J Am Acad Audiol 19:325–336 (2008)

Influence of Ultrahigh-Frequency Hearing Thresholds on Distortion-Product Otoacoustic Emission Levels at Conventional Frequencies

DOI: 10.3766/jaaa.19.4.5

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Abstract

This study examined the association between ultrahigh-frequency (UHF) hearing sensitivity and distortion-product otoacoustic emission (DPOAE) levels at conventional frequencies. Behavioral thresholds were measured from 2 through 16 kHz, and DPOAE levels were measured at discrete f_2 frequencies between 2 through 8 kHz in 553 young normal-hearing adult male participants. A DPOAE frequency sweep was measured with primary stimulus levels of L_1/L_2 = 65/55 dB SPL and an f_2/f_1 of 1.2. Significant negative correlations, although weak, were found between UHF behavioral thresholds and DPOAE levels. As UHF behavioral thresholds worsened, DPOAE levels decreased at all frequencies. When the data were categorized into two groups, "better" and "worse" UHF behavioral thresholds, significant differences were apparent between the two groups for DPOAEs. Additionally, those with better UHF thresholds had better conventional thresholds compared to those in the worse UHF threshold group. The results of this age-restricted, large-sample-size study confirm and augment findings from earlier studies demonstrating that UHF hearing sensitivity has some influence on DPOAE measures at frequencies from 2 through 8 kHz with moderate stimulus levels. However, because those with better UHF thresholds also had better conventional thresholds and the significant correlations found were weak, this work supports the importance of UHF hearing testing in conjunction with otoacoustic emission measures to identify basal cochlear insults not evident from behavioral testing at conventional frequencies.

Key Words: Distortion-product otoacoustic emissions, normal hearing, ultrahigh-frequency behavioral thresholds

Abbreviations: CAP = compound action potential; DPOAE = distortion-product otoacoustic emission; HF = high frequency; OAE = otoacoustic

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This work was supported by U.S. Army Medical Research Acquisition Activity, U.S. Special Operations Command, and the Bureau of Medicine and Surgery. The Chief, Bureau of Medicine and Surgery, Navy Department, Washington, D.C., Clinical Investigation Program, sponsored this report #S-03-082 as required by NSHSBETHINST 6000.41A. The views expressed in this article are those of the authors and do not reflect the official policy or position of the Department of the Navy, the Department of Defense, or the U.S. government.

emission; OHC = outer hair cell; PTA = pure-tone average; SNR = signal-to-noise ratio; SOAE = spontaneous otoacoustic emission; SSOAE = synchronized spontaneous otoacoustic emission; TEOAE = transient evoked otoacoustic emission; UHF = ultrahigh frequency

Sumario

Este estudio examinó la asociación entre la sensibilidad auditiva a ultra-alta frecuencia (UHF) y los niveles de las emisiones otoacústicas por productos de distorsión (DPOAE) en las frecuencias convencionales. Se midieron los umbrales conductuales desde 2 y hasta 16 kHz, y los niveles de la DPOAE se midieron a frecuencias discretas f2 entre 2 y 8 kHz en 553 adultos jóvenes masculinos oyentes normales. Se registró un barrido frecuencial de DPOAE con niveles primarios de estímulo de L1/L2 = 65/55 dB SPL y un f1/f2 de 1.2. Se encontraron correlaciones negativas significativas, aunque débiles, entre los umbrales conductuales de UHF y los niveles de las DPOAE. Conforme los umbrales conductuales de UHF se deterioraron, los niveles de DPOAE disminuyeron en todas las frecuencias. Cuando los datos se categorizaron en dos grupos – umbrales conductuales de UHF "mejores" y "peores" – se hicieron aparentes diferencias significativas entre los dos grupos para las DPOAE. Adicionalmente, aquellos con los mejores umbrales UHF tuvieron mejores umbrales convencionales, comparados con aquellos en el grupo de los peores umbrales UHF. Los resultados de este estudio con restricción de edad y con una muestra de gran tamaño confirman y destacan los hallazgos de estudio anteriores que demostraban que la sensibilidad auditiva en UHF tiene alguna influencia sobre las mediciones de las DPOAE, en las frecuencias de 2 a 8 kHz, con niveles moderados de estímulo. Sin embargo, dado que aquellos con mejores umbrales UHF también tenían mejores umbrales convencionales y que la correlación significativa encontrada era débil, este trabajo apoya la importancia de la evaluación de la audición en UHF en conjunto con mediciones de emisiones otoacústicas para identificar insultos cocleares basales, no evidentes en la evaluación conductual en frecuencias convencionales.

Palabras Clave: Emisiones otoacústicas por productos de distorsión, audición normal, umbrales conductuales de ultra-alta frecuencia

Abreviaturas: CAP = potencial compuesto de acción; DPOAE = emisión otoacústica por productos de distorsión; HF = alta frecuencia; OAE = emisión otoacústica; OHC = célula ciliadas externa; PTA = promedio tonal puro; SNR = tasa señal-ruido; SOAE = emisión otoacústica espontánea; SSOAE = emisión otoacústica espontánea sincronizada; TEOAE = emisión otoacústica evocada por transitorios; UHF = ultra-alta frecuencia

Basal cochlear condition has been shown to influence otoacoustic emissions (OAEs) measured at lower frequencies in both animals (Avan et al, 1991; Avan et al, 1995; Withnell et al, 2000) and humans (Avan et al, 1997; Arnold et al, 1999). Avan and colleagues (1991, 1995) report that cochlear damage from high-frequency acoustic sound resulted in reduced transient evoked otoacoustic emissions (TEOAEs) in guinea pigs. The reduction occurred at frequencies lower than the exposure frequency without any temporary threshold shifts in compound action potential (CAP) thresholds at the frequencies of the emissions. Similarly, Withnell and colleagues (2000) report that TEOAEs in guinea pigs were generally reduced in the 3–6 kHz range following exposure to a high-level 12 kHz tone, even though the CAP thresholds in the 3–6 kHz range were unchanged. In humans, Avan and colleagues (1997) found that TEOAE levels were negatively correlated with ultrahigh-frequency (UHF) hearing thresholds and age (mean = 34.5 years, SD = 7.5). In those without spontaneous otoacoustic emissions (SOAEs), 29 percent of the observed TEOAE variance was attributed to UHF thresholds. However, as stated previously, UHF hearing thresholds also were significantly correlated with age (r^2 = 0.40), and thus it was not possible to dissociate the influences of age and UHF thresholds on TEOAE levels. Similarly, Arnold and colleagues (1999) determined that larger distortion-product otoacoustic emission (DPOAE) levels measured between 4 and 8 kHz were correlated with better UHF thresholds. UHF and conventional pure-tone averages (PTAs) were also correlated, meaning that those with better UHF PTAs had better conventional PTAs as well. Thus, multiple regression analyses were completed to determine how much of the variance in DPOAE levels could be attributed to UHF and conventional PTAs. The results of these analyses indicated that UHF hearing sensitivity accounted for approximately 14 percent (sr^2; semipartial correlation coefficient) of the variance found in DPOAE levels, whereas only 0.2 percent (sr^2) of the variance in DPOAE levels was attributed to conventional PTAs. The authors also report that increased age was correlated with increased UHF thresholds, even though statistical significance was not reached. When the participants were categorized into "better" and "worse" UHF hearing groups (based on the median UHF PTAs), those who had better UHF thresholds had significantly larger DPOAE levels than those with poorer UHF thresholds. The amount of variance in TEOAE and DPOAE measures attributed to UHF thresholds is small, but both animal and human studies suggest that basal cochlear condition, determined by UHF thresholds, may influence OAEs generated with lower frequencies. A link between UHF hearing and OAE levels is suggested when comparing those with better and worse UHF thresholds resulting in larger or smaller DPOAE levels, respectively (Arnold et al, 1999).

Monitoring basal regions of the cochlea is important for detecting hearing loss caused by ototoxicity or noise exposure, which first occurs at UHFs (Fausti et al, 1999). Additionally, measuring UHF behavioral thresholds can provide an early reflection of aging in the auditory system (Stelmachowicz et al, 1989; Avan et al, 1997; Wiley et al, 1998; Groh et al, 2006). Even though OAE measures are correlated, at a low level, to UHF thresholds (Avan et al, 1997; Arnold et al, 1999), this finding does not suggest that OAE measures should be relied on solely at this time to identify those with decreased basal cochlear function that may precede hearing loss in the conventional frequency range. Rather, they should be complemented with the measurement of UHF hearing sensitivity.

In the current study, pure-tone behavioral thresholds were measured from 2 through 16 kHz, and DPOAE ($2f_1$–f_2) levels were measured at discrete frequencies (f_2) between 2 and 8 kHz with moderate stimulus levels in 553 young normal-hearing adult male participants. With minimal, if any, effects of age influencing the outcome, it was hypothesized that the results of this study with a large sample size and moderate stimulus levels would confirm and extend previous reports that there is a link between UHF hearing sensitivity and lower-frequency DPOAEs. This work could have implications regarding the importance of evaluating UHF hearing sensitivity separately from OAE measures in patients who have experienced possible basal cochlear compromise without corresponding behavioral threshold abnormalities at conventional frequencies.

METHOD

Participants

Five hundred fifty-three male basic U.S. Marine Corps trainees between 17 and 29 years of age (mean = 19.23 years, SD = 1.99) participated in this study. Eligibility requirements included males recruited to the Marine Corps, who would be undergoing mandatory weapons training. Participants were also required to be in good health as determined by a military-admission physical examination upon entry into military service. Trainees were recruited for participation in the current study from the Marine Corps Recruiting Depot, San Diego. Both the Naval Medical Center San Diego and San Diego State University Institutional Review Boards approved this study. After informed consent was obtained, various questionnaires regarding demographics, medical history, medications taken, and noise exposure were given to the recruits. The noise-exposure questionnaire assessed how many times the recruit had been exposed to specific noises (e.g., power tools, gunfire, recreational vehicles, live or recorded music) during the past year. Five choices for number of times exposed were possible for the noise-exposure questions: 0, 1–2, 3–5, 6–10, and >10.

The current study was part of a larger project being conducted by the Navy. To be included in the larger project, and subsequently the current project, participants had to meet the following criteria in both ears: clear ear canals, normal middle ear function, normal hearing sensitivity (≤25 dB HL at 2, 3, 4, and 6 kHz), symmetrical ultrahigh-frequency behavioral thresholds (<30 dB SPL difference between the ears), and present DPOAEs (procedures discussed below).

Procedures

Each participant underwent otoscopy and immittance measures completed by Navy corpsmen trained by a certified audiologist in otoscopy and tympanometry; certified audiologists were accessible to the corpsmen if problems occurred during the preliminary evaluation. Otoscopic examinations had to reveal clear ear canals for all participants. Tympanograms were measured using a 0.226 kHz probe tone and a pressure change in the ear canal equal to 200 daPa/sec. Resultant peak admittance, peak pressure, tympanometric width, and ear canal volumes had to be within normal ranges, as defined by the American Speech-Language-Hearing Association (1989). Participants had to have a detectable acoustic reflex (>0.02 mmho) at 1 kHz evoked by contralateral stimulation.

Certified audiologists collected pure-tone threshold and DPOAE data in four double-walled, sound-attenuated booths located within the Marine Corps Recruiting Depot medical clinic. Pure-tone threshold data were collected using pulsed tones at 2, 3, 4, 6, and 8 kHz. UHF behavioral thresholds were obtained at 10, 12.5, 14, 16, 18, and 20 kHz. DPOAEs ($2f_1–f_2$) were measured using a frequency sweep paradigm (often referred to as a DP-gram) with f_2 swept from 8 through 2.3 kHz (8, 7.1, 6.3, 5.6, 5.0, 4.5, 4.0, 3.5, 3.1, 2.8, 2.5, and 2.3 kHz). The frequency ratio (f_2/f_1) was 1.2, and the levels of the lower- (L_1) and higher-frequency (L_2) primary tones were 65 and 55 dB SPL, respectively.

Daily calibration was completed for each pair of earphones (conventional and UHF transducers) in all four sound booths using OSCAR electro-acoustic ear simulators. DPOAE daily calibration was completed using a frequency response of a 2 cc syringe that approximated a human ear canal. A complete acoustic calibration (industry standard) of all equipment was performed prior to, twice during, and after data collection.

Equipment

Tympanometry measures were completed using an Interacoustics Diagnostic Middle Ear Analyzer (Model #AT235). Conventional behavioral thresholds were obtained with an Interacoustics AC40 Clinical, High Frequency Audiometer and TDH-39P earphones. UHF behavioral thresholds were obtained using Koss Pro/KTX-6 earphones with the same clinical audiometers used for conventional frequencies. The maximum output for 10–16 kHz was 90 dB SPL, and for 18 and 20 kHz, 85 dB SPL. DPOAEs were measured using a digital signal processing personal computer sound card (16 bit); an ER-10CP DPOAE probe; a probe interface cable, which is a high-gain low-noise microphone amplifier; and Starkey Laboratories DP 2000 software loaded on Dell Latitude D600 laptop computers. The evoking signals (f_1 and f_2) were digitally generated on the computer and routed to the PC card, which presented the continuous signals to the ER-10CP probe placed at the entrance to the ear canal. The signal transduced by the ER-10CP microphone was amplified by the probe interface cable before being digitized by the analog-to-digital converter of the PC card, where software in the PC card's digital signal processing chip simultaneously averaged the responses in real time. The system has a narrow bandwidth (¼ Hz), which provides a high level of noise rejection and a low noise floor. The noise floor was monitored at and near the distortion-product ($2f_1–f_2$) frequency. Sampling of the ear canal sound pressure occurred until one of three stopping rules was met: (1) the noise floor at the distortion-product frequency was less than –10 dB SPL, (2) the difference between the DPOAE level and the noise floor was 6 dB, or (3) 4 sec of artifact-free sampling had been averaged.

Data Analyses

Only the right ear of each participant was analyzed for this study. The recorded DPOAE level had to be 6 dB above the noise floor and greater than –15 dB SPL to be included in the average. As a result, not every mean data point is the average of all participants. Missing data, those that did not meet the inclusion criteria, were replaced by the mean DPOAE level for that specific frequency. A decision was made to keep participants with missing DPOAE values because rejected data points, if not consecutive, were more likely to have been rejected based on spikes in the noise floor, not reaching a signal-to-noise ratio (SNR) of 6 dB, or the result of microstructure. Six DPOAE frequencies were tested per octave, which will result in fluctuating DPOAE levels across small steps in frequency. Thus, some DPOAE levels across the frequencies tested will not reach the SNR criterion for inclusion. Of the 6636 data points, there were 247 points where the criterion for inclusion was not met and for which the mean values were substituted. The 247 points were distributed relatively equally among the participants and for the different test frequencies, with the exception of the highest frequency tested. This will be addressed in the results section.

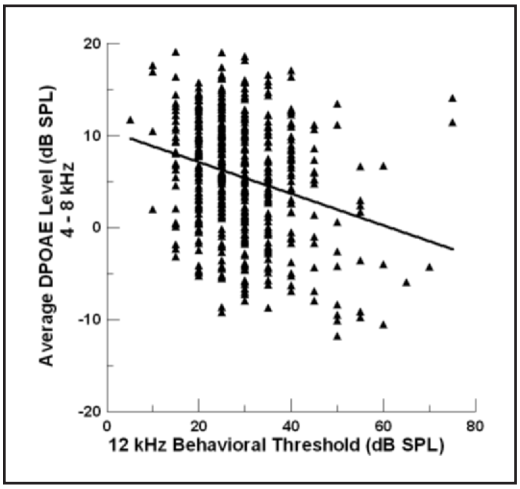

Figure 1. The correlation between average distortion-product otoacoustic emission (DPOAE) levels (dB SPL) from 4.5 through 8.0 kHz and the behavioral threshold at 12 kHz (r = –0.26).

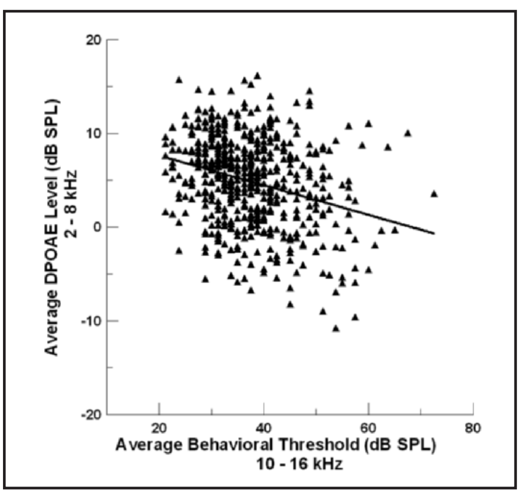

Figure 2. Scatter plot for the average distortion-product otoacoustic emission (DPOAE) levels (dB SPL) from 2.3 through 8.0 kHz and the average ultrahigh-frequency (10–16 kHz) behavioral thresholds (r = –0.29).

For the UHF behavioral thresholds, if a participant did not respond at the maximum levels, a "no response" was recorded for that frequency. Initially, there were 579 participants with DPOAE and UHF data; however, one, two, and 26 participants had no responses for behavioral thresholds at 12, 14, and 16 kHz, respectively. Unlike DPOAE measures, these participants were eliminated from any analyses due to lack of measurable behavioral UHF hearing sensitivity, leaving 553 participants. Additionally, behavioral thresholds at 18 and 20 kHz were excluded from all analyses because 180 and 322, respectively, of the remaining 553 participants did not have responses for these frequencies. Correlation and regression analyses were completed for the DPOAE and behavioral threshold data. The data were also categorized into "better" and "worse" average UHF behavioral thresholds, based on the median value for the average of 10–16 kHz, and repeated-measures analyses of variance (ANOVA-R) were completed (Statistica 6.0).

RESULTS

Individual correlations were examined between each UHF behavioral threshold (10, 12.5, 14, and 16 kHz) and each DPOAE level at the different test frequencies (12 frequencies between 2.3 and 8 kHz). These results indicated that as the behavioral threshold worsened, the DPOAE level also declined. Many significant negative correlations ($p < .01$) were found; however, only between 4 and 7 percent of the variance was explained by these results. Following the individual correlation analyses, three averages were calculated for the DPOAE levels (2.3–4.0 kHz, 2.3–8.0 kHz, and 4.5–8.0

kHz). Correlations were then determined between these DPOAE averages and individual UHF behavioral thresholds. Again, significant negative correlations ($p < .01$) were obtained between the three DPOAE averages and all UHF behavioral thresholds, indicating that as UHF behavioral thresholds worsened, so did DPOAE levels. However, the highest correlation was found between the DPOAE average from 4.5 through 8.0 kHz and the UHF behavioral threshold at 12 kHz ($r = -0.26$), which accounts for only 7 percent of the variance. This relationship can be seen in Figure 1. Next, an average UHF behavioral threshold was calculated from 10 through 16 kHz, and regression analyses were completed between the UHF average and each of the DPOAE averages. Each analysis was significant ($p < .01$), and the strongest association occurred between the average UHF behavioral threshold and the DPOAE average from 2.3 through 8.0 kHz ($r = -0.29$), accounting for only 8 percent of the variance in the data. Based on these analyses, as the UHF threshold increased by 1 dB, the DPOAE average level decreased by 0.29 dB SPL. Thus, as the average UHF behavioral threshold worsened, the average DPOAE level decreased, as shown in Figure 2.

Given that the associations between UHF behavioral thresholds and DPOAE levels were small, to further examine this relationship the data were also categorized into two groups, "better" and "worse" UHF behavioral thresholds, separated by the median value (37 dB SPL) for the average of 10–16 kHz. The mean conventional and UHF behavioral threshold averages for those classified as the better-hearing group (≤37 dB SPL) were 8.36 dB HL (SD = 7.29) and 30.91 dB SPL (SD = 3.81), respectively. For those in the worse-hearing group (>37 dB SPL), the mean conventional and UHF behavioral threshold averages were 10.71 dB HL (SD = 7.27) and 44.32 dB SPL (SD = 6.53), respectively. Figure 3 illustrates the differences in the average behavioral threshold for the better- (solid circles) and worse-hearing (open squares) groups for both conventional (Figure 3A—dB HL) and ultrahigh frequencies (Figure 3B—dB SPL). The differences between average behavioral thresholds are greater between the two groups for the UHFs than for the conventional frequencies. However, those in the better-hearing group did display better mean conventional behavioral thresholds compared to those in the worse-hearing group. To determine if the differences in UHF thresholds were significantly different between the better- and worse-hearing groups, an ANOVA-R was performed with group (better- or worse-hearing) and UHFs as the independent variables. A significant interaction was found for group by UHFs ($F[3, 1653] = 92.63$, $p < .01$), and Tukey's post hoc analyses showed significant ($p < .01$) effects of group for all UHFs

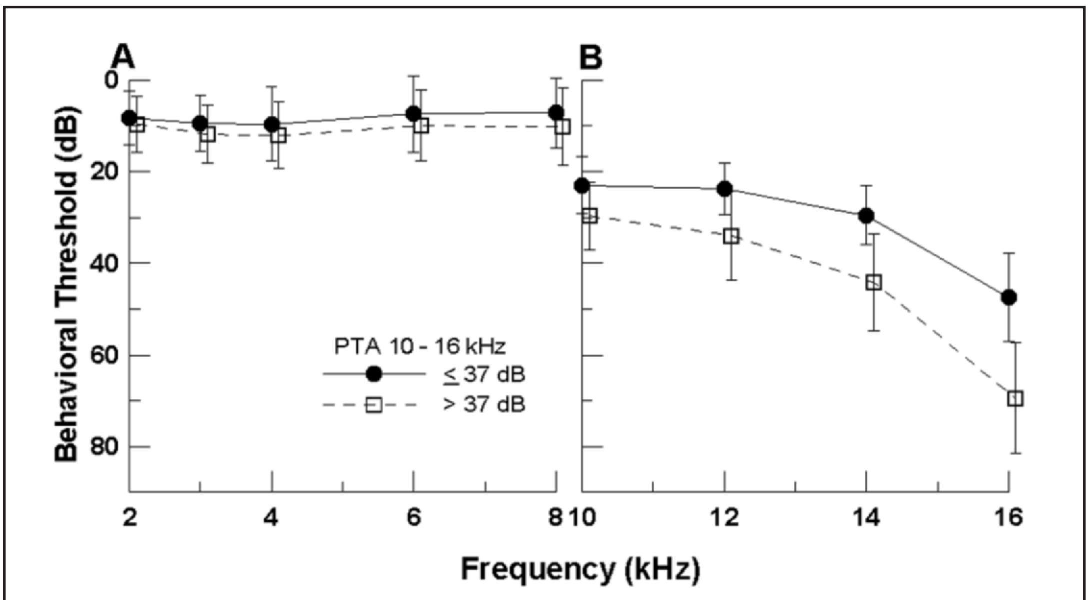

Figure 3. Mean behavioral thresholds at conventional (A, dB HL) and ultrahigh (B, dB SPL) frequencies for the better- (≤37 dB SPL) and worse-hearing (>37 dB SPL) groups based on the average (PTA) ultrahigh-frequency behavioral thresholds (10–16 kHz). Standard deviations are shown.

(10, 12.5, 14, and 16 kHz) examined. Thus, the two groups were significantly different from each other in their UHF thresholds. An additional ANOVA-R was completed to determine if the differences seen in Figure 3 for the conventional frequency thresholds were also significantly different between the better- and worse-hearing groups. No significant interactions were found between group and conventional frequencies; however, main effects for group ($F[1, 551] = 37.59$, $p < .01$) and conventional frequencies ($F[4, 2204] = 16.55$, $p < .01$) were significant. Thus, those displaying better UHF hearing also displayed better hearing at conventional frequencies compared to those with worse UHF hearing.

The mean DPOAE levels for the better- and worse-hearing groups are shown in Figure 4. A similar pattern is seen for DPOAE levels across frequency, with the greatest DPOAE levels found between 4.0 and 6.3 kHz. Those in the better-hearing group (solid circles) displayed greater DPOAE levels than those in the worse-hearing group (open squares) at all frequencies. Again, an ANOVA-R with group and frequency as independent variables was completed to determine if the differences in DPOAE levels were significantly different between the two groups. No significant interactions were found, and the main effects for group ($F[1, 551] = 23.01$, $p < .01$) and frequency ($F[11, 6061] = 126.69$, $p < .01$) were significant. This means that those displaying better average UHF hearing had larger DPOAE levels than those with worse UHF hearing.

As was noted in the method section, 247 DPOAE data points (out of 6636 data points) did not meet the criterion for inclusion and were eliminated. The mean value for the frequency eliminated was substituted. The eliminated points were distributed relatively equally among the participants and for the different test frequencies, with the exception of the highest frequency tested

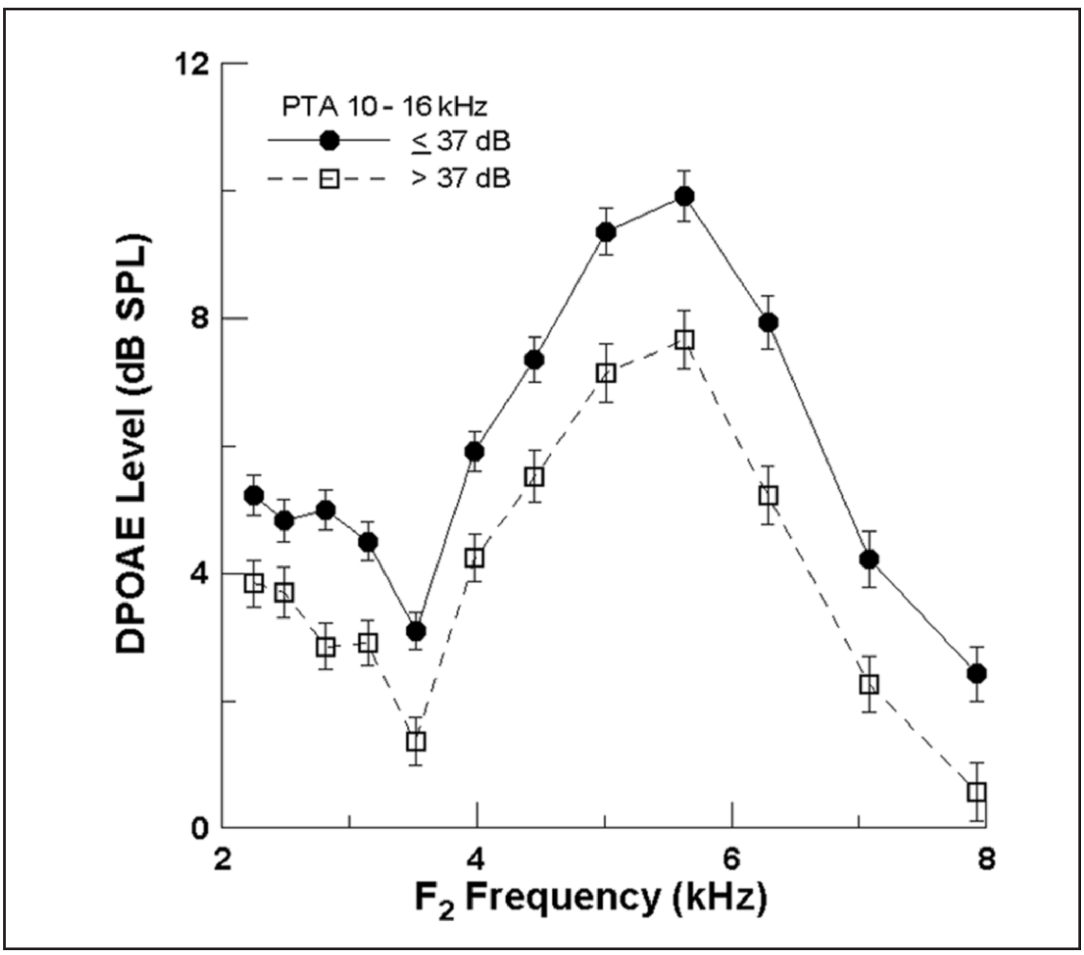

Figure 4. Mean distortion-product otoacoustic emission (DPOAE) levels for the better- (≤37 dB SPL) and worse-hearing (>37 dB SPL) groups based on the average (PTA) ultrahigh-frequency behavioral thresholds (10–16 kHz). Standard errors are shown.

(f_2 = 8 kHz), which could be related to the frequency response of the transducers used, where only 84 percent of the data met the inclusion criteria. For all other frequencies examined, an average of 97 percent of the data points met the inclusion criteria. Thus, all analyses were redone excluding the highest DPOAE frequency. The previously reported results did not change when the highest DPOAE frequency was eliminated from the analyses.

To ensure that noise exposure was not contributing to the categorization of participants as better or worse, the data obtained from the noise-exposure questionnaire were analyzed. The average number of times all participants were exposed to noise was three to five. The greatest exposure to noise was attributed to music, and the least exposure to noise was attributed to gunfire. When noise exposure was compared between those categorized as better or worse, both groups had an average number of noise exposure of three to five times.

DISCUSSION

In the current study, significant negative correlations were found between UHF behavioral thresholds and lower-frequency DPOAEs. Specifically, as UHF behavioral thresholds worsened, DPOAEs were reduced for frequencies from 2 through 8 kHz. This was true not only when comparing individual frequencies but also for comparisons between UHF hearing threshold means and DPOAE means for 2.3–4.5, 4.5–8.0, and 2.3–8.0 kHz. However, it should be noted that these significant correlations were small and only accounted for 8 percent of the variance in the data, at best. A more convincing argument that UHF behavioral thresholds and conventional-frequency DPOAEs are related occurred when the data were categorized into better and worse UHF behavioral thresholds, using methodology similar to that of Arnold and colleagues (1999). For this analysis, significant differences were found between the groups for DPOAE levels and UHF thresholds. Those who had better UHF behavioral thresholds had larger DPOAE levels compared to those with worse UHF thresholds. These findings corroborate and augment the results of Arnold and colleagues (1999), using a greater number of participants (553 compared to 50), lower DPOAE stimulus levels (L_1/L_2 of 65/55 compared to 75/75 dB SPL), and lower DPOAE stimulus frequencies (<4 kHz). However, it was also determined that those with better UHF thresholds and larger DPOAE levels also had better thresholds at conventional frequencies. Thus, it is difficult to differentiate which thresholds, UHF or conventional, are driving the differences found in DPOAE levels between the two groups.

Arnold and colleagues separated the influence of UHF thresholds compared to conventional-frequency thresholds using multiple regression analyses. The results of their analyses indicated that UHF thresholds accounted for approximately 14 percent of the variance found in DPOAE levels, whereas only 0.2 percent of the variance in DPOAE levels was attributed to conventional thresholds. So, even though UHF thresholds accounted for more of the variance in DPOAE levels than conventional thresholds, the variance accounted for is still small. Factors other than UHF and conventional-frequency thresholds must be contributing to DPOAE level variance.

Participants in the current study were not excluded based on positive noise-exposure histories or behavioral thresholds greater than 15 dB HL, as in previous studies assessing the influence of UHF hearing sensitivity on conventional-frequency OAE measures (Avan et al, 1997; Arnold et al, 1999). There were no differences in the average number of times of noise exposure between those categorized as better and worse for this study. Additionally, the typical noise exposure reported was for music, not gunfire as may have been speculated based on the participants enlisting in the military. Similarly, Torre and colleagues (forthcoming) examined a subset of the participants from the current study and report no significant differences in pure-tone thresholds between participants who did and did not report positive noise-exposure histories. Thus, it was concluded that positive histories of noise exposure were not causing the differences identified between the two groups. Additionally, the data were reanalyzed using only participants with thresholds ≤15 dB HL for 2 through 8 kHz (n = 312) to determine if allowing those with worse thresholds (≤25 dB HL; n = 553) were influencing the initial findings. Correlation and regression analyses between the DPOAE averages (2.3–4.0

kHz, 2.3–8.0 kHz, and 4.5–8.0 kHz) and average UHF behavioral thresholds (10–16 kHz) resulted in significant negative correlations ($p < .01$). As the average UHF behavioral threshold worsened, the average DPOAE level decreased. In agreement with the initial findings, the highest correlation was found between the DPOAE average from 4.5 through 8.0 kHz and the average UHF behavioral thresholds ($r = -0.22$), accounting for only 5 percent of the variance. Again, the most compelling results occurred when the participants were categorized into better and worse, based on the median UHF behavioral thresholds. As with the initial findings, the two groups did differ for UHF and conventional-frequency behavioral thresholds and DPOAE levels. Given that the results were unchanged using a stricter behavioral threshold inclusion criterion, it can be concluded that the differences found between the two groups were not a result of a more lenient inclusion criterion.

Increasing age has been shown to reduce OAE levels, starting as early as childhood (Bonfils et al, 1988; Collet et al, 1990; Lonsbury-Martin et al, 1991; Stover and Norton, 1993; Groh et al, 2006). Previous studies examining the influence of UHF thresholds on OAE measures exhibited a confounding influence of age on the results. Avan and colleagues (1997), whose participants were between the ages of 24 and 50 years, report that TEOAE levels were significantly correlated with age, in addition to UHF behavioral thresholds. When examining participants aged between 17 and 37 years, Arnold and colleagues (1999) found that age and lower-frequency DPOAE levels were correlated with UHF behavioral thresholds. Groh and colleagues (2006) found that TEOAE responses decreased with age in participants between 6 and 25 years and were significantly negatively correlated with hearing sensitivity at 16 kHz. Additionally, DPOAEs were significantly different between the youngest (6–10 years) and oldest (21–25 years) groups, with the younger group displaying larger DPOAE levels than the older group. In the current investigation, the mean participant age was 19 years ($SD = 2$), which should limit the influence of age on the results. When the participants were categorized into better and worse UHF behavioral thresholds, the mean age and standard deviation were essentially the same between the two groups. Given that these participants are entering the age range where initial declines in UHF thresholds and DPOAE levels have been reported and the criteria for participation included any participant with behavioral thresholds <30 dB HL at 2, 3, 4, and 6 kHz, age could still be affecting the results. However, when a stricter criterion for behavioral thresholds was employed (≤15 dB HL; $n = 312$), the results remained unchanged, implying that age was not a confounding factor. To avoid the effects of age on the results, younger children could be used to further explore the influence of UHF hearing thresholds on lower-frequency OAE measures.

Ears with spontaneous otoacoustic emissions (SOAEs) have been found to produce larger levels of evoked OAEs (Kemp, 1979; Burns et al, 1984; Furst et al, 1988; Avan et al, 1997; Prieve et al, 1997; Ozturan and Oysu, 1999; Kuroda et al, 2001; Schmuziger et al, 2005). Schmuziger and colleagues (2005) determined that ears with synchronized SOAEs (SSOAEs) had better UHF hearing sensitivity and larger TEOAE and DPOAE levels in comparison to those that did not have SSOAEs. In the current study, SOAEs were not measured in the participants, and it is possible that the influence of UHF behavioral thresholds on lower-frequency DPOAEs could have been even stronger had the participant population been restricted to those with or without SOAEs. However, given that females have been shown to display more SOAEs than males (Strickland et al, 1985; Bilger et al, 1990; Whitehead et al, 1993; Chan and McPherson, 2001) and larger SOAE levels than males (Whitehead et al, 1993), it is possible that the influence of SOAEs on the current results would be negligible because only male participants were tested.

Additionally, both UHF behavioral thresholds and OAE levels have been reported to differ depending on gender. Some have reported that female UHF hearing sensitivity is better than that of males (Stelmachowicz et al, 1989), whereas others have found no significant gender differences (Osterhammel and Osterhammel, 1979; Frank, 1990; Betke, 1991; Dunckley and Dreisbach, 2004). For DPOAEs, females have been reported to have larger levels from 2 to 6 kHz in some studies (Cacace et al, 1996; Shehata-Dieler et al, 1999) but not in others (Dunckley and Dreisbach, 2004). Previous studies examining the influence of UHF behavioral thresholds on OAE levels did not report effects of gender on their results (Avan et al, 1997; Arnold et al, 1999). The results from the current study, where only males were included, cannot address a possible gender influence in previous studies, but our results confirm that UHF hearing sensitivity has an influence on DPOAE levels at lower frequencies, and it can be speculated that the results would be similar for females.

Similar to UHF hearing sensitivity, high-frequency (HF) thresholds have been reported to influence OAE measures at lower frequencies. Murnane and Kelly (2003) report that hearing loss at frequencies greater than 2 kHz, even with no significant differences in thresholds from 0.25 through 2 kHz, resulted in significantly reduced TEOAE levels (0.75–2 kHz) compared to those who had normal hearing thresholds (≤30 dB HL) through 8 kHz. It should be noted that the participants ranged in age from 28 through 76 years, so the influence of age on their results cannot be excluded (Murnane and Kelly, 2003). Additionally, Avan and colleagues (1993) report that changes in behavioral thresholds from 6 through 8 kHz resulted in TEOAE level reductions at 1 kHz, when no change in behavioral threshold at 1 kHz was noted. The results from the current study and previous studies examining animals and humans lead to speculations as to why UHF and HF thresholds influence lower-frequency OAEs. Recall that those with better UHF hearing also had better conventional hearing, which could result in larger DPOAE levels. Arnold and colleagues (1999) used multiple regression analyses to separate the influence of UHF compared to conventional thresholds on DPOAE levels and found that only UHF thresholds contributed significantly to DPOAE levels (for stimulus levels of 75 dB SPL).

Two hypotheses regarding the influence of UHF and HF hearing sensitivity on conventional OAE measures have been posed in the literature (Avan et al, 1995; Avan et al, 1997; Arnold et al, 1999; Withnell et al, 2000; Murnane and Kelly, 2003). First, it is possible that cochlear damage has occurred in the conventional-frequency region, but this damage occurred below threshold. This means that reductions in OAE levels would be found without accompanying threshold changes. Second, it is possible that damage did not occur in the conventional region, which is why there is no change in threshold, but that OAE measures depend on the status of the cochlea at more basal locations. With suppression and/or enhancement of DPOAE levels when a suppressor tone is slightly greater than f_2, in both animals and humans, multiple sources have been implicated as contributing to the generation of DPOAEs (Kemp and Brown, 1984; Martin et al, 1987; Martin et al, 1999; Fahey et al, 2000; Martin et al, 2003). However, Withnell and Lodde (2006) report that sites basal to f_2 do not contribute significantly to the generation of guinea pig $2f_1$–f_2 based on acoustically traumatizing the basal portion of the cochlea. Further explorations of basal contributions to both animal and human DPOAE levels are warranted. The notion that the two hypotheses regarding the influence of UHF hearing sensitivity on lower-frequency OAEs are exclusive of one another is not probable. It is likely that the basal cochlea contributes to OAEs generated more apically and that OAEs may be more sensitive to outer hair cell (OHC) damage than behavioral thresholds. Unfortunately, at this time it is not possible to differentiate between these two hypotheses when examining humans. Morphological confirmation of OHC damage would need to be determined to differentiate between subclinical damage at conventional frequencies and basal damage influencing lower-frequency OAE measures.

The findings of the current study reiterate the importance of evaluating UHF hearing sensitivity in combination with OAE measures when monitoring basal cochlear function. Even though an association between UHF hearing thresholds and DPOAE levels measured at conventional frequencies has been reported in this study and previously, due to the weak correlations and relationship of conventional behavioral thresholds to DPOAE levels, it cannot be recommended at this time to rely solely on OAE measures at lower frequencies to infer damage at more basal locations. DPOAE measures at conventional frequencies and behavioral UHF hearing thresholds have been found to be repeatable over time within a participant, making these tests reliable and clinically useful (Laukli and Mair, 1985; Fausti et al, 1990; Frank, 1990; Frank and Dreisbach, 1991; Franklin et al, 1992; Roede et al, 1993; Zhao and Stephens, 1999). Thus, in combination these measures could provide an early reflection of aging and indication of basal cochlear damage (Avan et al, 1997; Groh et al, 2006).

Acknowledgments. We wish to thank Erika Zettner, who provided comments on an earlier version of this article.

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