Repeatability of Distortion Product Otoacoustic Emissions in Normally Hearing Humans

Abstract
Distortion product otoacoustic emissions (DPOAEs) at the frequency of f₁ – f₂ were measured in one or both ears of 12 young adults during 4 test sessions over a 6-week period. The purpose was to determine the variability in DPOAE amplitudes and 'detection thresholds' over repeated measurements using a computer-based time-averaging system. DPOAEs were generated with f₁ and f₂ relative to (f₁f₂)² in two basic paradigms: (a) fixed levels of f₁ = f₂ of 70 and 55 dB SPL over a stimulus range from 0.8 to 8 kHz in 0.2-octave intervals; (b) input-output functions in stimulus regions of 0.8, 1, 1.5, 2, 3, 4, and 6 kHz. L₁ from 35 to 70 dB SPL changing in 5-dB steps and L₂ at 6 dB below the amplitude of L₁. The mean variability of DPOAE amplitudes with equi-level stimulus was 1.8 dB (SD = 1.8) for L₁ = 70 dB SPL and 2.9 dB (SD = 2.7) for L₁ = 55 dB SPL. It was 1.7 dB (SD = 1.7) and 2.4 dB (SD = 2.0) for comparable levels of L₂ with L₁ at 6 dB below L₁. Variability in amplitude of the DPOAEs for the fixed-level condition was greatest overall above 6 kHz and below 1 kHz and in the 2-kHz region for one third of the subjects. Neither individual differences in emission amplitudes nor the presence of spontaneous otoacoustic emissions had a significant influence on the amount of amplitude variability within ears. Variability was not influenced by the length of time between measurements from 1 to 6 weeks. Median variability in detection threshold was from 0 to 5 dB SPL. According to these results, a change in DPOAE amplitude of more than 6-9 dB, depending upon stimulus levels, would indicate a significant change in cochlear status if recording conditions and middle-ear status are stable.
Introduction

Since the discovery of otoacoustic emissions by Kemp [1] in 1978, the possibility of their use for clinical applications has been increasingly recognized. Transiently evoked otoacoustic emissions (TEOAEs) are already established as a screening method in pediatric audiology [2-4]. Distortion product otoacoustic emissions (DPOAEs) are still undergoing evaluation for clinical use. These emissions can be measured over a broader frequency range than TEOAEs when measured with current techniques and instrumentation. Acoustic distortion products result from the nonlinearity of the cochlea, and it is likely that the outer hair cells are involved in their generation [5, 6]. Stimulating the cochlea with two pure tones at frequencies f1 and f2 leads to the generation of intermodulation distortion. The frequency 2f1 - f2 is the most prominent component that can be detected in almost all normally hearing humans [7]. Although there is high intersubject variability in DPOAE amplitudes and frequency dispersion, these emissions are stable over time within individual ears [8, 9]. Results from animal studies using manipulations known to damage outer hair cells, such as chronic noise exposure, drug administration and acoustic trauma, have revealed that DPOAEs are reduced in amplitude or can no longer be measured following such manipulations [for a review, see 7]. Because of the dependence of DPOAEs on cochlear integrity, their measurement should be well suited as an objective method for monitoring cochlear function. However, towards this end, it is important to determine the amount of variability of DPOAEs when repeated measurements are made in human ears with normal hearing. The purpose of this investigation was to assess the amount of this variability over a 6-week period when using an automatic, computer-based system used for making routine measurements.

Methods

Six women and 6 men (mean age: 26.3 years) who were in good general health were paid to participate as subjects. Ears were selected for repeated measurements of DPOAEs if they had normal middle-ear status by otoscopy and immittance procedures and if pure-tone air conduction thresholds were ≤20 dB HL from 0.5 to 8 kHz. Twelve right and 10 left ears were included. Two left ears were excluded: one did not meet the audiometric test criteria at one frequency, and test results for the other could not be used because of technical difficulties during one session. Subjects were tested during 4 sessions separated by 1-week intervals for the first 3 sessions and by a 4-week interval for the last test session. They were seated comfortably in a sound-treated room during measurements.

DPOAEs were generated using two main conditions. In the first, L1 and L2 were equal in level and were fixed at either 70 or 55 dB SPL. The geometric mean of f1 and f2 was at frequencies between 0.8 and 8 kHz (f1/f2 = 1.21) [10] and changed in 0.2-octave steps. In the second condition, input-output (IO) functions were generated at geometric mean frequencies of 0.8, 1.1, 1.5, 2.3, 4 and 6 kHz (f1/f2 = 1.22) and L1 = L2 + 6 dB SPL. Stimulus levels were decreased in 5-dB steps from L1 = 70 to 35 dB SPL for each stimulus frequency region. Spontaneous otoacoustic emissions were measured in the first test session according to methods described previously [11].

A computer-based system (Macintosh IIx) was used for DPOAE measurements. Stimuli at f1 and f2 were generated digitally by a two-channel 16-bit processor board (Audiodiag) and were delivered separately to two ER-2 (Etymotic Research) earphones. These were connected to an ER-10A probe system, which was placed securely in the subject’s outer ear canal using a foam ear tip. The ear canal sound pressure was recorded by the probe’s microphone system, and the signal was led to an ER-72 preamplifier followed by a custom-built low-noise amplifier with 10 dB of additional gain and a high-pass filter with a cut-off frequency of 400 Hz. The amplified microphone signal was fed to the analog/digital board within the computer. The signals were time-averaged for 65 samples with stimuli at 0.8 and 1 kHz and for 32 samples for the other frequencies. A noise rejection feature was used to eliminate any responses that occurred during noise that exceeded a reference criterion level. The initial reference noise floor level was determined at the beginning of a test session by taking 3 samples of the noise and setting the reference level at the lowest of the 3 samples. When the noise floor exceeded the reference level by 6 dB during the test was rejected. Measurement severity until the criteria were level of the noise floor were ing testing to account for with increasing frequency, throughout testing by obey the spectrum of the binaural.

Five measurement interos of response parameters: 2 = test 3, 2 weeks (test 1- test 4), 5 weeks (test 2- test 4). With the time-averag was determined that the reas litude exceeded the noise only levels of 2f1 - f2, mean- lyzed. For the IO functions, sulting in a criterion resop detection threshold of the tude of the responses and the IO functions were evaluated.

Results

DPOAEs could be r during each test session were not always present used to generate the IC DPOAE amplitude measured with L1 = L2 SPL (SD = 5.9), and for was -2.6 dB SPL (SD = Mean DPOAE amplit was lower: 7.5 dB SPL 1 sponds in mean amplitu right and left ears were p < 0.05). Amplitude r frequency regions of 1.5 displays the mean DPO frequency for the two f the right ears. For the I DPOAE amplitudes for L1 were 10.4 dB SPL (SD (SD = 6.5) for the right (SD = 5.8) and -3.3 dB.
mean age: 26.3 years) who were paid to participate as
for repeated measures
normal middle-ear sta-
tance procedures and if
residuals were <20 dB HL
at 10 levels were in-
cluded: one did not meet
at one frequency, and test
be used because of tec-
session. Subjects were
interval of a 4-week interval
3 seated comfortably in a
measurement.
and using two main condi-
cural sound pressure
were 60. The geometric mean
between 0.5 and 8 kHz (L1)
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(IO) functions were gen-
eral formulae 0.5, 1, 1.5, 2, 3,
L1 = L2 + 6 dB SPL. Stimul-

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in the ER-10A probe system,
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mean (Macintosh II) was

at L1 and L2 the two ears were
and were delivered sepa-

for each test session; however, responses
were not always present for the lowest levels
used to generate the IO functions. The mean
DPOAE amplitude for the 17 frequencies measured with L1 = L2 = 70 dB SPL was 9 dB
SPL (SD = 5.9), and for stimuli at 55 dB SPL it
was 2.6 dB SPL (SD = 6.7) for the right ears.
Mean DPOAE amplitudes for the left ears were
lower: 7.5 dB SPL (SD = 5.6) and 4.6 dB
SPL (SD = 6.1) for the stimulus conditions of
70 and 55 dB SPL, respectively. The differences
in mean amplitude of responses from right and left ears were not significant (t test; p < 0.05).
Amplitude maxima appeared in the frequency
regions of 1.5 and 3.5–8 kHz. Figure 1

displays the mean DPOAE amplitudes across
frequency for the two fixed stimulus levels for
the right ears. For the left ear, the mean
DPOAE amplitudes for comparable levels of
L were 10.4 dB SPL (SD = 5.1) and 1.3 dB SPL
(SD = 6.5) for the right side and 9.2 dB SPL
(SD = 5.8) and 3.3 dB SPL (SD = 6.5) for the

level by 6 dB during measurements, then the sample
was rejected. Measurements then continued succes-
sively until the criteria were satisfied. Samples of the
level of the noise floor were continuously revised dur-
ing testing to account for reductions in noise level
with increasing frequency. Probe fit was monitored
throughout testing by observing a running display of
the spectrum of the bilateral stimuli.

Five measurement intervals were used for compari-
son of response parameters: 1 week (test 1 – test 2, test
2 – test 3), 2 weeks (test 1 – test 3), 4 weeks (test 3 –
test 4), 5 weeks (test 2 – test 4) and 6 weeks (test 1 –
test 4). With the time-averaging system as described, it
was determined that a response was present if its am-
plitude exceeded the noise floor by 6 dB. Therefore,
only levels of 21 – 6 dB exceed this criterion were ana-
lyzed. For the IO functions, the last stimulus level re-
sulting in a criterion response was designated as the
'detection threshold' of the response series. Ampli-

tudes of the responses and detection thresholds from
these results were evaluated.

Results

DPOAEs could be recorded from all ears
during each test session; however, responses
were not always present for the lowest levels
used to generate the IO functions. The mean
DPOAE amplitude for the 17 frequencies measured with L1 = L2 = 70 dB SPL was 9 dB
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regions of 1.5 and 3.5–8 kHz. Figure 1
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frequency for the two fixed stimulus levels for
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DPOAE amplitudes for comparable levels of
L were 10.4 dB SPL (SD = 5.1) and 1.3 dB SPL
(SD = 6.5) for the right side and 9.2 dB SPL
(SD = 5.8) and 3.3 dB SPL (SD = 6.5) for the

left side, for stimuli of 70 and 55 dB SPL, re-
respectively. Because there were no significant
differences in inter- and intra-subject variabil-
ity between the right and left ears for the
majority of the parameters considered, the results
for the right ears are presented primarily.

Some subjects had markedly greater vari-
ability than did others. The range of individual
mean variability in DPOAE amplitudes over
all frequencies measured with stimuli at L1 =
L2 = 70 dB SPL was from 0.8 to 3.3 dB and for
L1 = L2 = 55 dB SPL from 3.8 to 4.4 dB. The
individual results in figures 2 and 3 for the fixed-
level condition illustrate these extremes. The
results from the subject with the most variabil-
ity are displayed in figure 2 and the least vari-
ability results are reproduced as figure 3. Both
of these results are from the right ear of fe-
male subjects who had spontaneous otoacous-
tic emissions in both ears. In addition to dem-

in figure 3 also illustrate the overall finding of greater variability for the lower stimulus levels and for the extreme low and high stimulus frequency regions. Overall, there was more variation in DPOAE amplitudes at frequencies below 1 kHz and above 6 kHz than for frequencies in the midfrequency region. However, greater variability around 2 kHz was noted in about one third of the subjects. This variability increased at lower stimulus levels. Despite the variations in amplitude, the overall shapes of the curves were generally reproduced with great accuracy, as figures 2 and 3 illustrate.

Overall variability was determined by averaging the amplitude differences between successive measurements. The amount of this variability was not influenced by the length of time between measurements. However, there were differences as a function of the levels of the stimuli. Both of these trends can be appreciated by the results displayed in figure 4. With fixed levels of either 1 or 2, the mean variances over all measurements greater for 1 = 2 = 5 stimuli of 70 dB SPL at the same trend with 1 = mean variability between stimulus conditions. Chang function of stimulus is the I/O functions. For levels of 1 = 70 and 55 dB SPL.
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Fig. 3. Four measurements of DPOAEs for a subject with minimal variability in emission levels.

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fixed levels of either 70 or 55 dB SPL for L1

and L2, the mean variability for the right ears

over all measurement intervals was 1.1 dB
greater for L1 = L2 = 55 dB SPL than for the

stimulus of 70 dB SPL. The left side revealed

the same trend with a 0.9-dB difference of

mean variability between low and high stimu

lus conditions. Changes in variability as a

function of stimulus level were also found for

the I/O functions. For comparable stimulus

levels of L1 = 70 and 55 dB SPL (L2 = 64 and 49

dB SPL), the mean variability for the right

ears was 1.7 and 2.4 dB and for the left side 1.9

and 2.4 dB, respectively. As stimulus levels

were reduced below 55 dB SPL, the trend for

greater variability continued, as illustrated by

the results for the right ears displayed in figure

5. The number of responses available for mak

ing these determinations decreased as the

stimulus level decreased. Therefore, sufficient

data were not available for L3 = 35 dB SPL to

obtain valid estimates of variability.
Fig. 4. Mean variability of the DPOAE response amplitudes with respect to the two fixed primary-tone levels over 6 measurement intervals. Error bars indicate 1 SD.

Fig. 5. Mean variability of the I/O functions with respect to stimulus levels from L1 = 70 dB SPL to L1 = 40 dB SPL in 5-dB steps. L2 was 60 dB lower in level than L1 (n = 12 right ears). Error bars indicate 1 SD.

Fig. 6. Mean response levels obtained from 12 right ears during each of the 4 test days: L1 = L2 = 70 dB SPL (a), L1 = L2 = 55 dB SPL (b).

Despite the influence of stimulus level on DPOAE amplitude variability, the variability was largely independent of the absolute amplitude of DPOAEs in individual ears. Figure 6 illustrates this finding from the mean DPOAE amplitudes for the fixed-level condition for all right ears. Mean results for each test session for each ear are plotted.

Changes that occurred in the overall configuration of the I/O functions were considered as either parallel or nonparallel in form. A shift was considered as parallel if an entire function moved either upward or downward from the reference function. That is, the general pattern of the function did not change, but the relative levels of the entire function were shifted. Nonparallel shifts were those that had inconsistent differences in levels over the course of the function. Parallel shifts were identified in 85 of the ears, 6 comparisons (20%). Nonparallel shifts were similar to the comparisons, and change in the overall I/O functions. Variability thresholds determinations was also evaluation threshold variability across frequency. How variation threshold variation in amplitude detection threshold did with stimulus frequen

Discussion

TEOAE measures as an addition to threshold screening and monitoring are stable in and in amplitude over response levels varying in [12]. The clinical use of thresholds established as that there are indications that DPOAEs may provide a clinical test. The authors investigate the test re measurements in non ears.

The spectral pattern of the DPOAEs obtained similar to those reported investigations of DPOAEs in hearing subjects recorded from all ears over sessions for th

Within individual ears, variability stable across t
Discussion

TEOAE measurements are used clinically as an addition to traditional audiological screening and monitoring methods. These emissions are stable in frequency composition and in amplitude over time with overall response levels varying approximately by 2.0 dB [12]. The clinical use of DPOAEs is not yet as established as that of TEOAEs. However, here are indications that the measurement of DPOAEs may provide specific advantages as a clinical test. The purpose of this study was to investigate the test repeatability of DPOAE measurements in normally hearing human ears.

The spectral patterns and amplitudes of the DPOAEs obtained in this study were similar to those reported in other comprehensive investigations of DPOAE amplitudes in normally hearing subjects [13]. DPOAEs could be recorded from all ears during each measurement session for the majority of stimuli. Within individual ears, DPOAEs were relatively stable across the four measurements obtained at time intervals from 1 to 6 weeks. Variability was dependent on the stimulus level but not on the absolute amplitude of the DPOAE. Reduction of primary-tone amplitudes from 70 to 55 dB SPL (L1 = L2) resulted in an increase in variability of approximately 1 dB. The same trend was found when L2 was 6 dB greater in amplitude than L1 although the amount of variation was smaller. For this level condition, decreasing L2 from 70 to 55 dB SPL led to an increase in mean variability of 0.7 dB and reducing L1 to 40 dB SPL did not increase mean variability more than 1 dB. Therefore, the stimulus configuration L1 > L2 (L1 = L2 + 6 dB), which was used for generating the I/O functions, was associated with less variability than the L1 = L2 condition. It has been found previously that the stimulus configuration L1 > L2 elicits higher DPOAE amplitudes [14]. However, the individual differences in DPOAE amplitudes at fixed stimulus levels did not influence the test-retest variability significantly in this study. Therefore, even patients with low response levels can be monitored for clinical purposes.

In addition to amplitude differences, I/O functions were evaluated for morphologic changes (including the parameter ‘detection threshold’) over the 4 test sessions. Both parallel and nonparallel shifts occurred in the I/O functions with repeated measures. However, random irregularities were more common than were ‘parallel’ shifts. Influences of the instrumentation, including the placement of the probe, would be more likely to account for the ‘parallel’ changes than the test-retest differences in the cochlea. Median DPOAE detection threshold variability ranged from 0 to 5 dB across all frequencies. However, in a few ears, detection threshold changes of up to 20 dB were present for single frequencies from one test to another. As reported previously, DPOAE detection threshold tends to correspond more closely than do other parameters...
with pure-tone threshold by frequency [15-17]. Therefore, although the detection threshold parameter was not highly variable for the majority of ears in this study, the few large deviations that were present should be considered when interpreting changes in clinical test findings. Careful testing with control for noise and probe placement should reduce this variability to a minimum.

The frequency region of the stimuli influenced the amount of variability in response amplitude. DPOAEs stimulated at 6-8 kHz had more variability than did those generated at lower frequencies. Ideally, a measuring system should be capable of detecting DPOAEs adequately in the entire audiofrequency range. However, the system used in this study probably had less than ideal sensitivity above 6 kHz. The increase in variability for one third of the subjects in the 2-kHz region was probably not related to the measuring system. This frequency region is known to have decreased response levels for reasons that are not yet fully understood [13]. The relatively large amount of variability at frequencies below 1 kHz was probably due to the greater influence of noise in this frequency region.

Measurement variability may be influenced by several factors external to the cochlea including middle-ear status, external and internal noise levels and instrumentation. Middle-ear influences, such as pressure changes or fluid, will alter the low- and mid-frequency components of the responses primarily and will have less effect on the high frequencies [18]. Changes in test procedure, instrumentation and environment can also lead to measurement differences. These factors were controlled in several ways in this study. A strict noise rejection level was used routinely. Probe fitting was monitored throughout testing. To determine the importance of probe fitting, measurements at fixed stimulus levels were made without replacing the probe during 4 repeated measurements for 2 subjects. Without probe replacement the mean variability in amplitude over all stimulus conditions was <1 dB.

It might be expected that spontaneous otocoustic emissions would influence variability. However, this was not the case in our results. Subjects with and without spontaneous otocoustic emissions did not differ significantly in the amount of variability in their responses. The finding of frequency stability of spontaneous otocoustic emissions [7] may be important in this respect.

The \( 2f_2 - f_1 \) DPOAE can be detected easily in an objective and noninvasive manner in almost all normally hearing human ears. Emission levels are relatively stable over time. In our study, the mean changes in amplitude of \( 2f_2 - f_1 \) with repeated measurements over several time intervals were 1.8 dB (SD = 1.8) with stimuli at 70 dB SPL and 2.9 dB (SD = 2.7) with stimuli at 55 dB SPL for right ears. Under relatively stable test conditions and with removal and replacement of the probe, changes exceeding 5.4 dB (mean + 2 SD) for 70 and 8.3 dB (mean + 2 SD) for 55 dB SPL stimulus levels can be interpreted as due to clinically relevant changes within the cochlea. This variability is higher than determined previously for TEOAEs [12]. However, the measurement of DPOAEs can offer a method of monitoring cochlear status over a range of frequencies approximately an octave higher than is currently possible with TEOAEs.

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La reproductibilité distortion des éMISSIONS DES SUJETS HUMANS

Les produits de distorsion (DPOAEs) à la fréquence dans une des deux ou trois d sessions pendant Le but de l'étude était de d'amplitudes des DPOAEs et des mesures répétées, en s'assurant de moyenne. Les 1 avec \( f_1 \) et \( f_2 \) par rapport à principaux: (a) niveaux fine sur une gamme de stimulus de 0,2-octave; (b) fonction somme de 0.8, 1.2, 1.5, 2, 3 et 4 et port de 5.4 dB et \( L_e \) à 6 di de \( L_c \). La variabilité moire

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References

La reproductibilité des produits de distorsion des émissions otoacoustiques chez les sujets humains à audition normale

Les produits de distorsion des émissions otoacoustiques (PDEOs) à la fréquence de 2f2 - f1 ont été mesurés dans une des oreilles de 12 jeunes adultes âgés de 4 sessions pendant une période de 6 semaines. Le but de l'étude était de déterminer la variabilité des amplitudes des PDEOs et la stabilité de détection par des mesures répétées, en utilisant un système informatisé de moyennage. Les PDEOs étaient générées avec f1 et f2 par rapport à (f1f2) dans deux protocoles principaux: (a) niveaux fixes L1 = L, de 70 et 55 dB SPL sur une gamme de stimulations de 0,8 à 8 kHz par pas de 0,2 octave; (b) fonctions d'entretien/dépasse dans les régions de 0,6, 1,5, 2, 3, 4 et 6 kHz, L, de 35 à 70 dB SPL par pas de 5 dB, et L, à 6 dB en dessous de l'amplitude de L, La variabilité moyenne des amplitudes des PDEOs avec des stimuli de même intensité était de 1,8 dB (c.i. = 1,8) pour L1 = 70 dB SPL et 2,9 dB (c.i. = 2,7) pour L1 = 55 dB SPL. Elle était de 1,7 dB (c.i. = 1,7) et 2,4 dB (c.i. = 2,0) pour des niveaux comparables de L1 avec L, 6 dB en dessous de L, La variabilité dans les amplitudes des PDEOs pour la condition niveaux fixes était plus grande pour toutes de 6 kHz et auto-sons de 1 kHz et dans la région de 2 kHz pour un tiers des sujets. Ni les différences individuelles dans l'amplitude des émissions ni la présence d'émissions otoacoustiques spontanées n'avaient d'influence significative sur l'importance de la variabilité de l'amplitude dans une même oreille. La variabilité n'était pas influencée par la durée de l'intervalle entre les mesures de 1 à 6 semaines. La médiane de la variabilité du seuil de détection était de 0 à 2 dB SPL. En fonction de ces résultats, une variation de l'amplitude des PDEOs de plus de 6–9 dB, en fonction du niveau de stimulation, pourrait indiquer une modification significative de l'état de la cochlée, si les conditions d'enregistrement et l'état de l'oreille moyenne sont stables.

References