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Effectiveness of Transient-Evoked Otoacoustic Emissions (TEOAEs) in Predicting Hearing Level

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Abstract

The purpose of the present investigation was to (1) determine the short-term test–retest reliability of the transient-evoked otoacoustic emission (TEOAE) parameters of echo level and reproducibility, as produced by the Otodynamic's ILO88 system; and (2) assess the ability of the ILO88 parameters of frequency spectrum, echo level, and reproducibility to identify ears with sensorineural hearing loss. Our results show that the short-term test–retest reliability for both echo level and reproducibility is excellent, reflecting the stability of TEOAEs and the low measurement error associated with the procedure for obtaining TEOAEs. The data suggest, however, that frequency-specific hearing levels (HLs) cannot be accurately predicted from the analogous frequencies depicted in the frequency spectrum produced by the ILO88 system. Although frequency-specific HLs cannot be predicted from the frequency spectrum, the parameters of echo level and reproducibility will clearly separate individuals with HLs ≤ 20 dB from individual with HLs > 20 dB for the octave frequencies of 500–4000 Hz. An echo level of < 6 dB and/or a reproducibility value of < 70 percent are associated with HLs > 20 dB between 500 and 4000 Hz. The combination criterion of an echo level of < 6 dB and a reproducibility value of < 70 percent appears to be a suitable screening method for identifying adult ears with an average HL of > 20 dB.

Key Words: Hearing threshold prediction, otoacoustic emissions (OAEs), pure-tone audiometry, transient-evoked otoacoustic emissions (TEOAE)

An otoacoustic emission (OAE) is acoustic energy emitted by the cochlea into the ear canal either spontaneously or in response to acoustic stimulation. OAEs are believed to be the result of an as yet unidentified cochlear active process that is responsible for controlling sensitivity and frequency tuning in the cochlea. In short, OAEs are believed to represent the activity of the cochlear amplifier proposed by Davis (1983). While OAEs are believed to be generated by the motile activity of the cochlear outer hair cells (OHC) in the form of contractions and elongations, which has been demonstrated *in vitro*, it is not known if OAEs are the result of OHC movement *in vivo*, or if OAEs are anything more than epiphenomena produced by cochlear activity. It is known, however, that OAEs are altered by noise exposure (Anderson and Kemp, 1979; Kemp, 1982), ototoxic agents (McFadden et al, 1984; Long and Tubis, 1988; Sie et al, 1991), and cochlear hearing loss (Kemp, 1978; Probst et al, 1987; Harris, 1990; Lonsbury-Martin and Martin, 1990; Smurzynski et al, 1990; Avan and Bonfils, 1993; Gorga et al, 1993), all of which affect the OHCs.

Of the forms of OAEs that have been studied, the distortion-product otoacoustic emission (DPOAE) and the transient-evoked otoacoustic emission (TEOAE) have received the most attention concerning clinical application (Glattke and Kujawa, 1991; Lonsbury-Martin et al, 1991). DPOAEs are produced by

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the simultaneous presentation of two primary tones, f_1 and f_2, differing in frequency in a prescribed manner with the most robust DPOAE at the $2f_1$–f_2 cubic difference frequency. TEOAEs are produced by a brief acoustic stimulation such as a click and are a delayed cochlear "echo" (Kemp, 1991) consisting of several frequency bands of dominant acoustic energy separated by narrower bands of weak acoustic energy (Sutton, 1985). Both types of OAEs have been shown to be generated by the same cochlear mechanism, the nonlinear active process, in which the OHCs play a major role (Smurzynski and Kim, 1992). Further, both DPOAEs and TEOAEs have been shown to have excellent within-ear stability (Berlin et al, 1991; Harris et al, 1991; Vedantam and Musiek, 1991; Franklin et al, 1992); however, the TEOAEs have demonstrated considerable between-ear variability in amplitude and frequency in normal-hearing ears (Kemp, 1978, 1982; Vedantam and Musiek, 1991; Robinette, 1992; Smurzynski and Kim, 1992).

Several investigators have studied the relationship between DPOAEs and pure-tone audiometry using normal-hearing subjects and subjects with sensorineural hearing loss (Gaskill and Brown, 1990; Harris, 1990; Martin et al, 1990; Probst and Hauser, 1990; Smurzynski et al, 1990; Avan and Bonfils, 1993; Gorga et al, 1993). In brief, the results of these investigations have suggested some correlation between HL at an audiometric frequency and the amplitude of a DPOAE when either the geometric mean frequency of the two primary tones or the f_2 frequency is the same as the audiometric frequency.

Of the two OAE measures, TEOAE measures may be in greater clinical use, due in part to the early commercial availability of the hardware and software developed by Bray (1989) (i.e., the ILO88 Otodynamics Analyzer [Kemp et al, 1990]) and the speed at which the measurement can be obtained, ≤ 60 sec per ear. While there are some published normative data on the ILO88 system (Vedantam and Musiek, 1991; Robinette, 1992), data on how hearing sensitivity affects TEOAEs as assessed by the ILO88 system are just beginning to emerge (Collet et al, 1991). Collet et al (1991) assessed the relationship between the TEOAE frequency spectrum provided by the ILO88 and HLs depicted by the audiogram using a stepwise multiple regression analysis to identify which audiometric frequency(s) contributed to different frequency bands in the frequency spectrum analysis. While these analyses indicated a correlation between the amplitude of a frequency-specific OAE and the HL at the homologous frequency, the relationship is very complex, as the amplitude of the OAE in a given spectral band is dependent not only on the hearing sensitivity within the band but outside the band as well. Thus, Collet et al (1991) concluded that construction of an audiogram was not possible from the TEOAE frequency spectrum amplitudes provided by the ILO88 system.

While TEOAEs, like DPOAEs, assess cochlear function and are not a direct measure of hearing sensitivity, they are being used in infant hearing screening (Glattke and Kujawa, 1991; Lonsbury-Martin et al, 1991; Stevens et al, 1991; White et al, 1993), differential diagnosis of auditory dysfunction (Bonfils and Uziel, 1989; Glattke and Kujawa, 1991; Lonsbury-Martin et al, 1991; Robinette, 1992), and monitoring of cochlear function (Brown et al, 1989; Lonsbury-Martin and Martin, 1990; Glattke and Kujawa, 1991; Lonsbury-Martin et al, 1991). Therefore, the purpose of the present study was to further investigate the relationship between TEOAE parameters, as depicted by the ILO88 system, and hearing sensitivity, as depicted on the audiogram. Stated differently, the question of interest is, to what degree do the TEOAE parameters of the ILO88 system, if any, relate to hearing sensitivity?

METHOD

Subjects

Two separate groups of subjects were used in this investigation. The first group of 30 subjects, ranging from 23 to 64 years of age, with a mean age of 46 years, was used to assess measurement error using short-term test–retest reliability of the TEOAE measures. The second group was used in the HL prediction segment of this investigation and consisted of 67 subjects ranging from 18 to 78 years of age, with a mean age of 44 years. From these subjects, 109 ears were chosen for study and were divided between normal hearing, which was defined as HLs of ≤ 20 dB for the octave frequencies 500–4000 Hz, and sensorineural hearing loss, which was defined as HLs of > 20 dB at each of the same frequencies. All subjects had normal otologic examinations, normal tympanograms, and contralateral acoustic reflex thresholds consistent with HL values at analogous frequencies (Silman and Gelfand, 1981).

Procedures

Each subject was tested in an IAC test booth by one of four audiologists experienced in obtaining TEOAEs who had no knowledge of the subject's hearing status. The TEOAEs were obtained by using the standard default mode of the Otodynamics Analyzer (Kemp et al, 1990), which generates a train of 80 μsec rectangular clicks at a rate of 50/sec at a peak SPL of 82 dB (± 2 dB). The ILO88 system was set in the nonlinear click mode where the clicks are presented in blocks of four with every fourth click reversed in phase and three times the amplitude of the previous three clicks. With the nonlinear presentation mode, the output of the ear canal monitoring microphone is averaged for a block of clicks, resulting in the cancellation of the linear portion of the response while the nonlinear TEOAE of the cochlea is extracted, thus reducing the effect of contaminating ear canal artifacts. The subaveraged response to a block of four clicks is alternately stored in one of two computer buffers for later analysis.

The waveform of the click stimuli in the ear canal was checked for excessive oscillation and as flat a frequency spectrum as possible using the "check fit" preview format supplied with the ILO88 before the TEOAEs were collected. In order to assess short-term measurement variability in the separate group of 30 subjects, a TEOAE measure was obtained at the beginning and at the end of a 30-minute audiologic evaluation. Test–retest data were obtained for only one ear chosen by the examining audiologist. In order to simulate clinical conditions, all subjects were drawn from the daily caseload of the Audiology Clinic at the Dartmouth-Hitchcock Medical Center and received the TEOAE assessment as part of their hearing evaluation. All TEOAE data were examined using the three parameters supplied by the ILO88 software: (1) frequency spectrum; (2) echo level; and (3) reproducibility.

The ILO88 system performs an averaged three point smoothed fast Fourier transform spectrum analysis of the TEOAEs, which is plotted against the averaged random noise in the ear canal. From this frequency spectrum display, the presence or absence of an OAE at specific frequencies of 500, 1000, 2000, 3000, and 4000 Hz was determined. The criteria used to assess the spectral display at each frequency was OAE energy centered about a 100 Hz band on either side of the frequency in question and at least 3 dB above the noise level in the same frequency band. Further, the ILO88 software provides a parameter of echo level, which is a computation resulting from a rms measure of the averaged raw echo waveform, converted to dB SPL, and represents an estimate of echo size plus ear canal noise. Last, the ILO88 software provides a parameter of reproducibility, which results from a crosscorrelation analysis on the two separately averaged TEOAEs that are stored in the two different computer buffers.

In order to determine the predictability of audiometric information from the TEOAE parameters of frequency spectrum, echo level, and reproducibility provided by the ILO88 software, these parameters were evaluated using clinical decision analysis (CDA) procedures (Jerger, 1983; Hyde et al, 1991; Turner, 1991), which are based on the theory of signal detection (Swets, 1988).

In this CDA model, *hit rate* (also called sensitivity) is the percentage of subjects correctly identified by a test score; *false alarm rate* (also called false positive rate) is the percentage of subjects incorrectly identified as positive by a test score; *correct rejection rate* (also called specificity) is the percentage of subjects correctly identified as negative by a test score; and *A'* is a measure of the overall performance of various test scores (Turner, 1991). A' values range from .50 for a test of no value to 1.00 for the perfect test. For the frequency spectrum parameter, the presence or absence of an OAE in the spectrum window at each of the five specific frequencies was used as test criterion. For the echo level and reproducibility parameters, different magnitude values were used as the test criterion.

RESULTS

The parameters of echo level and reproducibility were used for the test–retest measures with the scatter plots, correlations, and associated regression lines displayed in Figure 1. Clearly, the parameters of echo level and reproducibility produce very high test–retest correlations (.98 and .94, respectively) for the short-term retest condition, reflecting excellent TEOAE stability and little measurement error.

The frequency spectrum data were analysed using a 2 × 2 matrix with the absence or presence of an OAE constituting the columns and various HL criterion constituting the rows. The purpose of these analyses was to determine the extent to which subjects could be separated by HL based on the absence or presence of an OAE in the frequency spectrum at each of five frequencies: 500, 1000, 2000, 3000, and 4000 Hz. The HL categories were > 0 to > 50 dB in 10-dB steps. These analyses provided the percentage of subjects correctly identified as having HLs greater than a criterion HL (hits) and the percentage of subjects incorrectly identified as having HLs greater than a criterion HL (false alarms). The hit rates versus the false alarm rates are graphically portrayed in the receiver operating characteristic (ROC) curves displayed in the top panel of Figure 2, while the A' values associated with the different HL criterion are depicted in the bottom panel of the figure. The ability of the absence or presence of an OAE in the frequency spectrum to separate subjects by HL is reflected by how far each ROC curve is displaced towards the upper left corner where the hit rate is high and the false alarm rate is low. While subjects could be separated by HL at all five of the frequencies, the hit rate versus the false alarm rate for the majority of frequencies was poor, with the exception of 1000 Hz. In general, the frequencies of 500 and 4000 Hz had A' values of approximately .85, regardless of the HL criterion, while 2000 and 3000 Hz had A' values that varied by HL criterion ranging from below .80 at 0 dB HL to above .85 at 20 dB HL. The best test performance was demonstrated at 1000 Hz with A' values above .90 for the majority of the HL criterion. While 1000 Hz was the best performer of the frequencies studied, the best A' value of .94 is associated with a hit rate of 96 percent and a false alarm rate of 20

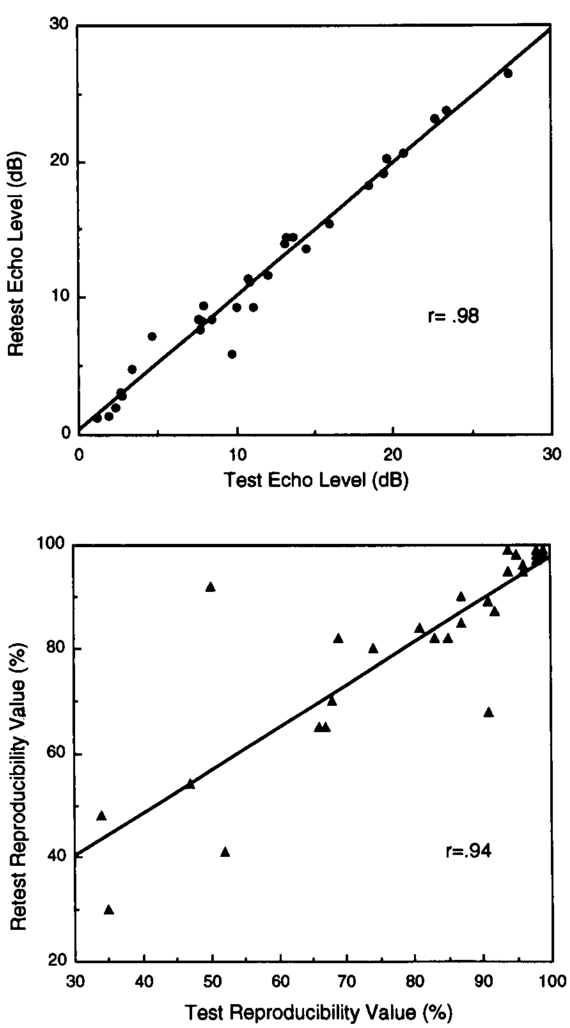

Figure 1 Test–retest correlations for echo level and reproducibility with regression lines.

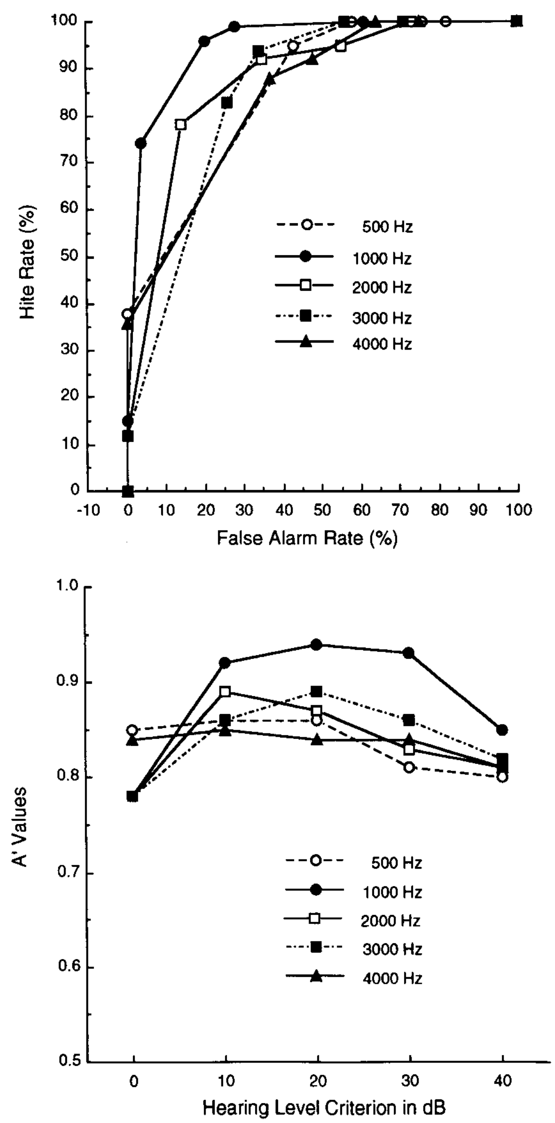

Figure 2 Top panel: receiver operating characteristic (ROC) curves for the frequency spectrum data at 500, 1000, 2000, 3000, and 4000 Hz. Bottom panel: A' values for the five frequencies at five hearing level (HL) criterion.

percent, using a HL criteria of 20 dB. In reviewing the data illustrated in Figure 2, one can see that the HL prediction from the frequency spectrum for any of the frequencies is generally very poor, with the exception of 1000 Hz. Conservative interpretation of these frequency spectrum data suggest that if an OAE is present at 2000, 3000, and 4000 Hz, then the HL at each of these frequencies is ≤ 30 dB. For 1000 Hz, if an OAE is present in the frequency spectrum, then the HL at 1000 Hz is ≤ 35 dB. For 500 Hz, if an OAE is present in the frequency spectrum, then the HL at 500 Hz is ≤ 10 dB. If an OAE is absent at any frequency band within the frequency spectrum, however, a clinically acceptable prediction of HL at the analogous frequency is not possible.

The echo level and the reproducibility data were each assessed in separate 2 × 2 matrices with the hearing loss and normal-hearing groups constituting the columns and different echo level values constituting the rows. The subjects were divided into two groups, one group with HLs > 20 dB for the octave frequencies of 500–4000 Hz and the other group with HLs ≤ 20 dB for the octave frequencies of 500–4000 Hz. The top panel of Figure 3 illustrates the ROC curve for the echo level analyses. Again, the further the ROC curve is displaced toward the upper left corner, the better the test performance. Included in the top panel of Figure 3 are the A' values associated with specific points on the ROC curve. An echo level criterion of < 6 dB produced a hit rate of 92 percent and a false alarm rate of 8 percent, resulting in the best A' value of .96. In addition to generating a ROC curve, the echo level data were used to plot cumulative distributions from the two subject samples, which allowed a direct comparison of the hit rate versus the correct rejection rate independent of pass/fail criteria. These complementary functions for echo level are displayed in the bottom panel of Figure 3. In general, interpretation of the hit rate versus correct rejection rate functions is that the higher the cumulative percentage is at the crossover point, the better the prediction parameter. For echo level, the crossover point occurs at the 96 percent level and is associated with an echo level of approximately < 6 dB. In short, an echo level criterion of < 6 dB will separate 96 percent of the ears with HLs of > 20 dB for 500–4000 Hz from the ears with HLs of ≤ 20 dB for 500–4000 Hz.

Similarly, a ROC curve and hit rate versus correct rejection rate cumulative distributions

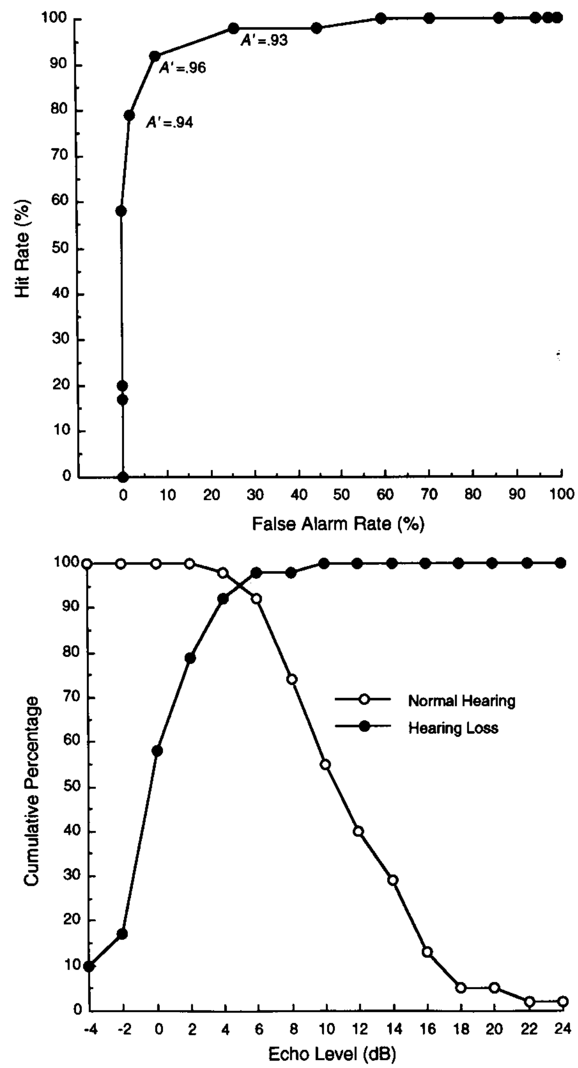

Figure 3 Top panel: receiver operating characteristic (ROC) curve for echo level with the A' values for < 4 dB, < 6 dB, and < 8 dB echo level criterion. Bottom panel: cumulative distributions of hit rates and correct rejection rates as a function of echo level.

were plotted for the reproducibility parameter and are displayed in the top and bottom panels of Figure 4, respectively. Included in the ROC curve are A' values for specific points on the ROC function. A reproducibility criterion of < 70 percent produced a hit rate of 91 percent and a false alarm rate of 5 percent, resulting in an A' value of .96. This finding is duplicated in the hit rate versus correct rejection rate cumulative distributions in the bottom panel of Figure 5. Stated differently, these analyses suggest that a reproducibility criterion of < 70 percent will separate 96 percent of the ears with HLs of > 20 dB for 500–4000 Hz from those ears with HLs of ≤ 20 dB for 500–4000 Hz.

Finally, the echo level and reproducibility data were subjected to a bivarient plot analysis,

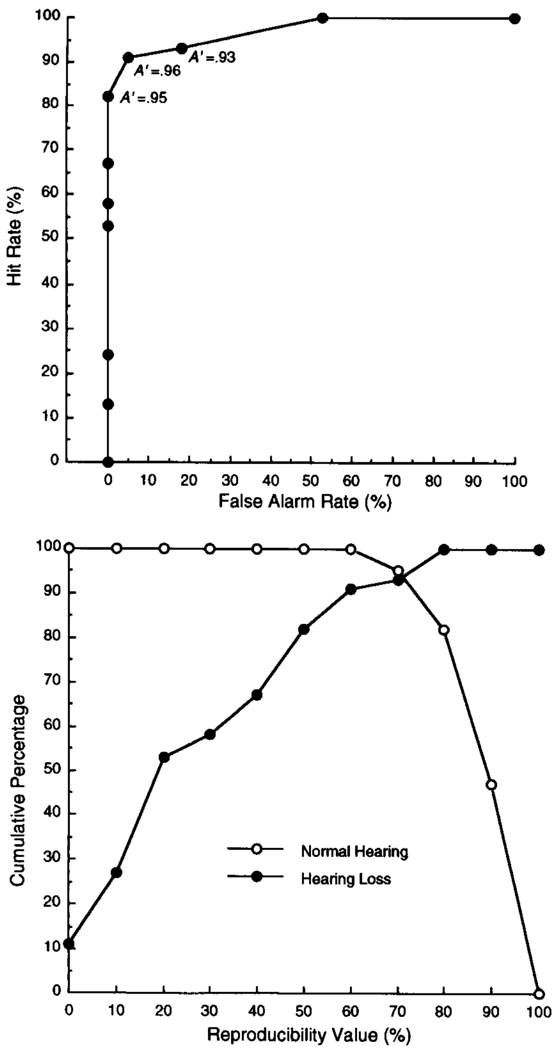

Figure 4 Top panel: receiver operating characteristic (ROC) curve for reproducibility with A' values for 60, 70, and 80 percent reproducibility criterion. Bottom panel: cumulative distributions of hit rates and correct rejection rates as a function of reproducibility.

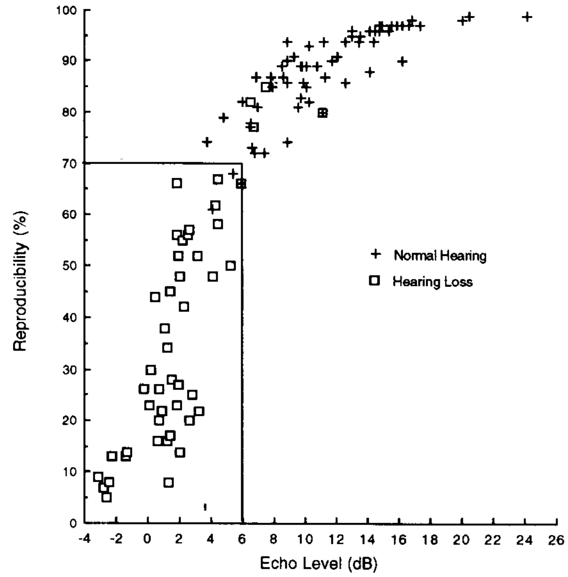

Figure 5 Bivariant plot of echo level versus reproducibility for the normal-hearing (HLs ≤ 20 dB, 500–4000 Hz) and hearing loss (HLs > 20 dB, 500–4000 Hz) groups.

which is displayed in Figure 5. Using an echo level of 6 dB and a reproducibility value of 70 percent as the abscissa and ordinate values, respectively, the normal-hearing ears and the hearing loss ears can be separated with little overlap in distributions.

DISCUSSION

The echo level and reproducibility values recorded for the normal-hearing listeners were consistent with those previously reported from our facility (Vedantam and Musiek, 1991) and another facility (Robinette, 1992). All of the normal-hearing ears produced very discernible OAEs in the raw waveform and rather high average echo level and reproducibility values. The TEOAE parameters of echo level and reproducibility, however, demonstrated a large range of values among the normal-hearing ears, a finding that is consistent with previous investigations using the ILO88 system (Vedantam and Musiek, 1991; Robinette, 1992). While the between-ear variability for the echo level and reproducibility parameters was high, the within-ear variability was very low, as reflected in the excellent short-term test–retest correlations. The finding of low within-ear variability is consistent with previous investigations (Berlin et al, 1991; Harris et al, 1991; Vedantam and Musiek, 1991; Franklin et al, 1993). In short, the TEOAEs appear to have excellent within-subject stability and may actually be viewed as a physiologically based "cochlear fingerprint" that only changes with alterations in cochlear function.

Direct comparison of the present TEOAE data for the parameters of echo level and reproducibility to previous data is not possible, as similar investigations used proprietary instrumentation that did not provide comparable TEOAE parameters. However, some degree of comparison between our TEOAE frequency spectrum data and the TEOAE frequency spectrum data reported by Collet et al (1991) is possible. In general, the frequency spectrum data of Collet et al (1991) show no TEOAEs when the hearing loss exceeds 45 dB at the octave frequencies of 1000–4000 Hz, which is 15 dB greater than the values recorded for this investigation and higher than the 25-dB and 35-dB values reported by Probst et al (1987) and Bonfils et al (1988), respectively, using proprietary systems. These differences in data may result from instrumentation differences among the studies, such as the sensitivity of the probe microphones, the nature of the stimulus click, the amount of signal averaging, and the filtering characteristics of the measurement system. Collet et al (1991), using the ILO88 system, report frequency spectrum data similar to those obtained in the present investigation, that is, the poorest representation of HLs in the frequency spectrum at 500 and 4000 Hz with the best representation at 1000 Hz.

The OAE frequency spectrum data produced by the ILO88 appears to be greatly influenced by the bandpass backfiltering characteristics of the system. In the ILO88 system, the OAE energy is bandpass filtered between 600 and 6000 Hz before signal averaging. These filter characteristics may account, in part, for the low number of normal-hearing ears in our sample having OAE energy in the frequency spectrum at 500 Hz. In all probability, there was some OAE energy present at 500 Hz for these normal-hearing subjects, but the OAE energy was filtered out of the spectrum and/or affected by low-frequency biological noise, such as respiration. Thus, the ILO88 system may not accurately separate ears into HL groups at 500 Hz from the frequency spectrum, due primarily to the system's backfiltering characteristics. The poor test performance at 4000 Hz may result from multiple factors, such as the effect of stimulus spectrum roll-off beginning at 4000 Hz, resulting in insufficient stimulus energy, and the effect of factors not reflected in the audiogram (i.e., noise exposure and aging). Further, middle ear characteristics affect the backward transmission of the OAEs into the ear canal, resulting in the attenuation of low- and high-frequency energy.

While the ILO88's frequency spectrum portrayal of OAE activity at 500 and 4000 Hz may have been affected by instrumentation and middle ear characteristics, we do not believe a similar explanation can be proposed for the poor separation of HLs by 10-dB steps at 2000 and 3000 Hz. The OAE representation in the 2000- and 3000-Hz bands may be affected by the inherent interear variability of the dominant frequency bands that make up TEOAEs (Sutton, 1985). Conversely, the OAE representation at 1000 Hz reflects the fact that the dominant frequency band for TEOAEs is between 1000 and 2000 Hz. Further, the backward transmission characteristics of the middle ear system allows the optimum transmission of TEOAEs between 1000 and 2000 Hz (Kemp et al, 1986). The present data are consistent with the findings of Collet et al (1991) that HLs at several frequencies are related to the amplitude of an OAE within specific frequency bands in the frequency spectrum.

The high hit rates and low false alarm rates reflected in the ROC functions for echo level and reproducibility suggest that these parameters do allow an accurate separation of ears based on an average HL of > 20 dB for the octave frequencies of 500–4000 Hz. An echo level criterion of < 6 dB appears to provide an adequate hit rate in identifying an average HL of > 20 dB for 500–4000 Hz. The trade-off between hit rate and false alarm rate using the < 6 dB criterion generated an overall prediction error of 4 percent, as reflected in the .96 A' value.

Use of a reproducibility value of < 70 percent results in a high hit rate and a low false alarm rate, with an excellent A' value of .96. Thus, meeting and or exceeding the reproducibility criterion value of 70 percent provides a clinically acceptable error of approximately 4 percent. Stated differently, if the ear has a reproducibility value of < 70 percent, then the average HL for 500–4000 Hz is in all probability > 20 dB. Conversely, if the reproducibility value is ≥ 70 percent, the ear has an average HL for 500–4000 Hz of ≤ 20 dB. Thus, identical situations exist for both the echo level and the reproducibility parameters; if the TEOAE values exceed the parameter criteria, the average HL for 500–4000 Hz is ≤ 20 dB, but if the TEOAE value is less than the parameter criteria, the average HL for 500–4000 Hz will be > 20 dB.

In summary, it appears that the ILO88 TEOAE parameters of echo level and reproducibility provide an acceptable prediction of average hearing for the octave frequencies of 500–4000 Hz. Stated differently, if the echo level is < 6 dB and the reproducibility value is < 70 percent, the average HL between 500 and 4000 Hz will be > 20 dB, as suggested by the ROC curves and cumulative distributions of hit rate versus correct rejection rate. Further, both echo level and reproducibility are very stable within subject measures of cochlear function.

Perhaps a combination of parameters provided by the ILO88 system, such as the frequency-specific OAE amplitude in the frequency spectrum and the analogous frequency reproducibility value provided by the updated ILO88 software, may improve the HL prediction from the frequency spectrum. Or perhaps there is only a weak association between OAE frequency spectrum data and HLs in some individuals as there is considerable OAE variability among ears with similar hearing sensitivity. In addition, OAEs are affected by small changes in cochlear physiology that do not result in comparable changes in auditory threshold measured to the nearest 5-dB interval with pure-tone audiometry.

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