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ABR and DPOAE Indices of Normal Loudness in Children and Adults

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Abstract

Loudness growth prediction using normal templates of loudness derived with ABR and DPOAE measures was investigated in 20 children 4 to 12 years and 20 adults with normal hearing. An ABR click latency-intensity function (LIF), ABR 2 kHz tone LIF, and DPOAE 2 kHz amplitude-intensity function (AIF) were recorded from each listener. A loudness-intensity function was also measured for each electrophysiologic stimulus. Children and adults exhibited similar intensity functions of ABR latency, DPOAE amplitude, and loudness. A statistically significant relationship was found between loudness and ABR latency and DPOAE amplitude. Loudness estimation equations derived with ABR latency and DPOAE amplitude accurately and reliably predicted the loudness-intensity functions of the listeners. Normative ABR and DPOAE templates of predicted loudness growth may have clinical application in site-of-lesion assessment or hearing aid fitting by distinguishing abnormal rates of loudness growth for individuals who cannot provide reliable behavioral measures.

Key Words: ABR, children, DPOAE, loudness, loudness growth, normal hearing

Abbreviations: ABR = auditory brainstem response; AIF = amplitude-intensity function; CMM = cross-modality matching; DPOAE = distortion product otoacoustic emission; f1 = lower frequency of DPOAE primary tones; f2 = higher frequency of DPOAE primary tones; L1 = level of the f1 primary tone; L2 = level of the f2 primary tone; LIF = latency-intensity function

Sumario

Se investigó la predicción del incremento en la intensidad subjetiva usando patrones normales de sonoridad derivados de mediciones de ABR y de DPOAE, en 20 niños con edades entre 4 y 12 años, y en 20 adultos, todos con audición normal. Se registró, para cada sujeto, una función de latencia-intensidad (LIF) del ABR evocado por clics, una LIF del ABR evocado con tonos de 2 kHz y una función de amplitud-intensidad (AIF) con DPOAE a 2 kHz. Se midió también una función de intensidad subjetiva-intensidad física para cada estímulo electrofisiológico. Los niños y los adultos exhibieron funciones de intensidad similares en la latencia de los ABR, en la amplitud de los DPOAE, y en la intensidad subjetiva. Se encontró una relación estadísticamente significativa entre la intensidad subjetiva, la latencia en los ABR y la amplitud en los DPOAE. Las ecuaciones para estimar la intensidad subjetiva derivada de la latencia en los ABR y de la amplitud en los DPOAE, predijeron con exactitud y confiabilidad las funciones de intensidad subjetiva-intensidad física de

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los sujetos. Los patrones normativos para obtener el incremento estimado de la intensidad subjetiva en ABR y DPOAE pueden tener una aplicación clínica en la evaluación del "sitio de la lesión", o en la adaptación de auxiliares auditivos. Es posible distinguir tasas anormales de incremento en la intensidad subjetiva en aquellos individuos que no pueden proporcionar mediciones conductuales confiables.

Palabras Clave: ABR, niños, DPOAE, intensidad subjetiva, crecimiento en la intensidad subjetiva, audición normal

Abreviaturas: ABR = respuestas auditivas del tallo cerebral; AIF = función de amplitud-intensidad; CMM = ordenamiento de modalidad cruzada; DPOAE = emisión otoacústica por producto de distorsión; f1 = frecuencia menor de los tonos primarios de las DPOAE; f2 = frecuencia mayor de los tonos primarios de las DPOAE; L1 = nivel del tono primario de la f1; L2 = nivel del tono primario de la f2; LIF = función latencia-intensidad

The assessment of loudness over a single or range of stimulus levels serves an important role in the fitting of amplification for individuals with hearing loss (Dillon, 2001). However, judgments of loudness require subjective responses that may not be reliably obtainable in all populations, particularly in young children. Studies using a behavioral procedure known as cross-modality matching (CMM) between loudness and line length have suggested that listeners only as young as four years are able to provide reliable loudness judgments. These loudness data have shown that children with normal hearing as young as four years show similar judgments of behavioral loudness growth over a range of intensity as adults (Teghtsoonian, 1980; Collins and Gescheider, 1989; Serpanos and Gravel, 2000, 2002). Accurate behavioral determinations of loudness may be limited in younger populations, however, and, similar to the limitation of behavioral hearing assessment, may not be reliable in the infant population younger than six months.

Investigators have therefore suggested the use of objective clinical procedures to predict loudness for difficult-to-test populations with electrophysiologic audiometric methods such as the acoustic reflex threshold (e.g., Kiessling, 1987; Northern and Abbott Gabbard, 1994) or the auditory brainstem response (ABR; e.g., Mahoney, 1985; Davidson et al, 1990). To date, however, loudness estimation using these electrophysiologic measures has not achieved clinical acceptance.

Currently, common clinical electrophysiologic parameters used to predict hearing status include the ABR wave V latency derived with click and tonal stimuli and distortion product otoacoustic emission (DPOAE) amplitude (ASHA, 1997). Therefore, these parameters could readily be incorporated into a clinical paradigm to predict loudness should a relationship be established. Though the relationship of hearing threshold to ABR wave V latency (Stapells, 1998; Sininger and Cone-Wesson, 2002) and DPOAE amplitude (Lonsbury-Martin et al, 1997; Hall, 2000) is well documented in the literature and widely accepted clinically, the relationship of loudness to ABR wave V latency or DPOAE amplitude is not.

Research on adult listeners with normal hearing or flat configurations of cochlear loss has revealed a relationship between behavioral loudness-intensity functions and click-evoked ABR wave V latency-intensity functions (LIFs; Serpanos et al, 1997). This preliminary finding suggests that an objective audiometric measure may be used to predict the behavioral experience of loudness. However, further study on the relationship between behavioral loudness and electrophysiologic measures is necessary using additional stimuli and younger listeners.

This study investigated a potential clinical application of loudness growth prediction using normal templates of loudness derived with ABR and DPOAE measures. The first part of this study investigated the relationship between behavioral loudness-intensity functions and ABR wave V LIFs and DPOAE amplitude-intensity functions (AIFs) in ten children and ten adults with normal hearing. The second part of the study investigated the accuracy with which ABR wave V latency and DPOAE amplitude predicted behavioral loudness in different groups of ten children and ten adults with normal hearing. The reliability of loudness estimation using the ABR and DPOAE parameters was assessed by retest results of these measures in a subset of five children and five adults. A long-term goal of this research is to develop normative ABR and DPOAE templates of predicted loudness functions by which abnormal rates of loudness growth may be determined. Loudness growth prediction using objective tests such as the ABR or DPOAE may be useful in determining the site-of-lesion of hearing impairment or in the hearing aid fitting process of individuals who are unable to provide reliable behavioral measures.

METHOD

Participants

A total of 40 male and female individuals consisting of 20 children 4 to 12 years (4 to 6 years: n = 8; 7 to 9 years: n = 6; 10 to 12 years: n = 6; mean age = 7.5 years) and 20 adults (mean age = 29.3 years; range = 21 to 58 years) with normal auditory function participated in this study. The individuals were solicited from the student or clinic population of the Department of Communication Sciences and Disorders at Adelphi University, Garden City, New York. Participants were paid and were required to provide written consent prior to participation. Normal auditory function was verified bilaterally via pure tone and speech audiometry (GSI-16, Grason-Stadler), immittance (tympanometry and middle ear reflexes; GSI-33 Middle Ear Analyzer, Grason-Stadler), DPOAE (Celesta 503 Distortion Product Otoacoustic System, Madsen, Inc.) screening (ASHA, 1997), and high-intensity click-evoked ABR (Nicolet Spirit Evoked Potential System, Nicolet, Inc.) testing at 80 dB nHL. Audiometric thresholds were less than 25 dB HL for the octave frequencies of 250 to 8000 Hz with no air-bone gap exceeding 10 dB at more than one audiometric frequency. Audiometric measures were conducted in a double-walled sound-treated test room (IAC 403). Immittance, DPOAE, and ABR test measures were recorded in a quiet test room.

Ten children (#1 to #10) and ten adult (#21 to #30) listeners were used in the first part of the study that examined the relationship between behavioral loudness-intensity functions and ABR wave V LIFs and DPOAE AIFs. A different set of ten children (#11 to #20) and ten adults (#31 to #40) were used for the second part of the study, which examined the accuracy with which ABR wave V latency and DPOAE amplitude predicted loudness. To assess the reliability of loudness estimation using the ABR and DPOAE parameters, retest procedures were obtained one month following the first test session from a randomly selected subset of five children (#11, #12, #16, #18, #19) and five adults (# 31, #32, #33, #34, #36).

PROCEDURES

One test ear was chosen for each participant with an effort to balance the number of right and left test ears for each group (children: right ears = 10, left ears = 10; adults: right ears = 11, left ears = 9). Identical acoustic stimuli (ABR click, ABR 2 kHz tone, and DPOAE 2 kHz tones) were used for both the behavioral loudness tasks and electrophysiologic procedures. ABR and DPOAE stimulus levels (described in sections below) were chosen to represent a range that may be used during loudness growth or electrophysiologic assessment, with upper levels chosen to prevent potential levels of discomfort. Prior to any testing, thresholds of audibility to the auditory stimuli were obtained from each participant. The threshold of discomfort was to serve as the loudness limit for all test conditions, though none of the participants reported discomfort to the highest levels.

Three electrophysiologic-intensity functions were recorded from the test ear of each listener: ABR click wave V LIF, ABR 2 kHz wave V LIF, DPOAE 2 kHz AIF. Three loudness-intensity functions were measured for each electrophysiologic stimulus: ABR click loudness-intensity function, ABR 2 kHz loudness-intensity function, DPOAE 2 kHz loudness-intensity function.

ABR LIFs

Ipsilateral ABR recordings (Nicolet Spirit Evoked Potential System) were obtained from the test ear of each participant using a four-electrode montage with silver-chloride disc electrodes placed at the vertex (Cz), earlobes (A1, A2), and forehead (Fz). The click and 2 kHz tone stimuli were presented monaurally through insert earphones (E.A.R.®-3A) up to one minute in duration to the designated test ear: 100 μsec rarefaction polarity clicks were presented at a rate of 61.1/sec; a 2 kHz 5-cycle alternating polarity Blackman tonal stimulus was presented in notched noise set at 20 dB pe SPL below the tone at a rate of 39.1/sec (Stapells et al, 1995). The EEG activity from the ipsilateral channel of the test ear (Cz to ipsilateral earlobe) was amplified and band-pass filtered from 100 to 3000 Hz using click stimuli, and 30 to 3000 Hz with the 2 kHz tonal stimuli. A 15 msec analysis time was used with artifact rejection of ±25 μv.

ABR recordings were obtained using 2000 stimulus presentations at stimulus levels ranging from 80 to 20 dB nHL in a descending series of 10 dB increments. Two ABR recordings were obtained at each stimulus level using the click stimulus, and three ABR recordings were obtained for the tonal stimulus. The ABR recordings at each level were superimposed; wave V was labeled at the last point on the peak before the large negative deflection (Hall, 1992). ABR wave V latencies were recorded and plotted for each stimulus level, yielding a click LIF and 2 kHz tone-evoked LIF for each individual.

DPOAE AIFs

DPOAEs (Celesta 503 Distortion Product Otoacoustic System) were recorded from the test ear of each listener. The probe, fitted with a sized eartip with an opening within a 1mm distance from the end of the probe tip, was used to deliver the stimuli into the participant's ear. The probe fit to the participant's ear canal was verified by the equipment "Probe Fit" mode, using bursts of 10 condensation clicks delivered into the ear canal. An adequate probe fit was determined by a short response latency, broad stimulus spectrum, and flat stimulus response curve. The selected test signal was 2 kHz, the frequency closest to the geometric mean of the two tone primaries, f1 = 1819 Hz, f2 = 2223 Hz (f2/f1 ratio = 1.22). A 78.64 msec time window was used, with a maximum of 1000 signal repetitions sampled at a rate of 26.04 kHz, yielding a total of 2048 data points per window.

The DPOAE response was identified as the cubic difference tone 2f1-f2 and was recorded over eight stimulus levels, ranging in 5 dB increments, with L1 = 35 to 70 dB SPL / L2 = 25 to 60 dB SPL. Response samples were collected until automatic stop criteria were met (i.e., when the ratio of the DPOAE amplitude to noise reached three times the standard deviation of noise, or the pre-specified number of accepted sweeps). A valid DPOAE emission was considered to be of an amplitude at 3 dB above the noise floor (Lonsbury-Martin et al, 1997). DPOAE amplitudes were recorded and plotted for each testable stimulus level, yielding an AIF for each individual.

Loudness-Intensity Functions

Using the identical electrophysiologic stimuli (ABR clicks, ABR 2 kHz tone presented in notched noise as described above, DPOAE 2 kHz tones), loudness matches were obtained at stimulus levels corresponding to those recorded with the electrophysiologic intensity functions (ABR stimuli: 20 to 80 dB nHL in 10 dB steps; DPOAE stimuli: L1: 35 to 70 dB SPL in 5 dB steps). Loudness measures were obtained using cross-modality matching (CMM) between loudness and line length (a graphic of a "caterpillar" of varying length), a procedure documented in previous studies with children (see Serpanos and Gravel, 2000). The CMM procedure uses two loudness tasks to yield one loudness-intensity function for each listener; length to loudness (task 1) and loudness to length (task 2). In the first task, the listener is asked to match the length of one of the graphics to equal the perceived loudness of the intensity of the presented signal. In the second task (the inverse of the first), the listener is instructed to adjust the level of the signal to make the loudness of the sound subjectively equal to the length of one of the eight graphics presented by the examiner. A single loudness-intensity function was derived for each listener to each stimulus by plotting the loudness level (task 2) by intensity levels (task 1) matched to the same line lengths. Three loudness-intensity functions were obtained for the test ear of each participant: ABR click loudness-intensity function, ABR 2 kHz loudness-intensity function, DPOAE 2 kHz loudness-intensity function.

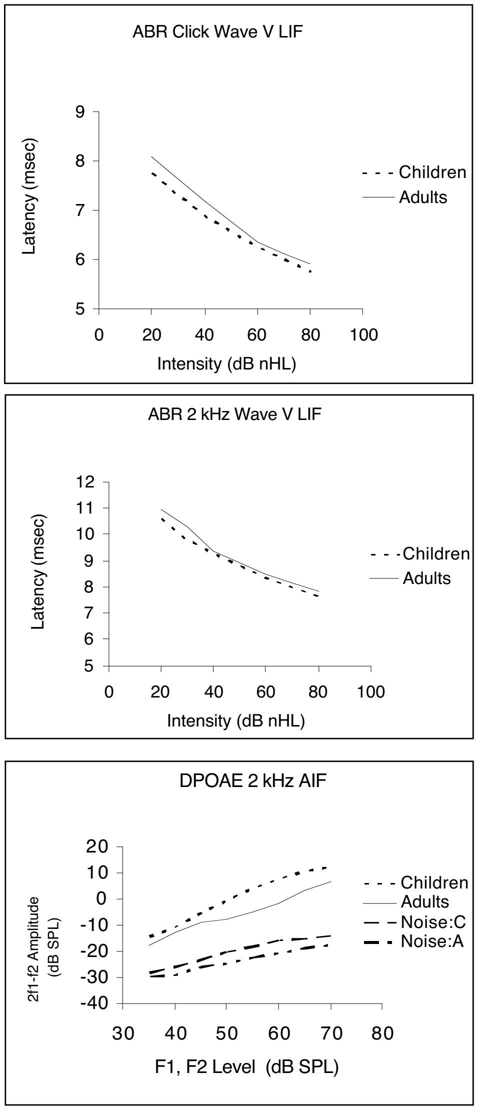

Figure 1. Mean electrophysiologic-intensity functions of 20 children (#1 to #20; short dashed lines) and 20 adults (#21 to #40; solid line): ABR click wave V LIF (top), ABR 2 kHz LIF (middle), DPOAE 2 kHz AIF (bottom), also shown with the mean noise floor of children (long dashed lines) and adults (long and short dashed lines).

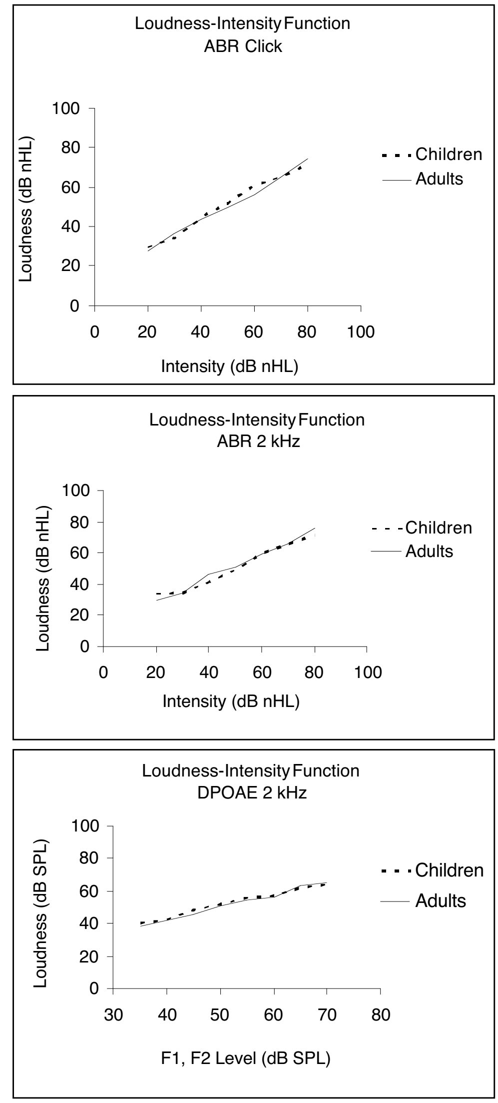

Figure 2. Mean loudness-intensity functions of 20 children (#1 to #20; short dashed lines) and 20 adults (#21 to #40; solid line) recorded with ABR clicks (top), ABR 2 kHz tone (middle), and DPOAE 2 kHz tones (bottom).

RESULTS

Electrophysiologic-Intensity Functions

Figure 1 presents the mean ABR click (top) and ABR 2 kHz tone (middle) wave V LIFs and DPOAE 2 kHz AIFs (bottom; also shown is the mean noise floor for each group) for the total groups of 20 children and 20 adults. Children and adults exhibited the same variability of the data (± 2 standard deviations) around each mean ABR (click and 2 kHz tone) and DPOAE (2 kHz tone) intensity function.

Linear regression analysis was conducted on the individual latency (Y; msec)-intensity (X; dB nHL) functions of the ABR stimuli (click and 2 kHz tone) and on the amplitude (Y; dB SPL)-intensity (X; dB SPL) functions of the DPOAE stimuli (2 kHz tones) to derive individual slope values that were averaged by group (Table 1 and Table 2). Mean slope values of -0.03 and -0.05 were obtained respectively for the ABR click and ABR 2

Table 1. Electrophysiologic-Intensity Function and Loudness-Intensity Function Slope Values for Children

	Electrophysiologic-Intensity Functions			Loudness-Intensity Functions		
	ABR LIF		DPOAE AIF	ABR		DPOAE
Subject #	Click	2 kHz Tone	2 kHz Tones	Click	2 kHz Tone	2 kHz Tones
1	-0.03	-0.12	1.07	0.57	0.65	0.61
2	-0.05	-0.06	0.83	0.54	0.57	0.51
3	-0.02	-0.05	1.17	0.37	0.61	0.72
4	-0.02	-0.03	0.83	0.78	0.85	0.84
5	-0.04	-0.05	0.78	0.77	0.81	0.61
6	-0.04	-0.04	1.06	0.86	0.75	0.96
7	-0.03	-0.04	0.91	0.82	0.93	0.70
8	-0.04	-0.05	0.97	0.55	0.89	0.92
9	-0.04	-0.03	1.10	0.82	0.53	0.66
10	-0.03	-0.06	1.07	0.91	0.52	0.65
11	-0.04	-0.04	0.97	1.02	0.68	0.90
12	-0.03	-0.03	0.88	0.96	0.75	0.54
13	-0.03	-0.04	0.83	0.73	0.65	0.85
14	-0.03	-0.03	0.70	0.64	0.57	0.68
15	-0.03	-0.05	0.80	0.84	0.66	0.46
16	-0.03	-0.08	1.17	0.54	0.74	0.75
17	-0.03	-0.04	0.35	0.52	0.62	0.73
18	-0.02	-0.06	0.87	0.71	0.70	0.52
19	-0.04	-0.05	0.76	0.72	0.60	0.53
20	-0.03	-0.05	0.89	0.99	0.91	0.76
Mean	-0.03	-0.05	0.90	0.73	0.70	0.70
SD	0.01	0.02	0.19	0.18	0.13	0.15

kHz LIFs for children and adults. The mean DPOAE 2 kHz AIF slope values were 0.90 (children) and 0.87 (adults).

Loudness-Intensity Functions

Figure 2 shows the mean loudness-intensity functions for the total group of 20 children and 20 adults measured with the ABR click (top), ABR 2 kHz tone (middle), and DPOAE 2 kHz tone (bottom) stimuli. The individual variability of the data for children and adults fell within ±2 standard deviation lines about the mean loudness functions generated with the three types of stimuli.

Linear regression analysis was conducted

Table 2. Electrophysiologic-Intensity Function and Loudness-Intensity Function Slope Values for Adults

	Electrophysiologic-Intensity Functions			Loudness-Intensity Functions		
	ABR LIF		DPOAE AIF	ABR		DPOAE
Subject #	Click	2 kHz Tone	2 kHz Tones	Click	2 kHz Tone	2 kHz Tones
21	-0.03	-0.05	0.68	0.78	0.80	0.62
22	-0.04	-0.04	0.72	1.00	0.97	0.39
23	-0.03	-0.07	0.62	0.70	0.60	0.76
24	-0.04	-0.05	0.77	0.70	0.84	0.73
25	-0.03	-0.04	1.01	0.63	0.79	1.06
26	-0.03	-0.05	1.22	0.90	0.76	0.64
27	-0.02	-0.03	0.66	0.55	0.95	0.60
28	-0.03	-0.05	1.52	0.60	0.61	0.88
29	-0.03	-0.06	0.55	0.74	0.89	0.70
30	-0.04	-0.05	0.76	0.60	0.58	0.60
31	-0.03	-0.04	0.86	0.83	0.55	1.02
32	-0.03	-0.02	0.93	0.69	0.90	0.64
33	-0.04	-0.05	1.50	0.69	0.65	0.97
34	-0.03	-0.05	0.89	0.79	0.79	0.89
35	-0.05	-0.06	0.72	0.89	0.89	0.91
36	-0.04	-0.06	1.30	0.77	0.82	0.75
37	-0.04	-0.05	0.88	0.88	0.83	0.95
38	-0.03	-0.04	0.64	0.73	0.95	1.18
39	-0.03	-0.05	0.30	0.81	0.90	0.84
40	-0.04	-0.06	0.77	0.70	0.51	0.56
Mean	-0.03	-0.05	0.87	0.75	0.78	0.78
SD	0.01	0.01	0.31	0.11	0.15	0.20

on the individual and group mean loudness (Y; dB nHL: ABR; dB SPL:DPOAE)-intensity (X; dB nHL: ABR; dB SPL:DPOAE) functions for each of the acoustic stimuli to derive individual and group slope values (Tables 1 and 2). Mean loudness-intensity function slope values to the ABR click were 0.73 for children and 0.75 for adults. The mean loudness-intensity function slope values were 0.70 (children) and 0.78 (adults) for both the ABR 2 kHz and DPOAE 2 kHz tone stimuli, respectively.

Relationship of Loudness and ABR Wave V Latency and DPOAE Amplitude

The relationship between behavioral loudness and ABR wave V latency and DPOAE amplitude was examined in ten children (#1 to #10) and ten adults (#21 to #30). Pearson product-moment correlation coefficients (r) were calculated using linear regression analyses and revealed statistically significant relationships between the respective mean behavioral loudness- and electrophysiologic-intensity functions recorded for identical stimuli in children (ABR click loudness and LIF: $r = -0.99$; $p = 0.001$; $df = 8$; ABR 2 kHz loudness and LIF: $r = -0.93$; $p = 0.001$; $df = 8$; DPOAE 2 kHz loudness and AIF: $r = 0.99$; $p = 0.001$; $df = 8$) and adults (ABR click loudness and LIF: $r = -0.97$; $p = 0.001$; $df = 8$; ABR 2 kHz loudness and LIF: $r = -0.99$; $p = 0.001$; $df = 8$; DPOAE 2 kHz loudness and AIF: $r = 0.98$; $p = 0.001$; $df = 8$).

Loudness estimation equations were derived for ABR and DPOAE measures using linear regression analysis between perceived loudness (Y; dB nHL) and ABR click wave V latency (X; msec), and ABR 2 kHz wave V latency (X; msec), and perceived loudness (Y; dB SPL) and DPOAE amplitude (X; dB SPL) from the ten children and ten adult listeners. The loudness estimation equations for children and adults using the ABR click, ABR 2 kHz, and DPOAE 2 kHz stimuli were as follows:

Children:

ABR wave V latency (Click):

Perceived Loudness (dB nHL) = 177.9 - (19.1 x ABR wave V latency) +/- 10.4 (SE, dB nHL)

ABR wave V latency (2 kHz tone):

Perceived Loudness (dB nHL) = 142.5 - (10.2 x ABR wave V latency) +/- 12.2 (SE, dB nHL)

DPOAE Amplitude (2 kHz primary tones)

Perceived Loudness (dB SPL) = 55.2 + (.58 x DPOAE amplitude) +/- .91 (SE, dB SPL)

Adults:

ABR wave V latency (Click):

Perceived Loudness (dB nHL) = 179.2 - (18.6 x ABR wave V latency) +/- 8.9 (SE, dB nHL)

ABR wave V latency (2 kHz tone):

Perceived Loudness (dB nHL) = 184.6 - (14.2 x ABR wave V latency) +/- 9.0 (SE, dB nHL)

DPOAE Amplitude (2 kHz primary tones)

Perceived Loudness (dB SPL) = 54.7 + (.58 x DPOAE amplitude) +/- .84 (SE, dB SPL)

The accuracy with which ABR latency and DPOAE amplitude can be used to predict loudness for individuals with normal hearing was investigated by a test of the loudness estimation equations in a different set of ten children (#11 to #20) and ten adults (#31 to #40). The individual electrophysiologic measures obtained from ABR and DPOAE testing of the participants were entered into the appropriate loudness estimation equation to generate predicted loudness-intensity functions. Figure 3 and Figure 4 present the group mean behavioral (measured) and mean predicted loudness-intensity functions of the ten children and ten adult listeners, respectively, derived with ABR click wave V latency (top), ABR 2 kHz wave V latency (middle), and DPOAE 2 kHz amplitude (bottom). Shown in each figure are the ±2 standard deviation lines of the behavioral (actual) loudness functions measured from the listeners.

To determine the relationship between the measured loudness-intensity functions and the predicted loudness-intensity

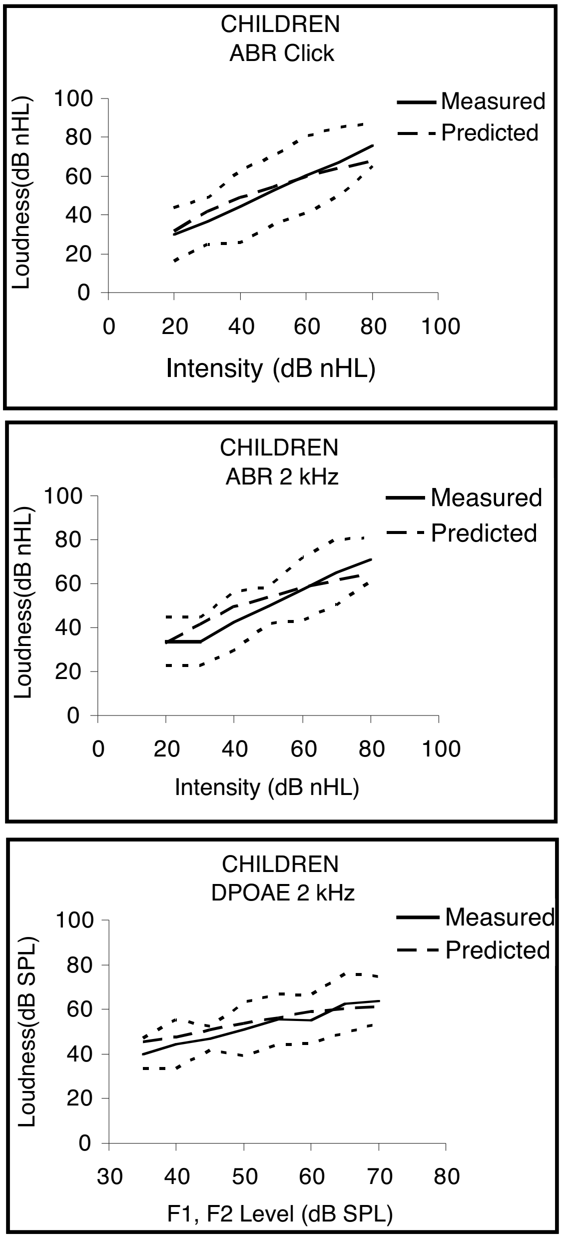

Figure 3. Mean measured (solid line) and mean predicted (long dashed lines) loudness-intensity functions for 10 children (#11 to #20) recorded with ABR clicks (top), ABR 2 kHz tone (middle), and DPOAE 2 kHz tones (bottom). Short dashed lines represent ± 2 standard deviation lines obtained from the measured (actual) loudness-intensity functions of the same listeners.

functions, separate Pearson product-moment correlation coefficients (r) were calculated for each stimulus and each group. Statistically significant correlations were obtained between the mean measured and mean predicted loudness-intensity functions of children and adults using the electrophysiologic values of ABR click wave V latency (children: r = 0.98; adults: r = 0.97; p = 0.001; df = 8), ABR 2 kHz wave V latency (children: r = 0.95; adults: r = 0.97; p = 0.001; df = 8), and DPOAE 2 kHz amplitude (children and adults: r = 0.98; p = 0.001; df = 8). The mean dB difference between the measured and predicted loudness-intensity functions at each stimulus level was within 11 dB (range: ABR click stimulus: 1.3 to 8.2 dB [children], 1.0 to 10.9 dB [adults]; ABR 2 kHz tone stimulus: 1.0 to 6.7 dB [children], 1.9 to 9.2 dB [adults]; DPOAE 2 kHz tones: 0.4 to 5.4 dB [children]; 0.8 to 10.8 dB [adults]).

Subsets of five children (#11, #12, #16, #18, #19) and five adults (#31, #32, #33, #34, #36) from the total groups of participants were used to repeat the behavioral loudness-intensity functions, electrophysiologic-intensity functions, and the predicted loudness-intensity functions to determine reliability. Pearson product-moment correlation coefficients (r) were calculated using linear regression analyses between the mean first and mean second (retest) measures by stimulus and group. Statistically significant correlations were obtained for children and adults between the mean first and mean second (retest) loudness-intensity functions for the ABR click (children: r = 0.96; adults: r = 0.98; p = 0.01; df = 3), ABR 2 kHz tone (children and adults: r = 0.99; p = 0.001; df = 3), and DPOAE 2 kHz tones (children: r = 0.96; adults: r = 0.98; p = 0.01; df = 3). The mean dB difference of the first versus second (retest) measured loudness-intensity functions at each stimulus level was within 9 dB (range ABR click: 0.5 to 6.4 dB [children], 0.4 to 5.5 dB [adults]; ABR 2 kHz tone: 0.2 to 3.8 dB [children], 0.4 to 6.0 dB [adults]; DPOAE 2 kHz tone: 0.3 to 3.6 dB [children], 0.1 to 8.8 dB [adults]).

Statistically significant correlations were obtained for children and adults between the mean first and mean second (retest) ABR wave V LIFs recorded with clicks (children and adults: r = 1.00; p = 0.001; df = 3) and 2 kHz tone stimuli (children and adults: r = 1.00; p = 0.001; df = 3), and DPOAE 2 kHz AIFs (children: r = 0.99; p = 0.001; df = 3; adults: r = 0.98; p = 0.01; df = 3). In addition, statistically significant correlations were obtained between the mean first and mean second (retest) loudness-intensity functions predicted with ABR click wave V latency (children and adults: r = 1.00; p = 0.001; df =

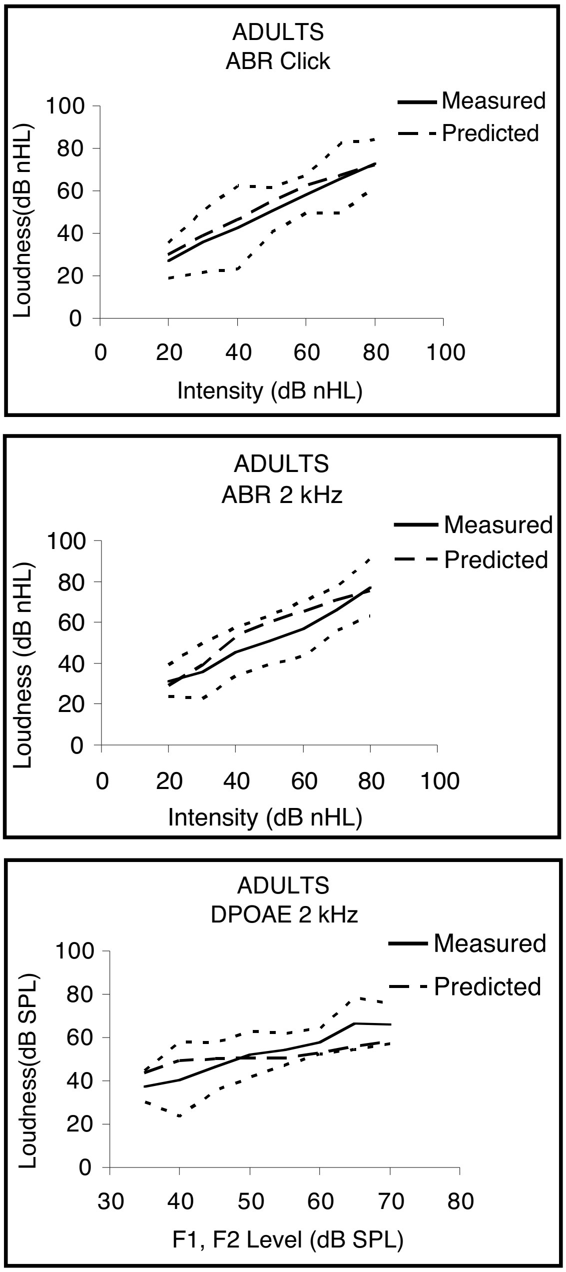

Figure 4. Mean measured (solid line) and mean predicted (long dashed lines) loudness-intensity functions for 10 adults (#31 to #40) recorded with ABR clicks (top), ABR 2 kHz tone (middle), and DPOAE 2 kHz tones (bottom). Short dashed lines represent ± 2 standard deviation lines obtained from the measured (actual) loudness-intensity functions of the same listeners.

3), ABR 2 kHz tone wave V latency (children: r = 1.00; adults: r = 0.99; p = 0.001; df = 3), and DPOAE 2 kHz amplitude (children: r = 0.99; p = 0.001; df = 3; adults: r = 0.97; p = 0.001; df = 3). The mean dB difference of the first versus second (retest) predicted loudness-intensity functions at each stimulus level was within 4 dB (range ABR click: 0.4 to 1.5 dB [children], 0.2 to 3.4 dB [adults]; ABR 2 kHz tone: 0.2 to 3.4 dB [children], 0.2 to 3.6 dB [adults]; DPOAE 2 kHz tone: 0.4 to 2.1 dB [children], 0.3 to 2.6 dB [adults]).

DISCUSSION

This study provided preliminary information on electrophysiological indices of normal loudness in children and adults using ABR wave V latency and DPOAE amplitude. Comparisons of electrophysiologic and behavioral intensity functions reveal that children and adults with normal hearing present with similar intensity growth rates (slopes) of ABR latency, DPOAE amplitude, and loudness.

As seen in Figure 1, the mean ABR click wave V LIF (top figure) and mean ABR 2 kHz tone LIF (middle figure) of children approximate the mean adult LIFs. The LIF slope values for children and adults (Tables 1 and 2) also support previously reported ABR LIF slope data reported for adults (Galambos and Hecox, 1978). Though the mean DPOAE amplitudes of children were -2.0 to -9.3 dB SPL higher than those of adults, similar mean DPOAE AIF slopes were noted between children and adults (Figure 1, bottom; Tables 1 and 2).

The mean loudness-intensity function slopes of children and adults recorded with ABR click (Figure 2, top), ABR 2 kHz tone (Figure 2, middle), and DPOAE 2 kHz tone (Figure 2, bottom) stimuli were also comparable. Previous loudness growth findings have supported similar rates of loudness growth between children and adults with normal hearing (Serpanos and Gravel, 2000, 2002).

The results of this study additionally demonstrated a statistically significant relationship between loudness and click or tone-evoked ABR wave V latency and DPOAE amplitude for children and adults. Prior ABR research on adults with normal hearing has also supported a relationship between loudness and the click-evoked ABR wave V latency (Serpanos et al, 1997).

Behavioral loudness-intensity functions were accurately predicted using ABR click or 2 kHz tone wave V latency-, and DPOAE 2 kHz amplitude-loudness estimation equations in ten children and ten adult listeners. The accuracy of loudness estimation was determined by the statistically significant correlations obtained between the mean behavioral measured (actual) loudness-intensity functions and predicted loudness-intensity functions for the groups of children and adults. In addition, the mean predicted loudness functions fell within the normal variability ± 2 standard deviations) of the mean measured loudness functions derived for each stimulus for children (Figure 3) and adults (Figure 4). Moreover, the mean dB difference in the loudness-intensity functions predicted by ABR click, ABR 2 kHz tone, and DPOAE 2 kHz tone stimuli was within 11 dB of the behavioral loudness-intensity functions recorded with the same stimuli. This difference is similar to the variability noted in behavioral loudness data from children and adults (Serpanos and Gravel, 2000, 2002). These findings suggest that ABR wave V latency and DPOAE amplitude accurately predict loudness, at least for children and adults with normal hearing.

The results also suggest that normal loudness estimation using ABR wave V latency and DPOAE amplitude measures are reliable. The electrophysiologic measures were found to be repeatable, as noted by the statistically significant correlations between the first and second (retest) ABR click wave V LIF, ABR 2 kHz wave V LIF, and DPOAE 2 kHz AIF of the individual participants. The literature has proven ABR wave V latency (Hood, 1998) and DPOAE amplitude (Prieve and Fitzgerald, 2002) to be reliable measures. In addition, the loudness measures using the CMM task were reliable for individual participants, as revealed by the statistically significant correlations between the first and second (retest) loudness-intensity function derived with ABR click, ABR 2 kHz tone, and DPOAE 2 kHz tone stimuli. The reliability of the CMM task for loudness growth assessment has been demonstrated in previous research with children 4 to 12 years and adults (Serpanos and Gravel, 2000, 2002). Statistically significant correlations were also obtained between the individual first and second (retest) predicted loudness-intensity functions using the loudness estimation equations derived for the ABR click and ABR 2 kHz wave V latency, and DPOAE 2 kHz amplitude, which supports the reliability of loudness estimation using ABR wave V latency and DPOAE amplitude. The mean dB difference between the first and second loudness-intensity function predicted by ABR click, ABR 2 kHz tone, and DPOAE 2 kHz tonal stimuli for the individual listeners was similar to the retest difference findings of the measured behavioral loudness functions in the same listeners, and in previous loudness studies.

The implication of these preliminary findings is that normal ABR wave V LIFs derived with clicks and tones and normal DPOAE AIFs can be used to predict normal loudness growth functions in children and adults. This implication would have to be interpreted with caution, however, since individuals with normal hearing and abnormal loudness growth (e.g., hyperacusis) were not included in this study. Normal ABR wave V LIFs and DPOAE AIFs could be used to derive normative ABR and DPOAE templates of predicted loudness functions by which abnormal rates of loudness growth may be determined. The ability to predict loudness objectively may prove useful for the purpose of site-of-lesion assessment or hearing aid fitting in individuals who cannot provide reliable behavioral measures. However, further study would be necessary on larger groups of subjects, both with normal and impaired hearing, to determine the clinical significance of these findings.

CONCLUSION

This study determined that children and adults with normal hearing present with similar intensity growth rates (slopes) of ABR latency, DPOAE amplitude, and loudness. A statistically significant relationship was demonstrated between loudness and the electrophysiologic measures of ABR wave V latency and DPOAE amplitude. ABR wave V latency and DPOAE amplitude measures were found to accurately and reliably predict normal loudness growth. An implication of the findings is that normal ABR click and tone evoked wave V LIFs and DPOAE AIFs can be used to predict normal loudness growth in children and adults with normal hearing. Normative ABR and DPOAE templates of predicted loudness functions may be developed to distinguish abnormal rates of loudness growth for individuals who cannot provide reliable behavioral measures. Though replication of these data and further study is necessary in larger groups with varying degrees and configurations of hearing loss, the findings from this study may have important implications for the clinical utility of the ABR and DPOAE measures for loudness growth prediction. The ability to predict loudness via objective electrophysiologic measures such as ABR and DPOAE may have invaluable application in site-of-lesion assessment or in the hearing aid fitting process of difficult-to-test populations such as young children, where loudness measures may be unattainable.

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