

An Evaluation of the Cross-Check Principle Using Visual Reinforcement Audiometry, Otoacoustic Emissions, and Tympanometry

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Abstract

Background: Early intervention to reduce the effects of congenital hearing loss requires accurate description of hearing loss. In pediatric audiology, a cross-check principle is used to compare behavioral and physiological tests.

Purpose: The purpose of this study was to investigate the correspondence of visual reinforcement audiometry (VRA) minimal response levels (MRLs), otoacoustic emissions (OAEs), tympanometry, and VRA test reliability to determine the odds of obtaining the expected cross-check results. We hypothesized that (1) when MRLs were within normal limits (WNL), OAEs would be present; (2) in the event of normal MRLs and absent OAEs, tympanograms would be abnormal; and (3) in the event of elevated MRLs and present OAEs, the tester's confidence in the MRLs would be judged to be only fair, rather than good.

Research Design: This was a retrospective study.

Study Sample: A previous study provided data from 993 infants who had diagnostic audiologic evaluations at 8–12 mo of age.

Data Collection and Analysis: The data were analyzed to compare VRA MRLs with OAE signal-to-noise ratios at 1, 2, and 4 kHz. Odds ratios and 95% confidence intervals were calculated to test the three hypotheses related to the correspondence among MRLs, OAEs, tympanometry, and the reliability of MRLs.

Results: The probability that OAEs would be present when MRLs were WNL varied from 12 to 26 to 1, depending on the test frequency. When OAEs were absent in the presence of normal MRLs, the odds of abnormal tympanometry varied from 5 to 10 to 1, depending on the test frequency. When MRLs were elevated (>20 dB HL), the odds suggested that examiners judged the MRLs at 1 and 2 kHz to lack reliability.

Conclusion: The results suggest that the cross-check principle is effective when employing VRA, OAE, and tympanometry to rule out or determine the degree, type, and configuration of hearing loss in infants.

Key Words: Cross-check principle, early intervention, minimum response level, otoacoustic emissions, pediatric audiology, tympanometry, visual reinforcement audiometry

Abbreviations: AABR = automated auditory brain stem response; ABR = auditory brain stem response; BOA = behavioral observation audiometry; DPOAE = distortion product otoacoustic emission; MRL = minimum response level; OAEs = otoacoustic emissions; SNR = signal-to-noise ratio; TEOAE = transient evoked otoacoustic emission; VRA = visual reinforcement audiometry; WNL = within normal limits

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Studies pertaining to children with hearing loss have shown that early identification and appropriate intervention are critical components in a child's development. The importance of these critical components is best explained by the negative consequences that can occur without appropriate, early intervention. Yoshinaga-Itano and colleagues (1998) reported the effects of early identification and intervention on the development of deaf and hard-of-hearing children. Their study compared the language abilities of children who were identified with hearing loss before 6 mo of age to those of children who were identified after 6 mo. For all children in this study, appropriate intervention began within 2 mo of identification. Children who were identified by 6 mo of age performed significantly better on tests of expressive and receptive language skills. This advantage in language development was consistent across all degrees of hearing loss and communication modes. Subsequently, Moeller (2000) reported similar results for infants for whom intervention was begun by 11 mo of age and found that family involvement played a role in their language outcomes.

In order to provide appropriate intervention, the type, degree, and configuration of hearing loss must be known. In pediatric populations, obtaining reliable audiologic information can at times be difficult. The reliability of behavioral testing, which requires the cooperation of the infant, is oftentimes questionable. When it is, other tests should be done to cross-check or confirm the behavioral results.

The concept of the cross-check principle was initially reported by Jerger and Hayes (1976). The purpose of their article was to show the importance of using multiple tests to confirm diagnosis in cases where behavioral results were not reliable. The protocol used in their evaluations began with behavioral audiometry; either behavioral observation audiometry (BOA), visual reinforcement audiometry (VRA), or play audiometry. The second measure used to confirm the results of the behavioral measure was immittance audiometry, including tympanograms and acoustic reflexes. In the event that the first two tests disagreed, auditory brain stem response (ABR) was used as a third measure. The article included five cases in which the initial diagnosis was questionable. In all five cases they found that the use of the cross-check principle provided a different and more accurate diagnosis.

Since 1976 there have been improvements in our pediatric test protocol. BOA is rarely used for audiometric threshold testing (Wilson and Thompson, 1984; Diefendorf and Gravel, 1996). For infants under 6 mo, the audiogram is estimated from toneburst ABR. However, once an infant can be conditioned for VRA, then those behavioral results become the primary test. Unlike standard pure-tone audiometry for adults, there is not a standard protocol for VRA with infants. Differ-

ences among practitioners and across clinic sites are likely to lead to more variation in audiometric results than is typically seen with adults or older children. Audiologists who have limited experience with infant behavioral testing tend to lack confidence in their results (Widen et al, 2005).

Turner (2003) reexamined the concept of the cross-check principle proposed by Jerger and Hayes and found that the concept was still valid, although the specific protocols have changed with advances in technology that are now available for audiologic evaluations. For example, once otoacoustic emissions (OAEs) came into clinical use, reports of their applicability as an important cross-check measure became prevalent (cf. Stach et al, 1993). The idea of investigating the traditional concept of the cross-check principle with a protocol utilizing VRA and OAEs brings us to our current study.

The purpose of this study was to examine the cross-check principle in a pediatric population using VRA, OAEs, and tympanometry. We compared the behavioral responses of VRA with the physiological measure of OAEs, using tympanograms as the third cross-check in cases where the first two tests disagreed. Although VRA is used to establish pure-tone thresholds, the term *minimum response level* (MRL) is often used instead of *threshold* to denote the likelihood that the response approximates threshold. MRL is a particularly appropriate term for tests of normal-hearing infants, when tests of actual threshold are modified once the infant responds consistently at a level considered within the normal range, for example, 15 or 20 dB HL for infants. Infants with MRLs of 20 dB HL are expected to have OAEs at the corresponding test frequencies (Gorga et al, 1993a, 1993b), provided middle ear function is normal. When middle ear function is impaired, especially in the presence of middle ear effusion (Koike and Wetmore, 1999) or negative middle ear pressure (Marshall et al, 1997), OAEs are generally absent despite normal hearing levels. OAEs are generally absent when hearing loss, either sensorineural or conductive, exceeds 30 dB HL. Of course, the correspondence between hearing threshold levels and OAEs is not perfect. Variability across individuals makes interpretation difficult when OAEs are used to estimate hearing loss in the 20–40 dB HL range. And neural hearing impairment, for example, auditory neuropathy, might yield robust OAEs in the presence of elevated hearing levels and normal tympanometry. Another variable that may influence the correspondence across tests is the reliability of the behavioral response. This is especially true with infants whose MRLs may vary depending on learning (conditioning success) or fatigue (habituation) effects.

Using a large data set from a previously published study, we took the opportunity to investigate the correspondence of MRLs, OAEs, tympanometry, and test

reliability to determine the odds of obtaining the expected cross-check results. We hypothesized that

1. when MRLs are within normal limits (WNL), OAEs will be present;
2. in the event of normal MRLs and absent OAEs, tympanograms will be abnormal; and
3. in the event of elevated MRLs and present OAEs, the tester's confidence levels for MRLs will be judged to be only fair, rather than good.

The criteria used to define normal and abnormal for these analyses are shown in Table 1.

METHOD

The data for this study were obtained from a larger study conducted to examine the efficacy of OAEs and ABRs in identifying hearing loss in infants and funded through a cooperative agreement between the Centers for Disease Control and Prevention and the Association of Teachers of Preventive Medicine. Descriptions of the original study have been published (Gravel et al, 2005; Johnson et al, 2005a; Johnson et al, 2005b; White et al, 2005; Widen et al, 2005).

Participants

The initial study was conducted at seven different birthing hospitals throughout the United States. To be enrolled in the study the infant was required to have failed the OAE screening but passed the automated auditory brain stem response (AABR) during the newborn hearing screening, in at least one ear. A total of 1524 infants met this criteria and were enrolled at birth. Parents provided their consent for the study, which had received approval from the Institutional Review Boards at the University of Hawaii, the Centers for Disease Control and Prevention, and each of the participating sites. Of the original 1524 infants, 993 returned for at least one diagnostic audiologic evaluation at 8–10 mo corrected age. These 993 infants provided the data for this current project.

Test Sites and Equipment

The diagnostic audiologic evaluations were conducted in seven separate audiology clinics that were associated with their birth hospitals in Cincinnati; Honolulu; Hyde Park, N.Y.; New York; Orlando; Providence, Rhode Island; and Wichita, Kansas. VRA testing was conducted in sound-treated test booths. The diagnostic audiometers with 3A insert earphones were calibrated to American National Standards Institute (1996) standards. The test booth setup was the same at six of the seven sites. The participant, a parent, and a test assistant were seated in the test booth with four reinforcer toys, two on each side of the infant. The participant was seated on the parent's lap facing the observation window. The examiner and the audiometric equipment were in a room next to the test booth with an observation window that allowed the tester to see the participant during the evaluation. At the seventh site, the tester and audiometer were in the test booth with the participant, with three reinforcer toys stacked to one side of the subject.

The OAE equipment varied across sites. Either transient evoked otoacoustic emissions (TEOAEs) or distortion product otoacoustic emissions (DPOAEs) were allowed. The OAE equipment was calibrated according to the manufacturer's recommendations. TEOAEs were conducted with a screening unit that used a stimulus level of 80 dB pSPL \pm 3 dB. DPOAEs were conducted with a screening unit that used f_1 stimuli of 65 dB SPL and f_2 of 55 dB SPL. All units recorded the resultant OAEs as signal-to-noise ratios (SNRs) by frequency bands from 1000 to 4000 Hz. GSI-33 Middle-Ear Analyzers were used to obtain tympanograms and were calibrated to the manufacturer's specification.

Personnel

All diagnostic evaluations were conducted by certified, licensed audiologists with extensive experience in pediatric audiology. At the six sites in which the examiner was located outside of the test booth, an assistant was used inside the booth. Most of the time this

Table 1. Criteria Used to Define Normal and Abnormal

Measure	Normal	Abnormal
Minimal Response Level	15 or 20 dB HL (within normal limits [WNL])	25 dB HL or greater (elevated)
Otoacoustic Emissions	3–6 or >6 dB signal-to-noise ratio (SNR) at 1 kHz >6 dB SNR at 2 and 4 kHz (present)	<3 dB SNR (absent)
Tympanometry	All three of the tympanometry measures are WNL	Any of the three tympanometry measures are abnormal
Peak Pressure	–200 to 100 daPa	< –200 or >100 daPa
Static Admittance	\geq 0.2 and <1.2 ml	<0.2 and \geq 1.2 ml
Tympanogram Width	\geq 30 and \leq 235 daPa	>235 or <30 daPa

assistant was an audiologist, an audiology student, or an assistant trained in VRA. At times when a trained assistant was not available, the parent would be instructed on how to maintain the appropriate attentive state from the infant participant. At the one facility in which the examiner and audiometer were inside the test booth with the participant, the examiner would control the equipment as well as maintain the attention of the participant. The audiologists who participated in this study were trained on the specific protocol prior to beginning the period of behavioral testing. Details of the training and protocol are provided elsewhere (Widen et al, 2005).

Procedures

At each diagnostic evaluation several assessments were performed including VRA, OAEs, and tympanograms. A detailed protocol for VRA testing was developed to ensure consistency across sites and is described in detail in Widen and colleagues (2005). VRA testing was conducted with the goal of obtaining minimum response levels at 500, 1000, 2000, and 4000 Hz for each ear using insert earphones. The pure-tone stimulus was a pulsed, warble tone of approximately 1–2 sec duration. Initial trials were to begin with a 2000 Hz, 35 dB HL stimulus. Specific steps for conditioning, probe, and control controls were followed to assure adequate stimulus control.

The test protocol began with a 20 dB down, 10 dB up step size until the subject responded below 35 dB HL; a 10 dB down, 5 dB up step size was used thereafter. The tester did not attempt to obtain responses below 15 dB HL. Once two responses had been obtained at 15 dB HL, the examiner would begin the next frequency, starting at 15 dB HL. If the lowest level obtained at the previous frequency was higher than 15 dB HL, the examiner would begin at the lowest level of response on the next frequency.

The examiner was to judge whether he or she thought the results were valid and repeatable. This judgment was recorded as “confidence level” and was categorized as “good” or “fair.” If the confidence level was less than fair, the MRL value was recorded as “could not test.”

OAEs were recorded by type (TEOAEs or DPOAEs) and by SNRs of <3 dB, 3–6 dB, or >6 dB at frequency bands of 1–1.9 kHz, 2–2.9 kHz, and 4–4.9 kHz. Screening tympanograms were done on each ear to test middle ear function. Values were recorded for ear canal volume in milliliters, admittance in milliliters, peak pressure in decapascals, and width in decapascals when available.

At the end of each diagnostic session the examiner determined if the evaluation was complete. If the examiner thought additional information was needed or suspected a hearing loss, the parents were asked to bring the infant back for another evaluation. If MRLs were greater than 20 dB HL and tympanograms were abnormal, infants were referred for medical follow-up and asked

to return after medical management. If at the follow-up audiologic evaluation MRLs were still above 20 dB HL, bone conduction testing was done. If MRLs were 15 or 20 dB HL with abnormal tympanograms, medical follow-up was recommended. However, no additional testing was done for the purpose of this study.

Data Analysis

Data for each infant’s visit were recorded on a data form. The forms were sent to the National Center for Hearing Assessment and Management, where they were entered into an SPSS database. The data were then checked for errors. This database, without identifying information, was shared with investigators at the Kansas University Medical Center.

The original database contained 993 participants. Each of these participants had returned for at least one diagnostic evaluation and may have come back for up to three diagnostic evaluations. For each participant the database contained 323 possible data fields, including demographic information and maternal and neonatal risk factors, as well as diagnostic evaluation results for each visit. Of those data fields only the ones containing information about MRLs, OAEs, and tympanograms were used for this current study. Each participant had the following data: a unique identifying number, a visit number, and for each ear the MRLs at 1000, 2000, and 4000 Hz; confidence levels for the corresponding MRLs; tympanometric test results with three measures; OAE results by type; and SNRs at the three corresponding frequencies. Most of the participants had complete data for both ears; however, some of them may have only had complete data for the “study” ear, that is, if only one ear had failed OAE and passed AABR. The database was then split to represent each ear at each visit, which are labeled “cases” in further discussion.

Of these resulting cases, to be eligible for the current study analysis the following criteria had to be met: an MRL and an OAE at a minimum of one frequency and a tympanogram (excluding nine cases with pressure equalization tubes). This left 1483 cases for analysis. One participant could be represented in this study multiple times, resulting in up to six cases, depending on how many ears were evaluated, how many diagnostic evaluations the infant had, and how complete the MRL and OAE data were at each visit. Examples of cases with representative results are displayed in Table 2. Reading from left to right, the VRA MRLs are earphone data obtained for one ear at one visit, and “Conf Level” denotes the examiner’s level of confidence for each MRL. Next the type of OAE is noted with its SNR values for each frequency. Following the values for tympanometric peak pressure, static admittance, and tympanometric width is the code for whether the tympanogram was judged to be normal or abnormal

Table 2. Representative Cases

ID	Visual Reinforcement Audiometry Minimum Response Levels (dB HL)			Confidence Level			Otoacoustic Emission (dB Signal-to-Noise Ratio)				Tympanogram			
	1 kHz	2 kHz	4 kHz	1 kHz	2 kHz	4 kHz	D/T	1 kHz	2 kHz	4 kHz	Peak	Static	Width	
											Pressure (daPa)	Admittance (ml)	(daPa)	N/AB
A	15	20	15	G	G	G	D	>6	>6	>6	-10	0.6	170	N
B	15	15	15	G	G	G	T	3-6	>6	>6	10	0.3	115	N
C	35	20	25	G	G	G	T	<3	<3	<3	-340	0.3	NP	AB
D	35	35	cnt	G	G	—	T	<3	<3	<3	NP	NP	NP	AB
E	30	25	25	G	G	G	D	<3	<3	<3	-120	0.1	250	AB
F	15	15	15	G	G	G	D	<3	3-6	>6	-145	0.1	265	AB
G	15	15	15	G	G	G	D	<3	>6	>6	NP	NP	NP	AB
H	15	15	15	G	G	G	T	<3	>6	>6	-275	0.3	260	AB
I	35	20	25	F	F	F	T	>6	>6	>6	15	0.3	160	N
J	35	20	20	F	G	F	T	>6	>6	>6	-85	0.2	110	N
K	45	dnt	15	F	—	G	T	>6	>6	>6	50	0.2	130	N
L	20	15	25	G	G	G	T	>6	>6	<3	20	0.2	145	N
M	20	15	30	G	G	G	T	>6	>6	>6	0	0.2	170	N

Note: cnt = could not test; dnt = did not test; G = good; F = fair; T = transient evoked otoacoustic emission; D = distortion product otoacoustic emission; NP = no peak; N = normal; AB = abnormal.

according to Table 1 and based on Nozza and colleagues (1994) and Roush and colleagues (1995). Cases A and B are clear-cut, with all tests in agreement: normal MRLs judged to have good reliability; present OAEs at 1000, 2000, and 4000 Hz; and normal tympanograms. Cases C, D, and E are also in agreement, with elevated MRLs, absent OAEs, and abnormal tympanograms. Cases F, G, and H are examples with normal MRLs, variably discrepant OAEs, and abnormal tympanograms. Cases I, J, and K represent instances where at least at one frequency MRLs are elevated when OAEs are present and the confidence in the MRLs was only fair. Cases L and M give a mixture of discrepancies.

Once the cases were determined, the database was divided into subsets by frequencies of 1000, 2000, and 4000 Hz. The number of cases varied across the frequencies analyzed, depending on the number of cases for which MRL and OAE results were obtained at corresponding frequencies.

For each hypothesis the data were analyzed by percentages and odds ratios. First, the percent of cases that agreed with the hypothesis was calculated. From the percentages, the odds ratios were calculated. The odds ratio is a statistical calculation used to estimate the probability of a particular event to occur given that another specified factor is present. A common example of an odds ratio is that of a single throw of a die. The odds that you will roll a 6 on a six-sided die are 1 to 5 (i.e., for every six times the dice is rolled, one time will be a 6 and five times will be a number other than 6). This 1 to 5 ratio means that you are five times more likely to roll a number other than 6 than you are to roll a 6 (Bland and Altman, 2000). An odds ratio of 1 to 1 means that there is no difference in the probability of an event

occurring with one factor compared to another factor (i.e., a ratio of 1 to 1 means you have a 50/50 chance).

In addition to assessing clinical relevance, confidence intervals are used to determine if an odds ratio is statistically significant (Agresti, 1990). A 95% confidence interval analysis is equivalent to testing a two-sided test using a type I error of 0.05. A 95% confidence interval provides a range of values based on the data from a sample. There is 95% confidence that the interval would include the population's values. A confidence interval that includes 1 would indicate that there is 95% confidence that the odds ratio is not significant. Consequently, a confidence interval that does not include 1 is significant because there is 95% confidence that the population will have an odds ratio within that interval and therefore have a ratio that is greater than 1 to 1.

RESULTS

Figure 1 presents the number of cases with a triad of test results for the three test frequencies, 1000, 2000, and 4000 Hz. By way of explanation, there were 1213 cases for 1000 Hz; MRLs were normal (15 or 20 dB HL) for 1116 but elevated (>20 dB HL) for 97. Of the normal MRLs, OAEs were present in 965 cases and absent in 151. Of the 97 cases with elevated MRLs, OAEs were present in 34 cases and absent in 63. These are the values that were used to calculate the odds ratios for Hypothesis 1. In the upper right section of the figure the breakdown of normal and abnormal tympanograms is given for the normal MRLs with either present or absent OAEs. These are the values used to calculate the odds ratio for Hypothesis 2. Hypothesis 3 is the focus of the lower right-hand portion of the figure, which

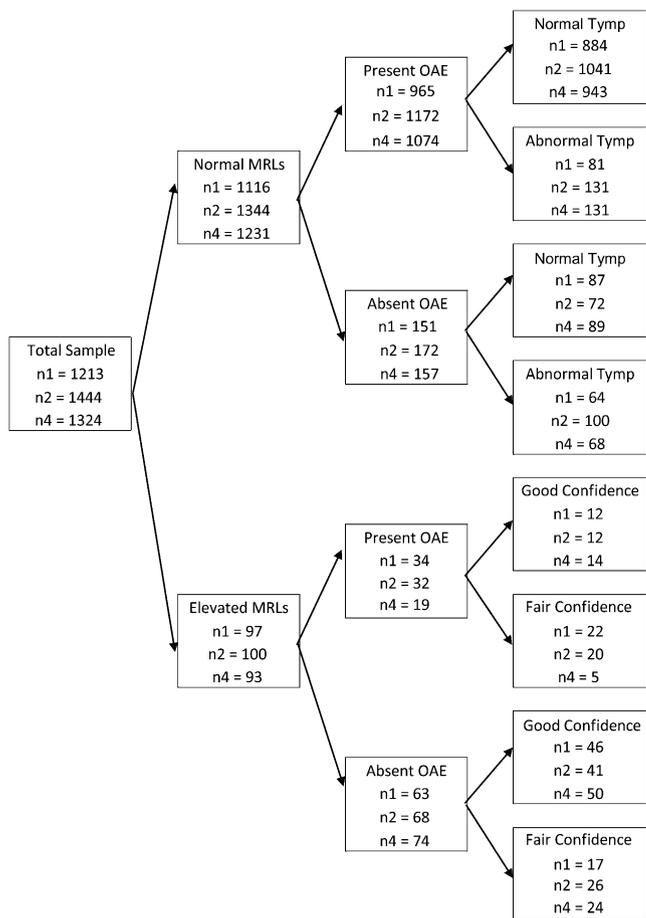


Figure 1. Diagram of test results for 1000, 2000, and 4000 Hz, showing number of cases (n1, n2, and n4) with each type of result. Normal minimum response levels (MRLs) = 15 or 20 dB HL; Elevated MRLs ≥25 dB HL; Present otoacoustic emissions (OAEs) = ≥3 dB signal-to-noise ratio (SNR) at 1 kHz and >6 dB SNR at 2 and 4 kHz; Absent OAEs = <3 dB SNR; Normal Tymp = all three tympanometric measurements (peak pressure, static admittance, and tympanometric width) were within normal limits per Table 1; Abnormal Tymp = any of the three tympanometric measurements were not within normal limits per Table 1; Good Conf. or Fair Conf. = level of confidence in the MRLs.

displays the confidence levels for elevated MRLs when OAEs are either present or absent. In a similar manner, the number of cases for each combination of test results for 2000 Hz is shown as n2 and for 4000 Hz as n4. For each hypothesis, odds ratios were calculated for each of the three test frequencies.

Hypothesis 1. When MRLs Are WNL, OAEs Will Be Present

For example, Table 3 repeats the numbers (n1) given in Figure 1 noting the percentages of present or absent OAEs for cases with normal and elevated MRLs at 1000 Hz and shows the calculation for the odds ratio. “Odds” is the ratio of the percentage of present OAEs and absent OAEs for both normal MRLs and elevated MRLs. “Odds Ratio” is the ratio of the two odds. This odds ratio tells us the probability that OAEs will be present when MRLs are WNL. At 1000 Hz it is 11.87 times more likely that OAEs will be present with normal MRLs than with elevated MRLs. In a like manner, the odds ratios were calculated for 2000 and 4000 Hz and can be found in the appendix.

Confidence intervals were calculated to determine if the odds ratios were statistically significant. The calculations for these confidence intervals are shown in the appendix. The confidence intervals for the odds ratios of each hypothesis indicate that the odds ratios are significant because they do not include a 1 to 1 ratio. Figure 2 (top) displays the odds ratios for Hypothesis 1 for all three test frequencies.

Hypothesis 2. In the Event of Normal MRLs and Absent OAEs, Tympanograms Will Be Abnormal

Table 4 shows the number and percentages of normal or abnormal tympanograms for cases with normal MRLs and absent or present OAEs for 1000 Hz. (See the appendix for 2000 and 4000 Hz.) In the manner described above, the odds ratios were then calculated for 1000, 2000, and 4000 Hz and are plotted in the middle section of Figure 2. This odds ratio tells us the probability that tympanograms will be abnormal when MRLs are normal but OAEs are absent. The 95% confidence intervals are all greater than 1.

Hypothesis 3. In the Event of Elevated MRLs and Present OAEs, the Confidence Level of the MRLs Will Be Fair

Table 5 shows the number and percentages of good or fair confidence levels for cases with elevated MRLs and present or absent OAEs at 1000 Hz (again, 2000 and

Table 3. Calculation of the Odds Ratio of Present Otoacoustic Emissions (OAEs) with Normal Minimum Response Levels (MRLs) Compared to Present OAEs for Elevated MRLs, 1000 Hz

MRLs at 1000 Hz	Present OAEs		Absent OAEs		Odds	Odds Ratio
	n	%	n	%		
Normal (n = 1116)	965	86.5	151	13.5	86.5/13.5 = 6.41	6.41/0.54 = 11.87 to 1
Elevated (n = 97)	34	35.1	63	64.9	35.1/64.9 = 0.54	

Note: Hypothesis 1 states that when MRLs are within normal limits, OAEs will be present. Calculations for 2000 Hz and 4000 Hz are shown in the appendix.

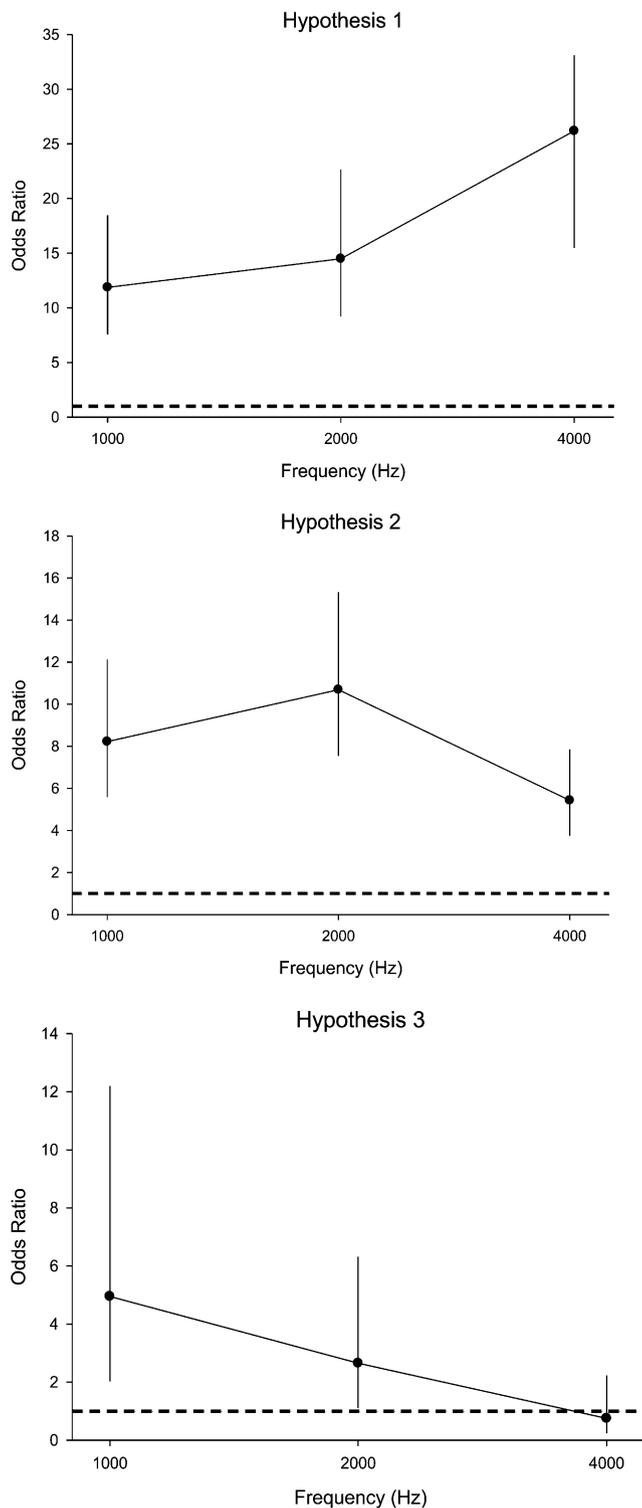


Figure 2. Point estimates (solid circles) and 95% confidence intervals (vertical lines) of the odds ratios for Hypotheses 1, 2, and 3 as a function of test frequency. A ratio of 1 to 1 is depicted by the horizontal dashed lines.

4000 Hz values can be found in the appendix). As before, the odds ratios and their confidence levels were then calculated for 1000, 2000, and 4000 Hz and are plotted in the bottom graph of Figure 2. This odds ratio tells us

the probability that the examiner's confidence level will be fair when MRLs are elevated and OAEs are present at 1000 and 2000 Hz. The odds ratios for 4000 Hz were not significant.

DISCUSSION

It has been many years since Jerger and Hayes (1976) first described the pediatric cross-check principle. Since then, advances in technology have provided new tools for assessing hearing loss. Therefore, this study was undertaken to evaluate the cross-check principle using a more current protocol. The study conducted by Johnson and colleagues (2005a) that was designed to examine the efficacy of OAEs and AABRs in identifying hearing loss in infants provided a large sample of infant audiometric data. For each infant subject, results were reported for, among other things, VRA, OAE, and tympanometric testing. Each infant had passed AABR hearing screening at birth and then returned for a behavioral hearing evaluation at 8 to 10 mo of age. It was assumed that some infants would have hearing loss at that time, since middle ear effusion is so common at that age. This provided a good opportunity to reexamine the cross-check principle using a protocol consisting of VRA, OAEs, and tympanometry that reflects today's practices.

Given that the infants had passed AABR screening at birth, it is not surprising that the majority had normal hearing when tested 8–10 mo later. When comparing the number of normal MRLs to the total sample of cases (Fig. 1), one can see that 92–93% had normal hearing levels. And 86–87% of those had present OAEs, as we hypothesized.

When considering the discrepancies between MRLs and OAEs (normal MRLs but absent OAEs) about half could be explained by abnormal tympanometry. This was more apparent at 2000 Hz (58%) than at 1000 and 4000 (42–43%). This makes sense when one considers the common audiometric configuration for otitis media with effusion with best thresholds at 2000 Hz (Fria et al, 1985). The reverse discrepancy (elevated MRLs and present OAEs) is harder to explain. We hypothesized that confidence in the reliability of the MRLs might be lacking in these cases. The results indicate that this might be true for 1000 and 2000 Hz, but the odds ratio was not significant for 4000 Hz. One possible explanation is that the assignment of good or fair confidence is quite imprecise and may vary considerably across examiners. It is possible that examiners may have a biased opinion about the reliability of the VRA if they have prior knowledge of OAE test results. For instance, they may be more likely to assign a good confidence level for a normal MRL if they know that OAEs are present at that same frequency band. The reverse is also true. They may be less likely to have good

Table 4. Calculations of the Odds Ratio of Abnormal Tympanograms with Normal Minimum Response Levels (MRLs) and Absent Otoacoustic Emissions (OAEs) Compared to Abnormal Tympanograms with Normal MRLs and Present OAEs, 1000 Hz

MRLs and OAEs at 1000Hz	Abnormal Tympanograms		Normal Tympanograms		Odds	Odds Ratio
	<i>n</i>	%	<i>n</i>	%		
Normal MRLs and Absent OAEs (<i>n</i> = 151)	64	42.4	87	57.6	42.4/57.6 = 0.74	0.74/0.09 = 8.22 to 1
Normal MRLs and Present OAEs (<i>n</i> = 965)	81	8.4	884	91.6	8.4/91.6 = 0.09	

Note: Hypothesis 2 state that in the event of normal MRLs and absent OAEs, tympanograms will be abnormal. Calculations for 2000Hz and 4000Hz are shown in the appendix.

confidence if they know that the OAE is absent at that frequency band. We think that this is not likely to be the case here, however, since our test protocol required that the examiner record his or her confidence in the MRL at the time of VRA testing, prior to conducting OAE testing.

Unrelated to the hypotheses, but of possible clinical interest, is the difference in number of cases as a function of frequency. The greatest number of cases were reported for 2000 Hz, which is not surprising since the test protocol began with 2000 Hz in the sequence of test frequencies. The infant was likely to be the most attentive at the beginning of the test. On the other hand, 1000 Hz had the least number of cases, possibly because it was the last test frequency in the VRA test sequence. The infant may have habituated by that point in the test, making it more difficult to get reliable results.

In the aggregate, the results of this study are neither surprising nor particularly enlightening. Some might consider the analysis by odds ratios to be unnecessary. We chose odds ratio analysis in order to provide some quantitative measure of test correspondence. As it turned out, odds ratios of these magnitudes indicate clear-cut correspondence. The only odds ratio that was not significant (Hypothesis 3 at 4000 Hz) can probably be explained by its small *n*. There were only five cases in which examiners had fair confidence in the elevated MRLs when OAEs were present (see the appendix).

The more interesting use of these data may be for interpreting discrepancies in an individual infant's test results. The representative cases shown in Table 2 can be used for this purpose. For example, if the clinician testing Case I had been unsuccessful with VRA testing but had recorded OAEs, she could calculate from Table 3 (and the appendix) that the odds of normal hearing when OAE SNRs are greater than 6 dB are 6 to 1 com-

pared to the odds of elevated hearing and present OAEs, which are insignificant (between 0 and 1). For Cases F, G, and H the clinician would have added confidence based on these data that the absence of OAEs at 1000 Hz relates to the abnormal tympanograms and not an error in VRA testing. The use of these odds for clinical interpretation is similar to plotting DPOAE amplitude on the template developed at Boys Town National Research Hospital, where an individual's test results are compared to the Boys Town database of normal and impaired ears (Gorga et al, 2005). One should keep in mind, however, that the participant sample used in the present study was limited to newborns who had passed AABR screening at 35 dB nHL; thus its usefulness is limited to infants who are at risk for mild hearing impairment.

CONCLUSION

Our study used fairly strict criteria for normal MRLs, present OAEs, and normal tympanograms. It is possible that had these normal values been defined differently we may have had a somewhat different outcome. For instance, we accepted 15 or 20 dB as a normal MRL; however, some might suggest that 25 dB should be accepted as a normal MRL. To be classified as present OAEs we accepted a signal-to-noise ratio of greater than 3 dB at 1000 Hz; however, we only accepted an SNR of greater than 6 dB at 2000 and 4000 Hz. Perhaps the criteria that were the strictest for this study were the normal values for tympanograms. It was required that each parameter (peak pressure, static admittance, and tympanogram width) be within normal limits to be considered normal. Accepting tympanograms as normal based on fewer requirements, for

Table 5. Calculation of the Odds Ratio of Fair Confidence Levels with Elevated Minimum Response Levels (MRLs) and Present Otoacoustic Emissions (OAEs) Compared to Fair Confidence Levels with Elevated MRLs and Absent OAEs, 1000 Hz

MRLs and OAEs at 1000Hz	Fair Confidence		Good Confidence		Odds	Odds Ratio
	<i>n</i>	%	<i>n</i>	%		
Elevated MRLs and Present OAEs (<i>n</i> = 34)	22	64.7	12	35.3	64.7/35.3 = 1.83	1.83/0.37 = 4.95 to 1
Elevated MRLs and Absent OAEs (<i>n</i> = 63)	17	27.0	46	73.0	27/73 = 0.37	

Note: Hypothesis 3 states that in the event of elevated MRLs and present OAEs, confidence level of MRLs will be fair. Calculations for 2000Hz and 4000Hz are shown in the appendix.

example, defining a tympanogram with a peak as normal and a tympanogram with no peak as abnormal, might lead to higher odds ratios.

In summary, our hypotheses were confirmed. With this large set of data from infants, we found that there is good agreement between MRLs and OAEs as we would expect. When the two measures do not agree, tympanometry is likely to provide an explanation at least half of the time. When MRL reliability is questionable, OAEs may be important to the ultimate test interpretation. In the larger clinical picture, the value of the cross-check principle has once again been substantiated.

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APPENDIX A
CALCULATIONS OF CONFIDENCE INTERVALS FOR ODDS RATIOS

Hypothesis 1. When MRLS Are WNL, OAEs Will Be Present

MRLs at 1000 Hz	Present OAEs	Absent OAEs
Normal	965	151
Elevated	34	63

Odds Ratio (OR) = 11.87 to 1
 Natural Log of OR = 2.47
 Standard Error = $\sqrt{(1/965 + 1/151 + 1/34 + 1/63)} = 0.228$
 Lower Limit (Log Scale) = $2.47 - (1.96 \times 0.228) = 2.02$
 Upper Limit (Log Scale) = $2.47 + (1.96 \times 0.228) = 2.92$
 Lower Limit (OR) = $\exp(2.02) = 7.56$
 Upper Limit (OR) = $\exp(2.92) = 18.48$
 C.I. = (7.56, 18.48)

MRLs at 2000 Hz	Present OAEs	Absent OAEs
Normal	1172	172
Elevated	32	68

OR = 14.49 to 1
 Natural Log of OR = 2.67
 Standard Error = $\sqrt{(1/1172 + 1/172 + 1/32 + 1/68)} = 0.230$
 Lower Limit (Log Scale) = $2.67 - (1.96 \times 0.230) = 2.74$
 Upper Limit (Log Scale) = $2.67 + (1.96 \times 0.230) = 3.50$
 Lower Limit (OR) = $\exp(2.74) = 9.20$
 Upper Limit (OR) = $\exp(3.50) = 22.65$
 C.I. = (9.20, 22.65)

MRLs at 4000 Hz	Present OAEs	Absent OAEs
Normal	1074	157
Elevated	19	74

OR = 26.19 to 1
 Natural Log of OR = 3.27
 Standard Error = $\sqrt{(1/1074 + 1/157 + 1/19 + 1/74)} = 0.272$
 Lower Limit (Log Scale) = $3.27 - (1.96 \times 0.272) = 2.74$
 Upper Limit (Log Scale) = $3.27 + (1.96 \times 0.272) = 3.50$
 Lower Limit (OR) = $\exp(2.74) = 15.49$
 Upper Limit (OR) = $\exp(3.50) = 33.12$
 C.I. = (15.49, 33.12)

Hypothesis 2. In the Event of Normal MRLs and Absent OAEs, Tympanograms Will Be Abnormal

MRLs and OAEs at 1000 Hz	Abnormal	Normal
	Tympanograms	Tympanograms
Normal MRLs and Absent OAEs	64	87
Normal MRLs and Present OAEs	81	884

OR = 8.22 to 1
 Natural Log of OR = 2.11
 Standard Error = $\sqrt{(1/64 + 1/87 + 1/81 + 1/884)} = 0.200$
 Lower Limit (Log Scale) = $2.11 - (1.96 \times 0.200) = 1.72$
 Upper Limit (Log Scale) = $2.11 + (1.96 \times 0.200) = 2.50$
 Lower Limit (OR) = $\exp(1.72) = 5.58$
 Upper Limit (OR) = $\exp(2.50) = 12.18$
 C.I. = (5.58, 12.18)

MRLs and OAEs at 2000 Hz	Abnormal	Normal
	Tympanograms	Tympanograms
Normal MRLs and Absent OAEs	100	72
Normal MRLs and Present OAEs	131	1041

OR = 10.69 to 1
 Natural Log of OR = 2.37
 Standard Error = $\sqrt{(1/100 + 1/72 + 1/131 + 1/1041)} = 0.181$

Lower Limit (Log Scale) = $2.37 - (1.96 \times 0.181) = 2.02$
 Upper Limit (Log Scale) = $2.37 + (1.96 \times 0.181) = 2.73$
 Lower Limit (OR) = $\exp(2.02) = 7.54$
 Upper Limit (OR) = $\exp(2.73) = 15.33$
 C.I. = (7.54, 15.33)

MRLs and OAEs at 4000 Hz	Abnormal	Normal
	Tympanograms	Tympanograms
Normal MRLs and Absent OAEs	68	89
Normal MRLs and Present OAEs	131	943

OR = 5.43 to 1
 Natural Log of OR = 1.69
 Standard Error = $\sqrt{(1/68 + 1/89 + 1/131 + 1/943)} = 0.187$
 Lower Limit (Log Scale) = $1.69 - (1.96 \times 0.187) = 1.32$
 Upper Limit (Log Scale) = $1.69 + (1.96 \times 0.187) = 2.06$
 Lower Limit (OR) = $\exp(1.32) = 3.74$
 Upper Limit (OR) = $\exp(2.06) = 7.85$
 C.I. = (3.74, 7.85)

Hypothesis 3. In the Event of Elevated MRLs and Present OAEs, Confidence Level of MRLs Will Be Fair

MRLs and OAEs at 1000 Hz	Fair	Good
	Confidence	Confidence
Elevated MRLs and Present OAEs	22	12
Elevated MRLs and Absent OAEs	17	46

OR = 4.95 to 1
 Natural Log of OR = 1.60
 Standard Error = $\sqrt{(1/22 + 1/12 + 1/17 + 1/46)} = 0.458$
 Lower Limit (Log Scale) = $1.60 - (1.96 \times 0.458) = 0.7023$
 Upper Limit (Log Scale) = $1.60 + (1.96 \times 0.458) = 2.50$
 Lower Limit (OR) = $\exp(0.7023) = 2.02$
 Upper Limit (OR) = $\exp(2.50) = 12.2$
 C.I. = (2.02, 12.2)

MRLs and OAEs at 2000 Hz	Fair	Good
	Confidence	Confidence
Elevated MRLs and Present OAEs	20	12
Elevated MRLs and Absent OAEs	26	41

OR = 2.65 to 1
 Natural Log of OR = 0.975
 Standard Error = $\sqrt{(1/20 + 1/12 + 1/26 + 1/41)} = 0.443$
 Lower Limit (Log Scale) = $0.975 - (1.96 \times 0.443) = 0.107$
 Upper Limit (Log Scale) = $0.975 + (1.96 \times 0.443) = 1.843$
 Lower Limit (OR) = $\exp(0.107) = 1.11$
 Upper Limit (OR) = $\exp(1.843) = 6.32$
 C.I. = (1.11, 6.32)

MRLs and OAEs at 4000 Hz	Fair	Good
	Confidence	Confidence
Elevated MRLs and Present OAEs	5	14
Elevated MRLs and Absent OAEs	24	50

OR = 0.75 to 1
 Natural Log of OR = -0.288
 Standard Error = $\sqrt{(1/5 + 1/14 + 1/24 + 1/50)} = 0.577$
 Lower Limit (Log Scale) = $-0.288 - (1.96 \times 0.577) = -1.41$
 Upper Limit (Log Scale) = $-0.288 + (1.96 \times 0.577) = 0.8429$
 Lower Limit (OR) = $\exp(-1.41) = 0.2420$
 Upper Limit (OR) = $\exp(0.8429) = 2.32$ * not significant
 C.I. = (0.2420, 2.23)