly for the 1–3 kHz frequency range.

In the whole group of subjects, SNR remained at a high level, on average 20 dB in the 1–3 kHz bands and sometimes exceeding 30 dB (Figure 4, Table 3), indicating a low level of noise during the test. Analysis of background noise during the measurements showed that the highest level occurred at 1 kHz, and the lowest at 4 kHz (Figure 1). This is consistent with other studies, and low-frequency noise in TEOAE measurements is usually attributed to physiological noise [26]. In experiments on the impact of background noise on newborn hearing screening tests [30], it was shown that the ambient noise level should not exceed 65 dB A. Improper measurement technique may cause a decrease in SNR, and a noisy environment may require extended test times to obtain reliable results.

In general, when low values of SNR were observed they tended to occur in the same ear and were accompanied by a significant dispersion in WWR. It can therefore be assumed that there may have been fluctuations in acoustic conditions at the time of TEOAE measurement, resulting in significant changes in the SNR at each measurement. Another possibility is an imperfect seal of the probe microphone in the ear canal. Measurements carried out on children of different ages showed that the average SNR for all subjects was greater than 3 dB at frequencies of 1.5, 2, 3, and 4 kHz [31]. Among neonates, the SNR was lowest, and ranged from around 3 to 9 dB. In children, SNR was the highest and ranged from 6 to 13 dB. The results of comparative tests [32] showed that the biggest difference in SNR between groups of infants and adults was 7 dB.

A decrease in the amplitude of TEOAEs at 2 kHz was reported to be related to the use of MP3 players among subjects aged 15–30 years [33]. This was explained as being due to subclinical damage to the cochlea, an effect not detectable by pure-tone audiometry. Other studies have shown that a reduction in TEOAEs at 2 kHz may be related to social noise exposure [34]. On this basis, one could assume that the group of students surveyed here did not often use portable music devices and did not have excessive exposure to social noise, as there was no reduction in TEOAE levels at 2 kHz.

The results of this study must be assessed with caution because of small sample size and sex distribution asymmetry. It is known that the magnitude of TEOAE is generally greater in females [34]. Because 73% of the group were women, the mean values of response level (Figure 1) and the SNR values (Figure 4) are probably slightly greater than those of general population. However, the main purpose of this study was to examine inter- and intra-subject variability of response level and SNRs and WWRs. There are no indications that this variability might be sex-dependent. We did not observe such a dependence, neither is it mentioned in any previous studies [21,22]. Despite the limited size of the sample, the spread of response level (Figure 1) and of SNR values (Figure 4) coincide well with the results obtained by other authors who examined a much larger population [34]. Therefore, we have reasons for supposing that the results presented here are valid and accurately represent properties of the method.

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In summary, the repeatability of TEOAE measurements using the Integrity device appears to be similar to that obtained using the ILO device [23,29].

Conclusions

Based on tests on a small group of young adults, the following conclusions can be formed:

- The greatest acoustic background noise level during TEOAE measurements was observed at frequencies of 1 and 2 kHz. Efforts to reduce the background noise level must be made, especially at these frequencies.
- TEOAE measurements showed that in most of the examined students, WWR was relatively stable. A similar stability might be expected when a wider population of young adults is examined.
- SNR depends on frequency, and reaches its lowest value at 4 kHz.
- Using otoacoustic emissions to screen hearing gives reliable results and might be applied more widely in screening the hearing of young adults.

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