Distortion Product Otoacoustic Emission Response Characteristics in Older Adults

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Objective: **The primary purpose of this study was to determine the distortion product otoacoustic emission (DPOAE) and noise response characteristics in a large sample of older adults. Another purpose was to evaluate how specific absolute DPOAE levels or DPOAE/Noise ratios differentiated hearing status in these individuals.**

Design: **A cross-sectional design was utilized for this study. As a part of the Epidemiology of Hearing Loss Study (EHLS), DPOAEs were measured in 937 of the 3429 participants aged 48 to 92 yr. The DPOAE and noise response characteristics were evaluated at 1000, 2000, 4000, and 8000 Hz. Absolute DPOAE level and DPOAE/Noise ratios were measured in the participants. The DPOAE data were compared with individual pure-tone frequencies (1000, 2000, 4000, and 8000 Hz) in the participants to investigate how DPOAE responses differentiated ears with normal hearing from impaired ears. Sensitivity, specificity, positive and negative predictive values, and accuracies were calculated for various absolute DPOAE levels and DPOAE/Noise ratios.**

Results: **Due to the considerable overlap between DPOAE responses and the noise levels at 1000 Hz, this frequency was not used for any analyses. Sensitivity and specificity were calculated for various DPOAE responses. Sensitivity and specificity varied by frequency for absolute DPOAE levels and DPOAE/Noise ratios. Receiver operator characteristic (ROC) analyses were used to determine which DPOAE responses differentiated normal hearing from hearing loss. The ROC analyses demonstrated that −6 dB SPL at 2000 Hz, −14 dB SPL at 4000 Hz, and −22 dB SPL at 8000 Hz and a +9 dB DPOAE/Noise ratio at each of these frequencies yielded the highest discrimination.**

Conclusions: **Sensitivity and specificity varied by DPOAE response characteristics and frequency. The decision as to which DPOAE response criterion used should be based on careful consideration of objectives and the possible consequences of misdiagnosis. The results of this study support the use of DPOAEs as a clinical measure for older adults.**

(Ear & Hearing 2003;24;20–29)

Clinical audiometry is the primary tool for measuring hearing loss, but this behavioral test requires a willing and cooperative individual able to attend during the lengthy task of threshold determination. In some settings, for example working with older adults with cognitive or physical disabilities, it would be desirable to have an objective measure of hearing. Because these individuals may not be able to respond during audiometric testing, otoacoustic emission (OAE) testing may offer one option for an objective measure of cochlear function. However, little is known about the response characteristics, such as sensitivity and specificity, of this measure in older adults.

Gold (1948) postulated the existence of OAEs and Kemp (1978) developed the instrumentation for measuring OAEs and provided evidence for the existence of OAEs using a signal averaging technique. Kemp (1978) described OAEs as sounds in the external auditory canal that originate from the physiological activity within the cochlea, described OAE frequency composition, and demonstrated how OAE characteristics changed as a function of signal level. Distortion product OAEs (DPOAEs) are produced when two slightly different pure-tone frequencies (f_1 and f_2 where $f_2 > f_1$) simultaneously stimulate the cochlea. They are associated with outer hair cell (OHC) movement (Brownell, 1982, 1990; Brownell, Manis, Zidanic, & Spirou, 1983) and are a reflection of the active, nonlinear processes in the cochlea. The human cochlea produces many DPOAEs (Pickles, 1988) but the most frequently measured and most robust DPOAE in humans occurs at $2f_1$-f_2 (e.g., Gaskill & Brown, 1990; Probst, Lonsbury-Martin, & Martin, 1991). This DPOAE is produced on the basilar membrane close to where f_2 is represented (Brown & Kemp, 1984; Gaskill & Brown, 1996; Martin, Lonsbury-Martin, Probst, & Coats, 1987; Martin, Ohlms, Franklin, Harris, & Lonsbury-Martin, 1990). As a result, the level at the $2f_1$-f_2 frequency can be used to assess cochlear function at f_2 (Brown & Kemp, 1984).

Interpreting DPOAE response data is difficult

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DOI: 10.1097/01.AUD.0000051847.66944.2B

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because of the presence of background noise from equipment (e.g., cooling systems or fans within a sound booth), or from the individual being tested (e.g., resonating noise from the person's breathing or vascular noise trapped within the closed ear canal). A high noise floor will interfere with measuring the DPOAE response. An example of the difficulty interpreting a DPOAE response can be seen for DPOAE data at or below 1000 Hz. For f_2 frequencies less than or equal to 1000 Hz, it is difficult to differentiate a DPOAE response from the noise floor because of the high noise levels associated with lower f_2 frequencies (Gorga et al., 1993).

If DPOAEs are to be used clinically to identify people with decreased hearing sensitivity, it is important to determine how well DPOAEs can differentiate normal hearing from hearing loss. Single DPOAE responses (i.e., absolute DPOAE level or DPOAE/Noise ratios) at one frequency have been used to evaluate hearing status. This technique, however, results in an overlap of responses between normal hearing and hearing impairment (Gorga et al., 1993; Gorga, Neely, Ohlrich, Hoover, Redner, & Peters, 1997; Gorga, Nelson, Davis, Dorn, & Neely, 2000; Gorga, Stover, & Neely, 1996). Specifically, some ears with mild hearing loss may produce robust DPOAEs whereas DPOAEs may be absent in ears with normal hearing. Absent DPOAEs in an individual with normal hearing may be a result of subtle outer ear and middle ear problems or cochlear factors such as the cancellation of responses from the multiple generators responsible for $2f_1$-f_2. These problems may attenuate DPOAE levels but may not affect pure-tone behavioral thresholds (e.g., Naeve, Margolis, Levine, & Fournier, 1992).

Researchers also have employed multivariable techniques to improve test performance by simultaneously investigating many variables (Dorn, Piskorski, Gorga, Neely, & Keefe, 1999; Dorn, Piskorski, Keefe, Neely, & Gorga, 1998; Gorga, Neely, & Dorn, 1999; Gorga et al., 2000). More specifically, predictions about hearing status at one frequency were based on DPOAE and noise levels at several frequencies. Dorn et al. (1999) examined areas under receiver operator characteristic (ROC) curves derived from single variables (DPOAE level and DPOAE/Noise ratio) and multiple variables to predict hearing status at each pure-tone frequency. For each test frequency, multivariable analyses produced larger areas under the ROC curve compared with single variable analyses. Similarly, Gorga et al. (1999, 2000) reported that the multivariable analyses were better predictors of audiometric status compared with univariate analyses. For example, sensitivities were between 70% and 90% for DPOAE/Noise ratios in multivariable analyses whereas 78% was the highest sensitivity achieved using the strictest DPOAE/Noise ratio (+9 dB). Multivariable analyses provided better sensitivity for predicting hearing status compared with single variable analyses, but these statistical procedures may be impractical in some clinical settings because some OAE equipment currently do not have the capability of applying the algorithm established by Gorga and his colleagues (Dorn et al., 1999; Gorga et al., 1999). Simple guidelines, such as a single DPOAE/Noise ratio or absolute DPOAE level, may be useful for clinical audiologists.

The effect of age on OAEs is critical to the understanding of OAE characteristics in older individuals. Researchers have reported mixed results for the age effect on OAEs such that some researchers found an age effect (Dorn et al., 1998; Kimberley, Hernadi, Lee, & Brown, 1994; Lonsbury-Martin, Cutler, & Martin, 1991) whereas others have not (Bertoli & Probst, 1997; Prieve & Falter, 1995; Stover & Norton, 1993; Strouse, Ochs, & Hall, 1996). These inconsistent findings may be in part due to the methodological differences in how researchers accounted for participants' hearing loss. Researchers studied individuals with normal hearing sensitivity to investigate the influence of age on OAEs (Lonsbury-Martin et al., 1991). The older group, however, while meeting the criterion for normal hearing thresholds, had poorer thresholds than the younger group. The variability in normal pure-tone thresholds may have contributed to the age effect. When researchers adequately controlled for, or statistically accounted for hearing loss, no effect of age on OAEs was found (e.g., Strouse et al., 1996). The diagnostic utility of OAEs in older adults has not been adequately studied. Because of the high prevalence of hearing loss (Cruickshanks et al., 1998), sensitivity, specificity, and positive and negative predictive values of DPOAE responses for hearing loss in older adults may be different in younger adults. Therefore, conclusions regarding diagnostic utility may differ.

The purpose of this study was to determine the sensitivity, specificity, predictive values, and accuracy of DPOAE responses across selected frequencies in a large, cross-sectional sample of older individuals from a population-based study of hearing loss. The specific research questions were: 1) What are the DPOAE and noise response characteristics in a large sample of older individuals, and 2) What DPOAE response discriminates normal hearing and hearing loss in these individuals?

METHODS

Participants

As part of the Epidemiology of Hearing Loss Study (EHLS) (AG11099), cochlear function was assessed in the participants using DPOAEs (Cruickshanks et al., 1998). Participants were 48 to 92 yr of age at the baseline examination and had previously participated in the Beaver Dam Eye Study (Klein, Klein, & Lee, 1996), a population-based study of ocular diseases in Beaver Dam, WI. Although the EHLS began in 1993, DPOAE testing was not added until mid 1994 due to funding delays. Participants seen at home or in nursing homes were not eligible for DPOAE testing because of the lack of portable testing equipment. DPOAE data were available for 937 of the 3439 participants in the EHLS. The mean age of the participants was 63.7 yr (SD = 9.6 yr), and 44.3% (N = 415) were men. Participants with DPOAE measurements were younger than participants without DPOAE data (Table 1). Table 1 describes how the sample of individuals with DPOAE data compared with individuals without DPOAE data and the EHLS cohort as a whole. After adjusting for age using the Cochran-Mantel-Haenszel statistic for general associations (Mantel, 1963), only the household income was statistically different between participants with DPOAE data and those without DPOAE data.

Table 2 shows the degree of hearing loss over certain frequencies (1000, 2000, 4000, and 8000 Hz) for both ears of the 910 participants with complete audiometric data. The number of participants, means, and standard deviations are provided for the category of hearing loss at each frequency. It can be seen from this table that as frequency increased, more individuals had elevated hearing thresholds. Additionally, individuals with normal hearing at 4000 and 8000 Hz still had mean thresholds that were higher than the normal hearing sensitivity thresholds at 1000 and 2000 Hz. This sloping high-frequency hearing loss is consistent with presbycusis.

Procedures

During the EHLS, the participants completed an interviewer-administered questionnaire regarding ear and hearing-related history, noise exposure, socioeconomic status, and lifestyle factors. The initial hearing examination included otoscopy (Nondahl, Cruickshanks, Wiley, Tweed, Klein, & Klein, 1996), a screening tympanogram (Wiley, Cruickshanks, Nondahl, Tweed, Klein, & Klein, 1996), and pure-tone air- and bone-conduction audiometry (Cruickshanks et al., 1998). DPOAEs were then measured using the Virtual system (Model 330, v 1.8) installed on a Macintosh II computer. The level for f_1 was 65 dB SPL, and the level of f_2 was 50 dB SPL. The f_2/f_1 ratio was set at 1.2 and f_2 was measured at 1000, 2000, 4000, and 8000 Hz. The individual was seated comfortably outside the sound booth and given instructions to remain as quiet as possible for the duration of the test. After the instructions were given, an appropriately sized probe tip was placed on the probe assembly and inserted into the ear canal with a good seal. Once the probe was placed in the ear canal, the level of the two frequencies was set according to protocol. The protocol automatically stopped after it ran through the four frequencies. At each of the four f_2 frequencies, 32 averages were obtained from data that were lower than the artifact reject criterion. The artifact reject was set at 10 dB based on the ambient noise level at the beginning of the test. The set of averages at the first test frequency was rejected if the noise level was more than 10 dB greater than the ambient noise level. Noise levels at subsequent test frequencies could not be more than 10 dB greater than the noise level at the previous test frequency or the run was rejected. If that level was not achieved after four sets of 32 averages, the test moved to the next f_2 frequency. After DPOAEs were measured in one ear, the same procedure was completed in the opposite ear.

Participants were excluded from statistical analyses if they had any of the following: 1) evidence on otoscopic examination of drainage or a visible air-liquid line behind the tympanic membrane; 2) the tympanogram was flat or a severely reduced peak compensated static acoustic admittance, peak Y_{tm} ($\leq$0.1 millimhos), or a high peak Y_{tm} ($\geq$3.0 millimhos); 3) a perforated tympanic membrane; or 4) an air-bone gap of $\geq$15 dB at 500 or 4000 Hz. Finally, if the levels of f_1 or f_2 at a specific frequency were not within 5 dB of the levels specified in the protocol, DPOAE data for that specific frequency were eliminated from any further analyses.

RESULTS

The distributions for the DPOAE and noise levels were evaluated to determine the amount of overlap between the two distributions. Ninety-five percent ranges for DPOAEs, noise floor, and DPOAE/Noise ratio for 1000, 2000, 4000, and 8000 Hz can be seen in Table 3. The distributions of DPOAE and noise levels overlapped, particularly at 1000 Hz. Consequently, no further analyses of 1000 Hz were conducted because of the inability to detect a DPOAE response greater than the noise level.

To evaluate the test performance, comparisons of the sensitivity and specificity of absolute DPOAE

TABLE 1. Characteristics of the Epidemiology of Hearing Loss Study participants with distortion product otoacoustic emission (DPOAE) data and those participants without DPOAE data

	Individuals with DPOAE Data (N = 937)		Individuals without DPOAE Data (N = 2502)				Total number of individuals (N = 3439)	
	%	N	%	N	p value*	p value**	%	N
Age group (years)								
48–59	40.6	380	34.4	860	<0.001		36.1	1240
60–69	32.9	308	29.3	734			30.3	1042
70–79	19.2	180	27.3	683			25.1	863
80–92	7.4	69	9.0	225			8.5	294
Female sex	55.7	522	56.6	1415	0.656		56.3	1937
Hearing loss	40.6	380	46.2	1155	<0.01	0.313	44.6	1536
Marital status								
Married	72.1	668	68.6	1682	0.022	0.596	69.6	2350
Single	3.7	34	3.6	88			3.6	122
Separated	0.3	3	0.4	10			0.4	13
Divorced	8.7	81	7.4	181			7.8	262
Widowed	15.1	140	20.0	490			18.7	630
Income ($)								
≤9,000	7.0	61	10.9	247	<0.001	0.002	9.8	308
10,000–19,000	21.1	184	24.4	552			23.5	736
20,000–29,000	19.6	171	20.9	471			20.5	642
30,000–44,000	22.3	195	22.2	501			22.2	696
45,000–59,000	14.9	130	12.0	270			12.8	400
≥60,000	15.2	133	9.7	218			11.2	351
Education (years)								
<12	23.1	216	22.9	572	0.503		22.9	788
12	45.7	428	46.8	1171			46.5	1599
13–15	14.8	139	15.8	395			15.5	534
≥16	16.4	154	14.5	362			15.0	516
Overall health								
Excellent	25.7	238	20.6	507	<0.01	0.120	22.0	745
Good	59.5	550	61.8	1520			61.2	2070
Fair	13.2	122	15.9	390			15.1	512
Poor	1.6	15	1.7	42			1.7	57
Smoking status								
Never	46.7	433	44.9	1102	0.627		45.4	1535
Past	38.8	360	40.0	983			39.7	1343
Current	14.5	134	15.1	371			14.9	505
Diabetes	10.2	93	9.4	229	0.518		9.6	322
Cardiovascular disease	12.8	118	14.0	343	0.357		13.7	461
Hypertension	48.6	449	50.5	1238	0.350		50.0	1687
Noise exposure	56.2	527	55.9	1399	0.863		56.0	1926
Occupation								
Manage/prof	22.3	197	18.2	430	0.038	0.099	19.3	627
Tech/sales/admin	23.8	210	24.7	584			24.5	794
Service	17.1	151	20.6	488			19.7	639
Farm/forest/fish	3.1	27	3.9	93			3.7	120
Prod/craft/repair	12.1	107	12.2	289			12.2	396
Operator/labor	21.5	190	20.3	480			20.6	670

** Comparison between EHLS participants with DPOAE data and participants without DPOAE data unadjusted for age using the chi-square test.*
*** Adjusted for age using the Cochran-Mantel-Haenszel statistic for general associations.*

levels and DPOAE/Noise ratios were conducted. Analyses of the absolute DPOAE levels were limited to data for participants where the noise floor was less than the 97.5th percentile of the distribution of the absolute DPOAE levels. For 2000 Hz, this noise level was 0 dB SPL; for 4000 Hz, the noise level was −15 dB SPL; and for 8000 Hz, the noise level was −20 dB SPL. Frequency specific DPOAE measurements were excluded from analyses if the noise floors exceeded these levels.

After participants were excluded for middle ear problems and excessive noise floors, data from 837 participants at 2000 Hz, 838 participants at 4000 Hz, and 831 participants at 8000 Hz were used for analyses. These individuals had both their pure-tone thresholds and DPOAEs measured for each specific frequency. As stated previously, absolute DPOAE levels and DPOAE/Noise ratios were used to differentiate hearing status. Hearing loss (the gold standard) was defined as thresholds ≥25 dB

TABLE 2. The numbers of participants with various degrees of hearing loss for 1000, 2000, 4000, and 8000 Hz across ears are shown for both ears. Means and standard deviations are also shown for degree of hearing loss within each frequency

	Right Ear Thresholds				Left Ear Thresholds			
	N	%	Mean	SD	N	%	Mean	SD
1000 Hz								
Normal (≤ 20 dB HL)	719	79.0	9.7	6.0	716	78.7	10.6	5.3
Mild (25–40 dB HL)	153	16.8	31.0	5.6	148	16.3	30.3	5.6
Moderate (45–65 dB HL)	27	3.0	50.7	5.8	36	4.0	50.3	6.1
Severe (> 65 dB HL)	11	1.2	94.0	20.0	10	1.0	100.5	22.3
All	910	100.0	15.5	14.5	910	100.0	16.3	14.7
2000 Hz								
Normal	586	64.4	9.8	6.9	559	61.4	10.6	6.3
Mild	198	21.8	30.6	5.5	206	22.6	30.4	5.4
Moderate	108	11.9	51.4	6.0	126	13.9	52.6	6.6
Severe	18	1.9	85.6	19.1	19	2.1	87.6	21.8
All	910	100.0	20.7	18.4	910	100.0	22.5	19.0
4000 Hz								
Normal	323	35.5	12.1	6.3	295	32.4	12.5	5.9
Mild	227	25.0	32.0	5.5	236	25.9	32.1	5.7
Moderate	263	28.9	55.3	6.6	260	28.6	54.3	6.7
Severe	97	10.6	80.0	12.6	119	13.1	81.1	13.5
All	910	100.0	36.6	23.8	910	100.0	38.4	24.3
8000 Hz								
Normal	220	24.2	13.8	5.9	170	18.7	13.4	6.2
Mild	187	20.6	32.3	5.7	216	23.7	32.6	5.5
Moderate	279	30.7	55.4	7.0	282	31.0	55.8	6.8
Severe	224	24.5	81.4	10.0	242	26.6	82.0	10.5
All	910	100.0	47.0	26.0	910	100.0	49.4	25.7

HL at the specific frequency evaluated. At 2000, 4000, and 8000 Hz, various absolute DPOAE levels and DPOAE/Noise ratios using 2- or 3-dB steps were applied in 2 × 2 contingency tables to calculate how well they differentiated normal hearing from hearing loss at those frequencies. From these contingency tables, sensitivity, specificity, positive predictive value, negative predictive value, and accuracy were calculated and ROC curves were constructed. Pairs of hit rate (sensitivity) and false alarm (1-specificity) percentages for DPOAE criteria were plotted to create the ROC curve. The more clearly a response from DPOAE tests is able to discriminate between normal hearing and hearing loss, the farther the ROC curve will deviate toward the upper left corner of the graph. A response that performs less favorably, or provides no information, will fall closer to the diagonal chance line running from lower left to upper right (Murphy, Berwick, Weinstein, Borus, Budman, & Klerman, 1987). By displaying a wide range of pairs of hit rate and false alarm percentages for various DPOAE responses, the ROC curve provides a clear picture of the performance of the DPOAE criteria.

The ROC curves that were constructed for absolute DPOAE level at frequencies 2000, 4000, and 8000 Hz can be seen in Figure 1. In this figure the ordinate represents the hit rate percentage and the

TABLE 3. The 95% ranges for DPOAEs, noise floors, and signal-to-noise ratios

Frequency	DPOAEs (dB SPL)	Noise Floor (dB SPL)	S/N ratio (dB SPL)
1000 Hz			
Right (n=913)	−22.9 to 14.8	−18.9 to 12.6	−11.8 to 14.9
Left (n=930)	−20.5 to 15.7	−18.1 to 12.2	−10.6 to 15.2
2000 Hz			
Right	−25.0 to 11.5	−28.0 to 0.3	−5.8 to 32.7
Left	−25.0 to 10.5	−27.6 to 2.0	−7.1 to 32.1
4000 Hz			
Right	−28.0 to 5.5	−28.1 to −12.9	−6.0 to 28.3
Left	−29.3 to 4.7	−27.9 to −10.9	−7.0 to 27.5
8000 Hz			
Right	−38.1 to −5.4	−39.8 to −21.7	−5.6 to 26.6
Left	−37.9 to −6.6	−39.5 to −19.7	−6.1 to 25.5

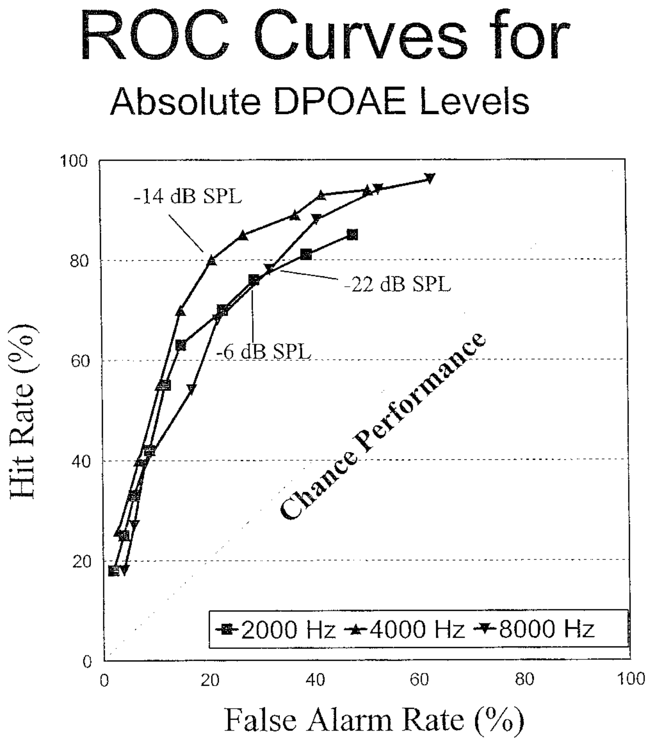

Figure 1. Hit rate as a function of false alarm rate for various absolute DPOAE levels at; 2000, 4000, and 8000 Hz. For the calculation of the ROC curves, hearing loss was defined as threshold greater than or equal to 25 dB HL. The dashed line from the lower left corner to the upper right corner represents a test that performs at the chance level. Selected absolute DPOAE levels are indicated on the curves.

abscissa represents the false alarm percentage. Because the data from the left and right ears were similar, only right ear data are presented in the figures. In general, the ROC curves for the three frequencies were displaced to the upper left of the figure. Based on the ROC curves in Figure 1, −6 dB SPL at 2000 Hz, −14 dB SPL at 4000 Hz, and −22 dB SPL at 8000 Hz were the frequency specific criteria that resulted in the greatest displacement to the upper left of the figure. In Table 4, the sensitivities, specificities, positive predictive values, negative predictive values, and accuracies for selected absolute DPOAE levels at 2000, 4000, and 8000 Hz are shown. For example, the absolute DPOAE level of −6 dB SPL at 2000 Hz had 76% sensitivity, 71% specificity, 57% positive predictive value, 86% negative predictive value, and 73% accuracy. In other words, 76% of individuals with hearing loss (≥25 dB HL) were accurately identified as a result of having an absolute DPOAE level of less than −6 dB SPL (sensitivity) whereas 71% of individuals with normal hearing had an absolute DPOAE level of ≥−6 dB SPL (specificity). The positive predictive value for −6 dB SPL at 2000 Hz was 57%, indicating that over half the individuals with absolute DPOAE levels below this DPOAE level had a hearing loss. In contrast, the negative predictive value for this level was 86%, demonstrating that most individuals with absolute DPOAE levels ≥−6 dB SPL had normal hearing. For 4000 Hz, an absolute DPOAE level of −14 dB SPL had sensitivity of 80% and specificity of 79% whereas at 8000 Hz, an absolute DPOAE level of −22 dB SPL had sensitivity of 78% and specificity of 68%. Accuracy, defined as the number of correctly identified individuals with hearing loss added to the number of correctly identified individuals with normal hearing divided by the total number of individuals, ranged from 68% to 81% for various absolute DPOAE levels across the three frequencies.

An example of the trade-offs between sensitivity and specificity for a particular DPOAE response criterion can also be seen in Table 4. At 4000 Hz, if an absolute DPOAE level of −14 dB SPL was used as the DPOAE response to differentiate normal hearing from hearing loss, 20% (1 − sensitivity) of the individuals ($N = 102$) with hearing loss (≥25 dB HL) would be missed because they had an absolute DPOAE level of ≥−14 dB SPL. Using this same criterion, 21% (1 − specificity) of the individuals (N

TABLE 4. Sensitivities, specificities, positive predictive values (PPV), negative predictive values (NPV), and accuracies for the two methods of predicting hearing status. Selected absolute DPOAE levels are presented on the left portion of the table, and selected DPOAE/Noise ratios are shown on the right portion of the table

	Absolute DPOAE Level						DPOAE/Noise Ratio					
Frequency	Cutpoint	Sensitivity	Specificity	PPV	NPV	Accuracy	Cutpoint	Sensitivity	Specificity	PPV	NPV	Accuracy
2000 Hz	−4	81%	61%	51%	86%	68%	+11	84%	65%	55%	89%	71%
	−6	76%	71%	57%	86%	73%	+9	77%	71%	57%	86%	73%
	−8	70%	77%	61%	84%	75%	+6	65%	80%	62%	82%	75%
4000 Hz	−12	85%	73%	84%	73%	80%	+11	86%	66%	82%	74%	79%
	−14	80%	79%	86%	69%	79%	+9	79%	76%	85%	68%	78%
	−16	70%	85%	89%	62%	75%	+6	64%	84%	88%	57%	71%
8000 Hz	−20	88%	59%	86%	62%	81%	+11	89%	62%	88%	65%	82%
	−22	78%	68%	88%	51%	76%	+9	81%	71%	90%	55%	79%
	−24	68%	78%	90%	45%	70%	+6	60%	82%	91%	40%	65%

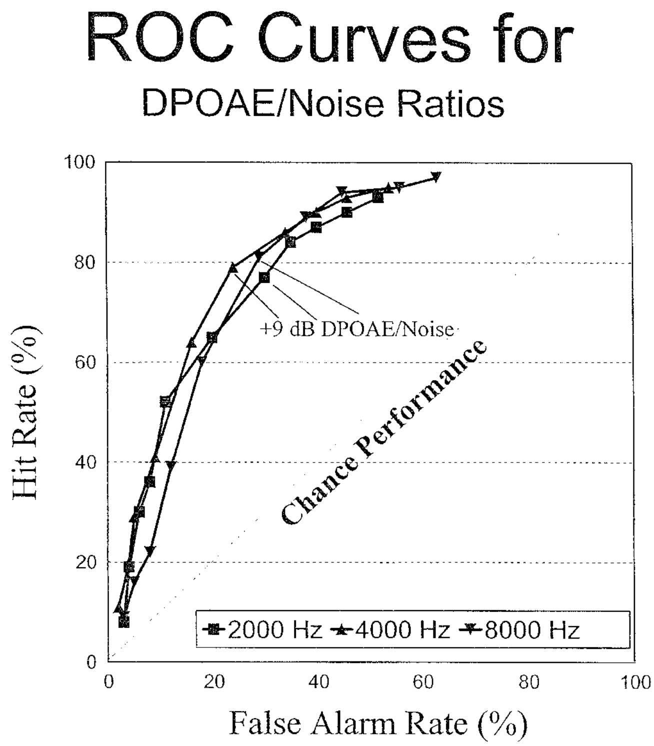

Figure 2. Hit rate as a function of false alarm rate for various DPOAE/Noise ratios at 2000, 4000, and 8000 Hz using the same calculation parameters as Figure 1. Selected DPOAE/Noise ratios are indicated on the curves.

= 62) with normal hearing (<25 dB HL) would be over-referred because they had an absolute DPOAE level of <−14 dB SPL. If the absolute DPOAE level criterion was changed to −12 dB SPL, sensitivity would increase to 85% and specificity would decrease to 73%. In other words, the percentage of missed hearing loss would decrease to 15% (*N* = 77) but the over-referrals would increase to 27% (*N* = 80).

ROC curves that were constructed for DPOAE/Noise ratios at 2000, 4000, and 8000 Hz can be seen in Figure 2. Similar to the absolute DPOAE level ROC curves, the DPOAE/Noise ratio ROC curves in Figure 2 were displaced to the upper left corner of the graph although the curves tended to overlap more in this figure compared with Figure 1. Based on the ROC curves in Figure 2, at each frequency, the +9 dB DPOAE/Noise ratio response criterion resulted in the greatest displacement to the upper left corner of the figure. Sensitivities, specificities, positive predictive values, negative predictive values, and accuracies for specific DPOAE/Noise ratios are shown in Table 4. At a +9 dB DPOAE/Noise ratio, sensitivity was 77% at 2000 Hz, 79% at 4000 Hz, and 81% at 8000 Hz. Specificity was 71%, 76%, and 71% at 2000, 4000, and 8000 Hz. The positive and negative predictive values were calculated using +9 dB DPOAE/Noise ratio as the cutpoint for all three frequencies. The trends for both predictive values of DPOAE/Noise ratios were similar to the values for absolute DPOAE level in that as frequency increased, positive predictive value increased and negative predictive value decreased. The accuracies for the three DPOAE/Noise ratios were between 65% and 82% for the three frequencies.

At 4000 Hz, if +9 dB DPOAE/Noise ratio was the criterion to differentiate normal hearing from hearing loss, 21% of the individuals (*N* = 110) would be missed and there would be 24% over-referrals (*N* = 72). When setting the DPOAE/Noise ratio criterion to a +11 dB DPOAE/Noise ratio, sensitivity at 4000 Hz increases to 86% but specificity decreases to 66%. A corresponding decrease in missed hearing losses (14% or 72 individuals) would be associated with an increase in over-referrals (34% or 102 individuals).

DISCUSSION

Distortion product otoacoustic emissions are a critical clinical tool for measuring cochlear function. This measure of cochlear function can be an integral component of the evaluation of nonresponsive adults or children and newborns. Because nonresponsive adults or older adults with cognitive deficits cannot actively participate in most tests of hearing sensitivity, a measure that does not require a behavioral response may be necessary to estimate auditory capabilities, particularly if auditory intervention is needed. A benefit of having DPOAEs as part of an audiometric battery is the ability to identify individuals with some degree of hearing loss.

A DPOAE response criterion that is highly sensitive and highly specific is preferred, but this combination of test characteristics is difficult to achieve (Flecther, Fletcher, & Wagner, 1988). When choosing a DPOAE response criterion that differentiates normal hearing from hearing loss based on a range of values, there is a trade-off between sensitivity and specificity. The use of a sensitive test is advantageous when testing individuals who are considered to be at high-risk for hearing loss such as older adults. High sensitivity minimizes the number of ears with hearing loss that will be missed. Highly specific tests are particularly useful because fewer false positives reduce the number of individuals subjected to unnecessary tests. Additionally, these results may affect an individual physically, emotionally, or financially. Because the sample of participants in the current study are older and at risk for hearing loss at higher frequencies, it may be preferable to choose a DPOAE response criterion with increased sensitivity at the expense of slightly decreased specificity. Accuracy, the percentage of individuals correctly classified, is an index of test performance, but this index does not weigh the relative costs or benefits associated with under or over-referrals. ROC analyses consider sensitivity and specificity and represent one approach to evaluating trade-offs between these two important characteristics of test performance.

Audiologists can use an absolute DPOAE level or DPOAE/Noise ratio when characterizing a DPOAE response. In this study, using the absolute DPOAE level approach, three different levels for the three frequencies measured (−6 dB SPL at 2000 Hz, −14 dB SPL at 4000 Hz, and −22 dB SPL at 8000 Hz) minimized the difference between sensitivity and specificity. Using the DPOAE/Noise ratio approach, +9 dB DPOAE/Noise ratio was the cutpoint that maximizes test performance at each of the three frequencies measured. Because a single DPOAE/Noise ratio can be used as a DPOAE response criterion, this ratio may have a clinical advantage over multiple absolute DPOAE levels. It is important to recognize that the performance of a DPOAE response criterion may vary by age group or other characteristics of the clinical population.

The number of participants (approximately 800 individuals) in the current study and in research completed by Gorga and his colleagues is similar (Dorn et al., 1999; Gorga et al., 1997), although the present study is somewhat less selective of its participants. It is, however, difficult to directly compare populations because of the expected differences between the groups of participants. The individuals in the previous studies were substantially younger and were recruited from a patient population of an audiology clinic within a hospital, hospital staff members, or from student populations of several area universities. Consequently, these participants may not sufficiently represent an older adult population. The individuals that participated in the current study were older compared with participants in other research and had a greater prevalence of hearing loss (Table 2). It can be seen in Table 2 that most individuals in the present study (approximately 80%) had normal hearing sensitivity at 1000 Hz but as frequency increased, the number of participants with some degree of hearing loss also increased. Furthermore, as frequency increased, the severity of hearing loss increased (i.e., more individuals had moderate and severe hearing loss). These differences in participant characteristics between the present study and published reports may have contributed to the lower sensitivity and specificity in the current study. Although studies that include a broader range of hearing sensitivity will have better sensitivity and specificity results, this broader range may not best represent the hearing patterns in older populations. A second potential reason for the variation in results could be the various types of DPOAE measurement systems that are currently used to collect data. Different DPOAE computer systems and measurement protocols may test and record DPOAE and noise levels in different ways. This may affect performance on sensitivity and specificity calculations.

A result that requires further explanation is the positive predictive value of 57% at 2000 Hz. Positive predictive value is the probability of hearing loss in an individual with a positive (abnormal) test result. The formula used to calculate positive predictive value utilizes sensitivity, specificity, and prevalence. The critical component of this calculation is the prevalence of hearing loss at 2000 Hz that is 35.5% in the current sample. The prevalence of hearing loss at 2000 Hz is considerably lower compared with the prevalences at 4000 Hz (64.4%) and 8000 Hz (75.8%). Briefly, for a given sensitivity and specificity, a lower prevalence of hearing loss leads to a smaller positive predictive value, which explains the poorer performance of this variable at 2000 Hz.

The results of the present study provide a starting point for developing a more effective DPOAE protocol to be used with older adults unable to complete conventional audiometry. This is important because the number of older adults, and consequently the number of older adults with hearing loss, will be growing. More specifically, the population of very old adults (80+ yr old) will be increasing at a faster rate compared with other age groups and the prevalence of cognitive deficits will be increasing within this very old group (Rabbitt, Diggle, Smith, Holland, & McInnes, 2001). An efficient, valid, and portable measure of auditory function is required for these older adults. The results of the ROC analyses suggest that a variety of DPOAE responses can be used depending on whether high sensitivity, high specificity, or a combination of both is the priority when utilizing this measure. Caution must be used when choosing a response criterion because of the trade-offs between sensitivity and specificity associated with different DPOAE responses. One of the remaining challenges is for researchers to ameliorate the problems measuring DPOAEs at 1000 Hz and below. This can be done by developing better instrumentation or noise reduction algorithms that separate DPOAEs from the noise floor or by using multivariate techniques (Dorn et al., 1999; Gorga et al., 1999). Low-frequency DPOAE responses have always been problematic (Gorga et al., 1993) but with advances in DPOAE technology, more reliable low-frequency DPOAEs can be obtained. DPOAEs may not be the primary audiometric tool in a clinic setting, but for the special populations who are unable to complete conventional audiometric testing, DPOAEs demonstrate some utility.

ACKNOWLEDGMENTS:

This research is supported by National Institutes of Health grants F32 AG05905 (P.T. III) and R01 AG11099 (K. J. C.). The authors would like to thank Dr. Michael Gorga for developing the DPOAE protocol and for providing suggestions for an analytical approach used in this study.

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Received June 12, 2002; accepted September 18, 2002

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