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A comparison of the intrasubject repeatability of the auditory brainstem and middle latency response elicited in young children

**The Annals of Otology, Rhinology & Laryngology,
Vol 97:264-271,1988.**

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COMPARISON OF THE INTRASUBJECT REPEATABILITY OF AUDITORY BRAIN STEM AND MIDDLE LATENCY RESPONSES ELICITED IN YOUNG CHILDREN

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The auditory brain stem response (ABR) and middle latency response (MLR) were studied in 48 young children (96 ears). The responses were elicited using low intensity stimuli (30-dB nHL clicks) and simultaneously were recorded on a dual time base. Both the ABR and MLR were elicited in 70 ears. In 12 ears, just one response was recorded (ABR in eight ears and the MLR in four ears). In 14 ears, neither response was recorded. Test-retest analysis on the same subject demonstrated that the ABR was more repeatable and easier to identify than the MLR. The test-retest difference was determined for the amplitude and latency of the ABR and MLR waveforms. The test-retest latency difference for wave Pa was found to be 3.6 times larger than for wave V. The normalized test-retest amplitude difference for P0-Na, Na-Pa, and Pa-Nb was found to be two to three times larger than for wave V. These data support the conclusion that the ABR, rather than the MLR, should be used to measure hearing in young children. The authors also advocate using minimal high pass (HP) filtering when recording the ABR in a sedated or sleeping child. Muscle artifact was not found to be a problem. The authors suggest the use of minimal HP filtering so that phase-shift distortion is minimized and a larger response amplitude can be recorded.

KEY WORDS - auditory brain stem response, intrasubject repeatability, middle latency response, test-retest analysis, threshold determination.

INTRODUCTION

One of the most important applications of auditory evoked potential (AEP) testing is the evaluation of hearing in neonates and young children. At the University of Tennessee's Newborn Center, all infants who are placed on the high risk registry are evaluated initially with a Crib-o-gram and then referred (regardless of Crib-o-gram result) for AEP testing at 4 months post-full term (13 months conceptional age). Ideally, all infants should be tested with AEP before they leave the newborn center; however, the availability of equipment and personnel, along with limited funds available to service an indigent population, have prohibited this in our study. The cost-effectiveness of auditory brain stem response (ABR) versus Crib-o-gram testing of newborns is still debated, without clear results.¹ Both tests appear to have high positive rates. Middle ear effusions are common in this age group and are responsible for 52.8%¹ to 61.9%² of the positive results. Because of the transient nature of many ABR abnormalities found in the newborn, follow-up evaluation is considered mandatory.³

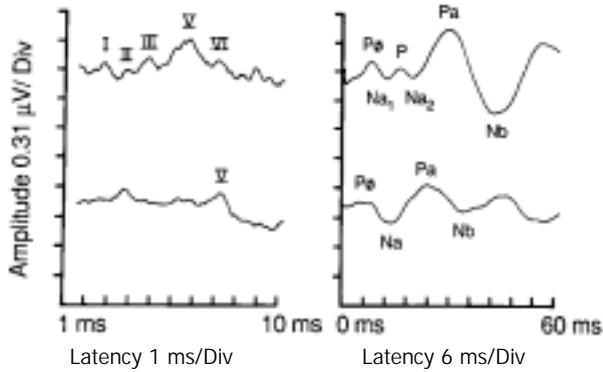
The goal of auditory evaluation of infants is to detect and habilitate hearing losses in children before 6 months of age.⁴ In our protocol, referral for AEP testing was done when a child was 4 months of age (13 months conceptional age). The age of the child at the time of testing is an important factor. Zimmerman et al⁵ have shown that the ABR undergoes dramatic changes in the first 2 weeks of life of a

full-term infant. As the subject's age increases, the ABR slowly approximates the adult's. Alberti et al² demonstrated that follow-up testing of children over 3 months of age has a lower failure rate than studies performed on newborns. Auditory habilitation still can be initiated after follow-up testing and completed before the child is 6 months of age. Screening AEP protocols often use a 30- to 40-dB nHL click stimulus,^{1,4} and children that have an ABR threshold above 40 dB are referred for auditory habilitation.

In our AEP testing protocol, ABR and the middle latency response (MLR) are recorded simultaneously on a dual time base. There has been much debate in the literature as to which response is the best predictor of hearing sensitivity in the newborn.⁶ Early researchers who have used steeply sloping analog filters have reported recording the MLR reliably in children; however, recent studies using gradually sloping filters have found the MLR to be recorded unreliably.⁷ It is the purpose of this paper to compare the ABR and MLR elicited from young children and to confirm or refute the reported difficulty in recording the MLR in this subject population. The ability to record each response with a near-threshold stimulus will be determined by documenting its test-retest repeatability. An argument will be made that the response with the smallest test-retest difference will be more repeatable and thus more recognizable by an observer as a true response. It therefore will be the more accurate measurement of hearing.

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Method used in waveform labeling. Top waveforms are from adult presented with 70-dB nHL stimulus. Bottom waveforms are from infant presented with 30-dB nHL stimulus.

METHODS

Subjects. Forty-eight children under the age of 13 months were evaluated by the University of Tennessee AEP Laboratory over a 12-month period. No child was sedated. The mean age was 8.0 months, with a standard deviation of 2.7 months and a range of 1 to 12 months. The vast majority of children were referred from the University of Tennessee-Memphis Newborn Center. Most of these children were identified as being at risk for hearing loss because of low birth weight. One of the children had Down's syndrome; the rest had no neurologic diagnoses. All children had normal results on otologic examination. Comparisons of the ABR and MLR were made in 42 children (82 ears) who had an AEP recorded (ABR and/or MLR) at 30 dB nHL. Ears with a threshold of greater than 30 dB nHL were not evaluated, since below-threshold recordings will have a high and equal variability for both test conditions.

Equipment. The Pathfinder II (Nicolet Corp) was used to record the ABR and MLR simultaneously on a dual time base. The stimuli were 70- and 30-dB nHL 0.1-ms rarefaction clicks presented at a rate of 9.7/s through TDH-49 headphones housed in Mx-41 cushions. Zero decibels nHL equals 39 dB pe SPL (peak equivalent sound pressure level). If no AEPs were recorded with the 30-dB nHL stimuli, then the stimulus intensity was increased in 10-dB nHL increments until threshold was found. The time base was 10 ms for the ABR and 60 ms for the MLR. Recording filters were 15 to 3,000 Hz for the ABR and 15 to 250 Hz for the MLR (Butterworth filters with 12-dB/octave slopes). All waveforms represented an average of 1,000 stimulus presentations. No subject was sedated; most were tested during natural sleep; and all were tested in a Tracoustic model RS-255A soundproof booth.

Waveform Identification. A response was considered valid in this study if identified in two of two recordings. If the waveform was seen only once in the

two averages, additional responses were recorded. Analysis of the waveforms recorded from the 70-dB nHL data and the additional 30-dB nHL recordings was used clinically to determine if the waveforms were present. Only the first two recordings, however, were considered in the test-retest analysis. A subject was considered to pass the auditory testing if either an ABR or MLR was present at 30 dB nHL. If the subject had a 40-dB threshold, then the result was considered to be borderline. Thresholds greater than 40 dB were considered abnormal.

Data Analysis. Waveform repeatability was determined by analyzing the waveform pairs presented to each subject. If more than two waveforms were recorded, then the first two waves were analyzed. If no response was identified for either ABR or MLR, a best-guess measurement was taken. If the presenting stimulus was below the subject's threshold (neither the ABR nor the MLR could be identified), then the ear was eliminated from analysis. The waveforms were labeled according to Kavanagh and Domico.⁸ Wave P0 was identified as the slow component of the ABR, and wave Na was identified as the lowest trough between wave Pip and wave Pa (Na1 or Na2, whichever was lower; see Figure). The latency and amplitude of wave V were recorded for the ABR. The latency for waves P0 and Pa, along with the P0-Na, Na-Pa, and Pa-Nb amplitudes, was recorded for the MLR. In a few waveforms, Nb and the trough after wave V had a latency longer than the time base. In this situation, the data point at the end of the time base was used for statistical analysis. All waveforms were measured by the same observer. There is no statistical advantage to having more than one observer for the type of analysis used in this study.

Latency data were recorded on a different scale (time base) for ABR and MLR. The wave latency difference in the wave pairs was corrected for scaling errors for waves V (10-ms time base) and P0 (60-ms time base) by the following equation:

$$\text{Latency difference} = \text{ABS}(A-B)/10 \text{ ms}$$

where ABS is the absolute value, A is the recording from the first waveform, and B is the recording from the second waveform.

The wave latency difference for waves P0 (60-ms time base) and Pa (60-ms time base) was corrected for scaling errors by the following equation:

$$\text{Latency difference} = \text{ABS}(A-B)/60 \text{ ms}$$

where ABS is the absolute value, A is the recording from the first waveform, and B is the recording from the second waveform.

Latency data were not normalized, since the magnitude of this parameter has little effect on wave peak identifiability, only on location.

TABLE 1. TEST-RETEST DIFFERENCES OF WAVE LATENCY (PERCENT CHANGE OF WAVE PEAK IN RELATION TO LENGTH OF TIME BASE)

Wave Peak	Time Base* (Weight Factor) (ms)	Mean*	Standard Deviation*	Variance*	Significance ^t Wave V vs MLR	Variance-Ratio (Larger/Smaller)
V	10	1.7%	1.94%	3.75%		
P0 (V)	10	5.8 %	3.55 %	30.69 %	p < .0001	8.18
P0 (V)	60	1.0%	0.92%	0.85%	p < .0001	4.41
Pa	60	6.2 %	6.02 %	36.18 %	p < .0011	9.64

* Scaled by equation: Scaled data = [ABS(A-B) /weight factor] x 100 % , where ABS is absolute value, A is first observation, and B is second observation. Weight factor is equal to time base.

t Two-tailed paired t test used to calculate significance on means and standard deviation from analysis of variance.

The amplitude difference for all wave slopes (ABR and MLR) was normalized to 1.0. This correction was done because amplitude does affect peak identifiability. For example, a 0.2-uV variation will affect the identification of wave V more than Pa, because Pa is a much larger waveform. The normalization of the data will allow equal weight to be given to a 50% reduction in wave amplitude (regardless of the average wave amplitude). Scaling errors did not exist, because the vertical scale for the ABR and MLR recordings was the same. Normalization was performed by an equation similar to the one used to determine unilateral hypoactivity during electronystagmographic testing.⁹

$$\text{Amplitude difference} = \text{ABS}(A - B) / A + B$$

where ABS is the absolute value, A is the recording from the first waveform, and B is the recording from the second waveform.

Means for the scaled latency difference and the normalized amplitude difference underwent statistical analysis using analysis of variance and t tests. The variances of these parameters also were compared using the F-max test. Since 82 data points were recorded for each condition, a ratio in variances greater than 1.7 will denote a significant difference with p<.01 (Tables 1 and 2). Because the t and F-max tests were significant, the data were examined more closely to determine underlying explanations for these differences.

Reliability of a clinical procedure or instrument is defined as the correlation between measurements repeated on the same subject.¹⁰ Intraclass correlations were calculated for the ABR and MLR from variance component estimates obtained from analyses of variance.¹¹ After transformation, difference

in reliability of latency and amplitude differences for the ABR and MLR were tested with a two-tailed paired t test.¹²

Data reliability is related to the variances of the test-retest differences in the two data sets.

$$\text{Reliability} = R_{12} \text{ (correlation between } Y_1 \text{ and } Y_2)$$

$$\text{Var} [Y_1 - Y_2] = \text{Var}[Y_1] + \text{Var} [Y_2] - (2 R_{12} * (\text{Var} [Y_1])^{1/2} * (\text{Var} [Y_2])^{1/2})$$

where Y1 is the first data set, Y2 is the second data set, and Var is the variance.

Only the variance due to retesting and not due to the different patients or different ears was evaluated. We estimated R12 by an intraclass correlation formula. (This refers to the correlation between repeated measurements recorded within ears on the same patient.)

$$R_{12} = (S_e^2 + S_{e/p}^2) / (S_p^2 + S_{e/p}^2 + S_e^2)$$

where s2 is the variance of the entire data set, p is the patient variance, a is the test-retest variance (error), and a/p is the variance of ears within patients.

RESULTS

In the 48 subjects (96 ears) who were tested, 82 ears had an AEP response recorded (ABR or MLR) at 30 dB nHL, four ears had an AEP threshold of 40 dB nHL, nine ears had a threshold above 40 dB nHL, and one ear was not tested because the subject awoke (Table 3). A response had to be identified in both initial waveforms to be considered valid. The ABR was not identified in four of 82 test ears (4.9%), and wave Pa of the MLR was not identified in eight of 82 test ears (9.7%) . This was not a significant difference (X² test, p>.2). For the 164

TABLE 2. TEST-RETEST DIFFERENCES OF WAVE AMPLITUDE (DATA NORMALIZED)

Wave Slope	Time Base (ms)	Mean*	Standard Deviation*	Variance*	Significance ^t V Amplitude vs MLR	Variance Ratio (MLR Slope/V Amplitude; Larger/Smaller)
V amplitude	10	12.6 %	12.2 %	149 %		
P0 (V)-Na	60	25.0%	20.6%	426%	p < .0001	2.86
Na-Pa	60	26.8 %	19.6 %	386 %	p < .0001	2.59
Pa-Nb	60	29.9 %	21.7 %	469 %	p < .0001	3.15

* Normalized by equation: Normalized data= [ABS(A-B)/A+B] x 100%, where ABS is absolute value, A is first observation, and B is second observation

t Two-tailed paired t test used to calculate significance on means and standard deviation from analysis of variance.

TABLE 3. ABSENCE OF EITHER ABR OR MLR

	AT 30 dB nHL		
	Responses (ABR or MLR) Present in 2 of 2 Recordings*	One Response (ABR or MLR) Absent in 1 of 2 Recordings †	One Response (ABR or MLR) Absent in 2 of 2 Recordings †
ABR	79/82	0	3
MLR	74/82	6	2

Does not include ears in which no response could be identified.

* All responses identified.

† One response not identified.

waveforms (82 waveform pairs), wave V was not identified in seven (4.3 %), wave P0 in two (1.2 %), and wave Pa in ten (6.1 %). In three of our subjects (six waveforms), wave V was not recorded when wave P0 was. Three possible explanations exist for this occurrence: 1) the high frequency energy in the first time base obscured the response; 2) the scaling differences of the time base obscured the response (the down slope of wave V on the shorter time base will not be as steep and, thus, not be as visible); or 3) the shorter time base missed the response.

Because there are three differences in the recording techniques used, it is impossible to tell with certainty which had the greatest effect; however, it is our belief that the last explanation was not the major factor. The mean latency of wave V was equal to 7.34 ms (standard deviation, 0.53 ms), and the latency of wave P0 was approximately 1.4 ms longer than that of wave V (this is due to the phase shifting of analog filters) (Table 4). In two subjects who had no identifiable wave V, wave P0's latency was less than 9.8 ms. In the third subject, the latency of wave P0 was prolonged, but additional recordings identified wave V at 7.83 ms. Thus, the absence of a recorded wave V in these subjects was not solely related to the length of the ABR time base.

The determination of the presence or absence of a response in these waveforms was a subjective decision and underscores the value of using the test-retest latency and amplitude difference as a method for comparing response identifiability.

TEST-RETEST DIFFERENCES OF SCALED LATENCY AND NORMALIZED AMPLITUDE DATA

Data Repeatability. Statistical analysis was performed after correction for possible scaling errors in

TABLE 4. SUBJECT LATENCY AND AMPLITUDE DATA

	FOR 30-dB nHL CLICK STIMULUS		Amplitude (uV)	
	Latency (ms) Mean	SD	Mean	SD
Wave V	7.34	0.53	0.27	0.11
P0	8.70	0.97		
Pa	28.79	6.13		
P4 -Na			0.29	0.15
Na-Pa			0.43	0.24
Pa-Nb			0.29	0.24

Forty-two subjects; mean age, 8.0 months, and SD, 2.8 months.

latency data and after normalization of the amplitude data. The scaled latency difference for wave Pa was 3.6 times greater than that seen for wave V, (p<.0001) (Table 1). If scaling differences were not corrected, this comparison would be even more significant. Wave P0 (recorded on the 60-ms time base) was also less repeatable than wave V (recorded on the 10-ms time base) if no adjustment for time base scale was made (p<.0001). Wave P0 was more repeatable than wave V if an adjustment for scaling differences was made (p<.0011) (Table 1). The same pattern was observed for variance ratios; all differences were significant.

The wave V amplitude was two to three times more repeatable than the slopes of P0-Na, Na-Pa, and Pa-Nb (Table 2). Wave V differed by an average of 12%, whereas the MLR waveforms differed from 25% to 30%. The test-retest P0-Na amplitude difference was 1.98 times greater than the wave V amplitude difference (p<.0001), the Na-Pa amplitude difference was 2.13 times greater than the wave V amplitude difference (p<.0001), and the Pa-Nb amplitude difference was 2.37 times greater than the wave V amplitude difference (p<.0001).

Data Reliability. The reliability of the ABR (wave V) latency difference was found to be significantly greater (p < .0001) than those estimated for MLR (waves P0 and Pa) latency differences. There were no significant differences shown between the reliabilities of amplitude differences for the ABR and MLR (Table 5).

Latency and Amplitude Data. The mean latency and amplitude data for the group of subjects are presented in Table 4. As expected, latency values

TABLE 5. INTRASUBJECT RELIABILITY OF LATENCY AND AMPLITUDE MEASUREMENTS

Variance components (percent variation)	Wave Peak (Latency)			V Amplitude	Wave Slope (Amplitude)		
	V	P0	Pa		P0-Na	Na-Pa	Pa-Nb
Subject	0.184(67.7)	0.290(3.1)	8.45(22.3)	0.004(28.4)	0.007(31.2)	0.012(21.0)	0.000(0.0)
Ear/subject	0.067(23.4)	0.590(62.8)	15.96(42.2)	0.003(19.7)	0.003(12.0)	15.96(21.9)	0.025(43.0)
Test-retest	0.034(11.8)	0.321(34.1)	13.40(35.5)	0.007(51.9)	0.013(56.8)	13.40(57.1)	0.034(57.0)
Reliability	88.20	65.90	64.50	48.10	43.20	42.90	43.00
Z transformation*	1.38	0.79	0.77	0.53	0.46	0.46	0.46
Significance							
Wave V vs MLR		p<.0001	p<.0001		p<.13	p<.13	p<.13

*Standard deviation = $\sqrt{\frac{1}{n-3} + \frac{1}{n-3}}$ where n = 164.

TABLE 6. FILTERING PARAMETERS USED BY INVESTIGATORS TO EVALUATE HEARING IN YOUNG CHILDREN

Author	Band Pass (Hz)	Slope (dB/octave)
Bradford et al ¹³	250-3,200	6
Cornacchia et al ¹⁴	100-2,000	6
Dennis et al ¹⁵	250-1,600	
	100-3,000	12 or 24*
	150-3,000	12 [†]
Despland and Galambos ¹⁶	150-3,000	12 [†]
Goldstein et al ¹⁷	100-3,000	
Fawer et al ¹⁸	250-1,600	
Harris et al ¹⁹	250-3,200	
Hecox and Galambos ²⁰	80-3,000	
Kileny ²¹	150-3,000	12 [†]
Lary et al ²²	300-3,000	
Levi et al ²³	250-5,000	
Mendelson et al ²⁴	100-3,000	
Mjoen ²⁵	150-4,500	
Mochizuki et al ²⁶	80-1,200	
Mokotoff et al ²⁷	100-3,000	
Orlowski et al ²⁸	150-3,000	12 [†]
Paludetti et al ²⁹	250-3,000	
Rotteveel et al ³⁰	30-3,000	12
Schulman-Galambos and Galambos ³¹	150-1,500	12 [†]
Shimizu et al ¹	100-3,000	
Stockard et al ³²	100-3,000	
Zubick et al ³³	150-3,000	

* Authors used Pathfinder II by Nicolet.

† Assumed by fact that researchers used CA-1000 by Nicolet.

are slightly prolonged compared to those for normal subjects.

DISCUSSION

Experimental Design. Experimental studies comparing the efficacy of MLR and ABR in predicting auditory sensitivity have for the most part compared response threshold. The response with the lowest threshold is felt to be the more predictive of the true behavioral threshold. This experimental design has two drawbacks. First, it requires multiple recordings to find threshold. Second, it requires a subjective judgment to identify the presence or absence of a waveform. In our report, data were generated not only on the presence or absence of the waveform (Table 3), but also on the repeatability of the waveform. It is reasoned that waveforms that are more repeatable will be more identifiable and thus a more desirable parameter to measure. Repeatability of the waveforms elicited by a low intensity stimulus can be measured objectively by determining the test-retest differences among the various waveforms recorded from each subject. Except for the determination of complete absence of all response, the observer does not have to make a judgment about the presence or absence of individual waveforms. If a response (both ABR and MLR) was absent (subthreshold), neither the ABR nor the MLR was analyzed. The incorrect identification of data as subthreshold that actually contained a very poorly defined response will not bias the variability

comparisons in the remainder of the data. Any data that contained a well-defined waveform (either **ABR** or **MLR**) were analyzed. If only one waveform was identified (for example, ABR) and the other was absent (for example, MLR), then a best-guess measurement is made for the absent waveform. In a recording with no response, it would be possible for the observer to measure either latency or amplitude so that it equaled the expected value; however, it is very unlikely that both of these parameters could be made equal to that found in a true waveform.

The use of intrasubject test-retest differences in order to determine the identifiability of AEPs has not been reported previously in the literature. A decrease in waveform repeatability can be created by both subject factors (eg, level of arousal) and background noise. Subject factors are most important when recording the MLR (waves Na, Pa, and Pb). These factors were kept to a minimum by recording the ABR and MLR simultaneously on a dual time base, and by recording the waveform pairs in a relatively short period of time. Another major cause of decreased repeatability is background noise. It can be argued that an increase in variability will correspond to a decrease in signal-to-noise ratio. Variability also will hinder the identification of an absent response. In other words, it is easier to identify an absent response if each waveform in the pair has the same flat configuration, rather than an undulating baseline caused by background noise. Whether waveform variations are caused by subject factors or noise, they will cause the waveforms to be less repeatable and thus affect identification.

The two parameters that can be measured are latency and amplitude. The variability of these measurements can be determined by a number of methods. We chose to normalize all amplitude differences so that a 50 % reduction in waveform amplitude would have an equal effect on waveform variability regardless of the height of the complex. Latency measurements were scaled by dividing the latency difference in the waveform pairs by the length of the time base. This was done because the change in peak position apparent to the examiner is dependent upon the scale of the digitized waveform. Thus, a 5-ms latency change will have less of an observable effect on a 60-ms time base than on a 10-ms time base. As a control, wave P0 was scaled for both a 10- and a 60-ms time base. If no correction for the time base scale was done, the difference in variability between wave V of the ABR and wave Pa of the MLR would be more pronounced than shown in Table 1.

The variability for latency was much greater than that found for amplitude. This is to be expected, since the observer tended to search more for an amplitude deflection that approximated the expected waveform than for a particular position (latency).

TABLE 7. PARAMETERS FOR RECORDING OF MLR IN CHILDREN

Author	Filter Slope (dB/octave)	Band Pass (Hz)	Stimulus (dB)	Number, Age	Result
Wolf and Goldstein ⁴¹	48	25-75	30	5, 1-4 d	MLR recorded in all subjects
Wolf and Goldstein ⁴²	48	25-85	10, 30, 50	5, 1-4 d	MLR recorded in 3 of 5 subjects
McRandle et al ⁴³		20-125	55	20, 1-4 d	Composite MLR from all subjects recorded
Frye-Osier et al ⁴⁴	48	25-85	20, 40, 60	10, 1-3 d	MLR recorded in all subjects
Mendel et al ⁴⁶	24	25-85	20, 40, 60	18, 1-7 d	As a group had MLRs down to 20 dB
Mendelson and Salamy ⁴⁵	24	10-500*	30, 45	18, 1-8 mo	76% of MLRs present at 30 dB nHL
	24	25-175*			94% of MLRs present at 45 dB nHL
	24	20-175	60	15, premature	MLR can be recorded reliably in newborns, and waveforms in term infants are similar to those in adults
				15, term	
				15, 3-4 yr	
Suzuki et al ⁴⁷	Digital	HP 20	60	26, 1-7 yr	83% had detectable Pa; none had detectable Ph
	Digital	HP 30	60	26, 1-7 yr	<40% had detectable Pa; none had detectable Pb
Engel ³⁸			72	24, 0-5 d	MLRs in only 8 of 24 newborns
Okitsu ³⁷	18	30-300	30, 40, 50	20, 0.3-3.3 yr	Pa in 29% at 30 dB nHL (sleeping); Pa in 36% at 40 dB nHL (sleeping)
	6	20-300	50	20, 0.3-3.3 yr	No significant difference from the 30-300 Hz, 18 dB/octave condition
Hirabayashi ⁴⁰		0.5-3,000	20, 40, 60	37, < 2-7 yr	Pa in infants and younger children very unstable
Rotteveel et al ³⁰	12	5-250	70	25, birth	Pa and Nb "hardly recognizable"; Pa and Nb identified in group averages
				25, 3 mo	

HP - high pass.

* Cascading filters.

Filtering Parameters and Stimulus Intensity Level.

The band pass filter used to record the MLR in this study approximates that used by many laboratories. The filtering for the ABR (15 to 3,000 Hz), however, differs from that used in most clinical trials (Table 6).^{1,13-33} By setting the high pass (HP) filter to 15 Hz (instead of 100 to 150 Hz), phase shift distortion of the waveform is minimized and response amplitude will be larger.^{8,34} The use of minimal HP filtering has been advocated by researchers,³⁵ but has not found widespread clinical use. In our study, the use of an open filter setting for the ABR resulted in the recording of both wave V and the slow component (PO) on the 10-ms timebase.

Although HP analog filtration of the ABR (100 to 150 Hz) causes phase shift distortion,³⁶ it also eliminates muscle artifact and thus may be beneficial in the adult subject. In a sedated or sleeping young child, however, muscle artifact is not a major factor. No child (less than 13 months of age) evaluated in our protocol (using a band pass of 15 to 3,000 Hz) was sedated. In only one of the 48 children did we have to suspend testing in one ear because the child awoke. It is doubtful that using an HP filter of 150 Hz in this child would have allowed the recording of a response, since once the subject awoke the major concern was not muscle artifact, but preserving the electrodes. In an awake cooperative child in whom muscle artifact is a problem, however, HP filtration may be beneficial.

It should be remembered that the lowest discernible frequency when recording with a 10-ms time base is 100 Hz (1/time base). Frequencies below this value will tend to induce a baseline shift, since their

wavelengths are longer than the recording time base. Baseline correction can be used to eliminate this shift. Thus, even though the same analog filtering was used on the two time bases in our study, activity below 100 Hz will not be recorded as well on the 10-ms time base as on the 60-ms time base. The major effect that HP filters have on the ABR is one of phase shift distortion. Filters phase-shift frequencies that they pass. Thus, to avoid undesirable phase shift distortions, the cut-off frequency of the filter should be several octaves below the major frequency of the response.

The click intensity level in our screening protocol was set at 30 dB nHL. Only 5% of the ears (four of 86) that did not have an AEP response at 30 dB nHL had one at 40 dB nHL. This is similar to the 6% value found by Alberti et al² in follow-up AEP testing.

Analysis of Test-Retest Repeatability Data.

Researchers are divided on whether ABR or MLR is best for the evaluation of hearing of newborns and young children. Many researchers have found the MLR to be recorded inconsistently in this population,³⁷⁻⁴⁰ while others advocate its use.⁴¹⁻⁴⁶ Musiek et al⁶ and Suzuki et al⁶ felt that the differences in the various research results may be due to the filter slopes used to record data. They observed that laboratories that reliably recorded the MLR used steeply sloping filters (> =24 dB/octave) and those that did not reliably record the MLR used gradually sloping filters (< = 6 dB/octave). Scherg⁴⁸ and Suzuki et al⁴⁹ demonstrated that steeply sloping filters will phase-shift the response with a resultant decrease in amplitude wave P0⁴⁹ and an augmentation of waves

Nb and Pb.^{48,49} Kavanagh and Domico⁸ also recorded this effect and noted that although the MLR was augmented, the intersubject variability of normative values also increased. Thus, the augmentation caused by phase shifting may not be desirable. While there is agreement that wave Pb is not recorded reliably with gradually sloping filters in young children, there is much confusion regarding the recordability of wave Pa. Suzuki et al,⁴⁷ using 60-dB stimuli, found that wave Pa was recorded in 83% of children 1 to 7 years of age. Hirabayash⁴⁰ describes wave Pa to be very unstable in infants and young children; and Okitsu³⁷ recorded wave Pa in only 29% of sleeping children 0.3 to 3.3 years of age who were presented with a 30-dB click. Some of the differences in these results may be explained by the high test-retest variability of the MLR and the differences in criteria used by observers to judge the presence or absence of a response.

High pass filtering is also an important variable, since HP filters above 20 Hz (digital filter) have been shown to reduce wave Pa's detectability in children to below 40%.^{47,49} Thus, authors using HP filters with cutoff frequencies above 20 to 30 Hz may be eliminating the biologic response. Table 7^{30,37,38,40-47} summarizes various reports pertaining to the use of MLR in the evaluation of hearing in young children.

The phase shifting by our filters could have created an augmented wave Pa. This would tend to

bias the study toward showing a more repeatable MLR. Nevertheless, our data still showed wave Pa to be less repeatable and thus harder to identify than wave V of the ABR.

The age of the child is also an important variable, because the ABR rapidly changes up to 1 month (post-full term).⁵ It then enters a phase in which it slowly approaches normal adult values over the next 1.5 to 4 years. Our children were all in this second phase of maturation. Thus, the variability of the evoked response may be even more profound in the newborn infant (≤ 1 month), whose auditory system is undergoing rapid maturation. This was demonstrated by Rotteveel et al,³⁰ who studied longitudinally the MLR for 25 subjects at birth and at 3 months of age. They found that waves Pa and Nb were "hardly recognizable" in term infants but were "seen" at 3 months of age.

Analysis of Variance: Variability due to Ears and Patients. Waves P0 and Pa also were found to have a greater variation between ears than between subjects (Table 5). This is an unexpected finding, since stimulus and subject parameters were the same in all test conditions. The testing order of the ears was not randomized. The two left data sets usually were collected first. This gives rise to the possibility of central adaption or habituation with repeated stimulation. Another possibility is a decrease in the myogenic contribution as the subject relaxes. This present study was not designed to investigate these phenomena, and further research in this area is needed.

ACKNOWLEDGMENT - The authors thank E. A. Tolley, PhD, Department of Biostatistics and Epidemiology, University of Tennessee, Memphis, for her help with the statistical analysis of the data.

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