Recording Auditory Steady-State Responses in Young Infants

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Objectives: **This study examined the auditory steady-state responses evoked by amplitude-modulated (AM), mixed-modulated (MM), exponentially-modulated (AM^2), and frequency-modulated (FM) tones in 50 newborn infants (within 3 days of birth) and in 20 older infants (within 3–15 wk of birth). Our hypothesis was that MM and AM^2 tonal stimuli would evoke larger responses than either the AM or FM tones, and that this increased size would make the responses more readily detectable.**

Design: **Multiple auditory steady-state responses were recorded to four tonal stimuli presented simultaneously to each ear at 50 dB SPL. The carrier frequencies of the stimuli were 500, 1000, 2000, and 4000 Hz and the modulation rates were between 78 and 95 Hz. Recordings lasting 12 minutes were obtained for each of the three types of modulation: 100% AM, MM (100% AM and 20% FM) and AM^2. In six infants, responses to 20% FM were also recorded.**

Results: **In newborn infants, MM and AM^2 stimuli produced responses that were on average 15% larger than AM stimuli. For AM, MM, and AM^2 stimuli, the percentage of significant responses was 67%, 73%, 76%, respectively. Responses to FM stimuli were clearly evident in newborn infants and were about half the amplitude of the AM responses. Responses recorded in the older infants were 17% larger when evoked by MM and AM^2 stimuli, rather than AM stimuli. Responses in the older infants were, on average, 32% larger and showed a higher incidence of significant responses than for infants in the first 3 days of life. For AM, MM, and AM^2 stimuli, the percentage of significant responses was 82%, 82%, 84%, respectively. In both newborn and older infants, the overall percentage of significant responses was decreased by the 500 Hz results, which showed lower amplitudes and were less frequently detected than responses evoked by other frequencies.**

Conclusions: **The responses to MM and AM^2 tones were larger than those evoked by AM tones. Using these stimuli will increase the reliability and efficiency of evoked potential audiometry in infancy. Responses at 50 dB SPL are more easily detected at 3–15 wk of age than in the first few days after birth. Comprehensive frequency-specific testing of hearing using steady-state responses will likely be more accurate if postponed until after the immediate neonatal period.**

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Infant hearing loss should be identified and treated early to prevent delays in the development of speech and language (Rach, Zielhuis & van den Broek, 1988; Yoshinaga-Itano, Sedey, Coulter & Mehl, 1998). Hearing loss is identified using either the click-evoked auditory brain stem response (ABR) or otoacoustic emissions (OAE) as screening procedures (Norton, Gorga, Widen, Folsom, Sininger, Cone-Wesson, et al., 2000). Estimating the audiogram by obtaining frequency-specific auditory thresholds is essential for proper treatment, since the amplification of hearing aids should be adjusted across frequencies to compensate for hearing deficits that vary with frequency. Audiometric thresholds can be obtained using behavioral testing in most infants older than 6 mo (Widen & O'Grady, 2002). Before this age and in older infants who cannot be tested behaviorally, tone-evoked ABR tests are recommended as a way to estimate the audiogram (Stapells, 2002). However, these tests are time consuming. Auditory steady-state responses might estimate the audiogram more efficiently than tone-ABRs, although there are less normative and clinical data available for these responses (Picton, John, Dimitrijevic & Purcell, 2003; Rance & Rickards, 2002) than for tone-ABRs (Stapells, 2000; Stapells, Gravel & Martin, 1995).

Human auditory steady-state responses (ASSRs) evoked by amplitude-modulated (AM) tones with modulation frequencies between 70 and 110 Hz have been used to assess hearing in infants using either single stimuli (Rickards, Tan, Cohen, Wilson, Drew & Clark, 1994) or multiple simultaneous stimuli (Lins, Picton, Boucher, Durieux-Smith, Champagne, Moran, et al., 1996). However, the reported detectability of the responses has varied across the different studies (see Table 1). This variability was due to factors such as to the age of the infants tested, the intensity and frequency of the stimuli, the acoustic noise levels in the recording environment, and the duration of the recording. Most of the studies have

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TABLE 1. Auditory steady state responses in infants: thresholds and response-detectability

Study	Age	Time	Environment*	Stimulus	Frequency	Thresholds†	Response-Detectability
Rickards et al. 1994	1–7 day	0.5–3.5 min	NN	single MM	500	41	43 dB HL-54%; 58 dB HL-95%
					1500	24	28 dB HL-66%; 43 dB HL-98%
					4000	35	38 dB HL-60%; 53 dB HL-95%
Levi et al. 1995	1 mo	100 sec	SA	single AM	500	36	combined: 30 dB HL-50%
					1000	42	
					2000	34	
Lins et al. 1996	1–10 mo	3–13 min	SA	multiple AM	500	33	38 dB HL-50%; 48 dB HL-90%
					1000	22	43 dB HL-55%; 43 dB HL-100%
					2000	17	21 dB HL-70%; 41 dB HL-95%
					4000	21	20 dB HL-50%; 40 dB HL-100%
	3–11 mo		NSA	multiple AM	500	41	NA
					1000	44	
					2000	35	
					4000	26	
Savio et al. 2001	0–1 mo	3–8 min	NSA	multiple AM	500	57	61 dB HL-75%; 81 dB HL-90%
					1000	55	53 dB HL-65%; 73 dB HL-90%
					2000	51	52 dB HL-50%; 72 dB HL-95%
					4000	48	45 dB HL-60%; 65 dB HL-95%
	7–12 mo				500	46	61 dB HL-90%; 81 dB HL-100%
					1000	44	53 dB HL-90%; 73 dB HL-100%
					2000	37	52 dB HL-85%; 72 dB HL-100%
					4000	33	45 dB HL-100%; 65 dB HL-100%
Rance and Rickards 2002	1–8 mo	20–90 sec	SA	single MM	500	50	NA
					1000	45	
					2000	35	
					4000	30	
Cone Wesson, Parker et al., 2002	1–120 days	20–90 sec	NN	single MM	500	NA	56 dB HL-65%; 76 dB HL-84%
					1000		52 dB HL-78%; 72 dB HL-82%
					2000		46 dB HL-85%; 66 dB HL-100%
					4000		55 dB HL-90%; 75 dB HL-93%
Cone Wesson, Rickards et al., 2002	0–79 mo (mainly <12 mo)	20–90 sec	SA	single MM	500	50	NA
					1000	34	
					2000	26	
					4000	39	
Present Study	0–3 days	12 min	NN	multiple AM^2	500	NA	46 dB HL-51%
					1000		50 dB HL-72%
					2000		47 dB HL-98%
					4000		44 dB HL-82%
	3–15 wks		SA		500	NA	46 dB HL-55%
					1000		50 dB HL-86%
					2000		47 dB HL-100%
					4000		44 dB HL-96%

** Environment of test. The Savio data and the second set of data from the Lins study were obtained without any sound attenuation in the presence of loud air-conditioning noise, where normal adult thresholds were elevated to about 30 dB HL.*

† Thresholds are in dB HL. Intensities reported in SPL were converted to HL using information about the earphones provided in the papers. Due to variability in the acoustic characteristics of the infant ear canal, the results are not accurate by more than ±5 dB. The thresholds for the Levi study are correct in this table. Previously quoted results (in Picton et al., 2003) were in error (caused by a mistake in reading the dotted and dashed lines in their figure). The thresholds for the Rance and Rickards data were estimated from their Figure 1 for those infants with behavioral thresholds less than 30 dB HL.

NN = neonatal nursery; SA = sound-attenuated chamber; NSA = no sound attenuation; MM = mixed-modulated; AM = amplitude-modulated; AM^2 = exponentially modulated; NA = data not available.

combined findings across a broad range of ages. However, Savio, Cardenas, Perez-Abalo, Gonzalez, and Valdes (2001) have clearly shown that the response becomes more easily detectable with increasing age. Response detection varies with the frequency of the stimulus, with the 2 kHz stimuli usually producing more reliable steady-state response and giving lower thresholds. Since the background electrical noise in the recording decreases with averaging, distinguishing a response from the background noise becomes more reliable as the testing duration is increased (Luts & Wouters, 2004; Luts, Desloovere, Kumar, Vandermeersch & Wouters, 2004; Picton, John, Purcell and Plourde, 2003). This may explain the differences between the thresholds of Rance and Rickards (2002) and those of Lins et al. (1996), who used longer recording durations and reported lower thresholds.

Lins et al. (1996) found that, on average, the auditory steady-state responses in the first few months of life are between one-third and one-half the size of the adult response and the physiological threshold-estimates are 10–15 dB higher. Since the speed and accuracy at which frequency-specific thresholds can be estimated using auditory steady-state responses depends on the size of these responses, increasing response amplitude allows their recognition to occur more rapidly and accurately. Cohen, Richards, and Clark (1991) originally showed that using simultaneous AM and frequency modulation (FM), or "mixed-modulation" (MM), produced larger responses than AM stimuli. The mechanism by which MM produces larger responses is the addition of the responses which are evoked independently by the AM and FM stimuli (John, Dimitrijevic, van Roon & Picton, 2001). This type of response summation also occurs in infants tested prior to 3 mo of age (Brennan, Stevens & Brown, Reference Note 1). We have recently shown that stimuli with exponential modulation envelopes (e.g., AM^2 using an amplitude-envelope determined by the square of the sine function) also evoke larger responses than AM tones, likely due to the steeper slopes of the envelopes (John, Dimitrijevic & Picton, 2002). The present study compares the response amplitudes for AM, MM, and AM^2 stimuli in infants. In a subset of infants, we also evaluated the responses to FM stimuli to see if responses to pure FM stimuli could be recorded in the first 3 days of birth, and also to determine whether the MM response could be predicted from the sum of the AM and FM responses.

Reducing the background electrical noise levels (e.g., due to transient movements and electromyogenic potentials) in the recording will also improve detection. Since longer recording times will increase the signal-to-noise ratio (SNR) of the recordings, we used testing durations of 12 minutes rather than the shorter durations used in most other studies (Table 1). Further, we used weighted averaging rather than simple averaging to decrease the effect of trials with higher noise levels (John, Dimitrijevic & Picton, 2001).

METHODS

Subjects

This study involved 70 full-term infants at the Foothills Medical Centre in Calgary. All infants had normal 1 and 5 min APGAR scores (7 or above). Parents were approached about the study in the first 48 hr after their infant's birth. Parents were not paid for their participation, and inclusion in the study was completely voluntary. Approximately one in five families decided to participate in the study.

There were two groups of infants. A set of 50 full-term newborn infants (23 female) made up the "newborn" group. Their gestational ages ranged between 37 and 42 wk (mean, 39.7 wk). All subjects were tested within 74 hr of birth (mean, 42 hr; standard deviation [SD], 14 hr). The data from four subjects were not analyzed because of high noise levels (see Data Analysis section), leaving data from 46 subjects for our analysis. Six of these infants were tested binaurally, and of the 40 remaining infants, 20 were tested using the left ear and 20 using the right ear. These infants were tested in a small, carpeted, quiet room on the ward.

A second group of 20 infants (10 female; mean gestational age, 39.3 wk, range, 36–42 wk), termed the "older" group, were tested between 3 and 15 wk after birth (mean, 7.0 wk; SD, 3.3 wk). Two of these infants were tested binaurally and the remaining 18 infants were tested monaurally (eight with right ear). Infants from this second group were tested in a sound attenuated testing chamber.

All subjects were first screened for normal hearing using the Bio-logic Navigator-Pro running A-Baer software (Bio-Logic System Corp., Mundelein, IL), which presents 35 dB normal-hearing level clicks at a rate of 37.1 Hz, and automatically evaluates the evoked potentials. During the recordings, the subjects were either held by a parent or placed in an isolette. Most infants slept during the recordings (about 60–75 minutes, including electrode preparation and A-Baer screening).

Stimuli

The stimuli were constructed as previously described (John & Picton, 2000a; Picton, John, Dimitrijevic & Purcell, 2003). Figure 1 shows the time waveforms and frequency spectra of the stimuli used in this study. As can be seen from the first row of the figure, AM tones have excellent acoustic frequency-specificity since the spectral power only occurs at the carrier frequency ($\mathbf{f_c}$) and at two side-bands $\mathbf{f_c} \pm \mathbf{f_m}$. The second row of Figure 1 shows an MM stimulus with AM of 100% and FM of 20%. The highest frequency of the FM is aligned with the largest amplitude of the AM, since this evokes larger responses in both infants and adults than does MM stimuli created using other relative phases (Cohen et al., 1991; John, Dimitrijevic, van Roon & Picton, 2001; Brennan et al., Reference Note 1). This causes a slight shift of the acoustic energy to higher frequencies (i.e., the power in the spectrum is skewed a little to the right, rather than being symmetrical, around $\mathbf{f_c}$). The third row shows an exponential stimulus, where the modulation function has been squared prior to its multiplication with the carrier frequency (John, Dimitrijevic & Picton, 2002). For simplicity we call this AM^2 even though only the modulation envelope follows a square function, rather than the entire signal being formed by squaring the AM signal. The final row of the figure shows a tone that is frequency modulated at 20% (i.e.,

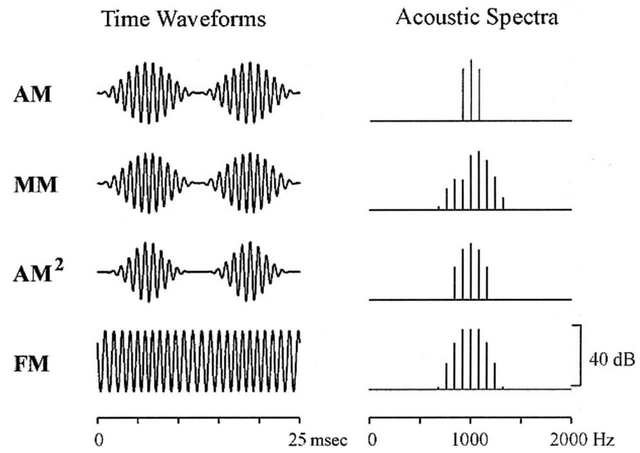

Fig. 1. Steady-State Stimuli. The left column of the figure shows examples of the different types of stimuli used in this study. The right column shows the spectra for these stimuli plotted on a logarithmic scale. For all stimuli the modulation rate is 80 Hz and the carrier is a 1000 Hz tone. The first row is an amplitude-modulated (AM) stimulus modulated at 100%. The second row shows a mixed modulation (MM) stimulus, which is a combination of AM 100% and frequency-modulated (FM) 20%. The third row shows a stimulus AM with an exponential envelope with the exponent equal to 2. Compared with the AM stimulus, this AM^2 stimulus has (a) decreases in the stimulus rise- and decay-times; (b) increases in the rise and decay slopes; and c) increases in the periods of silence that occurs between the peaks of the modulation envelope. The last row shows an FM stimulus modulated at 20%.

±10%), which, like the AM tone, has spectra that include energy at the sidebands at $\mathbf{f_c \pm f_m}$, but which also includes low-intensity sidebands at $\mathbf{f_c \pm 2f_m}$ and $\mathbf{f_c \pm 3f_m}$.

Stimulus creation, data collection and response evaluation were all accomplished using the multiple auditory steady-state response (MASTER) technique (John, Lins, Boucher & Picton, 1998; Lins & Picton, 1995) and software (John & Picton, 2000a; see also www.mastersystem.ca) running on Bio-logic's Navigator-Pro System. The Navigator-Pro controlled the 24 kHz digital-to-analog conversion of the stimulus waveforms using 16-bit resolution. The acoustic stimuli were presented using Etymotic-ER-3 insert earphones (which are equivalent to Etymotic 3A, but are custom built to 300 Ohm for the Bio-logic instrumentation). Although the Navigator-Pro simultaneously presented four stimuli to each ear, each of the four AM carrier frequencies was separately calibrated, using a Bruel and Kjaer DB 0138 coupler, to the desired intensity measured in root-mean-square sound pressure level (RMS SPL). The combined stimulus was 5 dB more intense than the individual stimuli due to the constructive addition of the individual waveforms. The four individual modulated tones of the AM, FM, MM, and AM^2 stimuli were each calibrated to be 50 dB SPL, leading to a combined stimulus intensity of about 55 dB SPL.

The carrier frequencies were 500, 1000, 2000, and 4000 Hz for both ears. These carrier frequencies were modulated at frequencies between 78 and 95 Hz, with each carrier frequency associated with a unique modulation frequency (which was different for the two ears). Both carrier and modulation frequencies were adjusted to be integer submultiples of the epoch duration of 1.024 sec. The actual stimulus parameters are listed in Table 2. For the sake of simplicity, we shall refer to the modulation frequencies without decimal places. Although not necessary for the recordings, the modulation frequencies increased with increasing carrier frequency. This simplifies the visual analysis of the responses, since both modulation and carrier frequency increase from the left to right in the response spectra.

Steady-State Responses

Initial A-Baer screening data were collected with an electrode placed on the high forehead just below the hairline ("frontal") referenced to an electrode placed on the mastoid ipsilateral to the ear stimulated, with the contralateral mastoid serving as ground. Default filter (100–1500 Hz) and amplification settings were used for A-Baer screening.

Auditory steady-state responses were recorded from the same frontal electrode referred to an electrode placed at the midline on the posterior neck at the level of the ear, with the mastoid serving as ground. The electrencephalogram (EEG) was collected using a filter band-pass of 1 to 300 Hz (12 dB/octave)—a gain of 10,000 and a sampling rate of 1000 Hz—and was digitized with 16-bit resolution. Individual data epochs of 1024 points each (1.024 sec) were rejected if they contained any value which exceeded ±100 μV. Sixteen individual data epochs were collected and linked together into sweeps lasting 16.384 sec. As each sweep was completed it was added to a running average sweep, which was sub-

TABLE 2. Stimulus frequencies (Hz)

	Left Ear				Right Ear			
f_c	500	1000	2000	4000	500	1000	2000	4000
f_m	80.08	84.96	89.84	94.73	78.13	83.01	86.91	91.80

mitted to a Fast Fourier Transform. The resulting amplitude spectrum enabled steady-state responses to be measured in the frequency domain. For each experimental condition, 45 sweeps, or approximately 12 minutes of data, were collected. Weighted averaging of the data was performed to decrease the effects of transient increases in EEG-noise levels that did not exceed the artifact rejection levels (John, Dimitrijevic & Picton, 2001).

Three measurements were evaluated: the amplitudes and phases of the steady-state responses and the background EEG noise levels. The amplitude of the steady-state response to a given carrier frequency was measured as the amplitude of the signal at the frequency of modulation. The mean and circular SDs for the phase were calculated using circular statistics (Picton, Dimitrijevic, John, & van Roon, 2001; Zar, 1999). The amplitude of each response was compared with an EEG noise estimate comprised of the amplitudes in adjacent regions of the spectrum. More specifically, the RMS amplitudes of 60 frequencies above (i.e., 60 × 0.061 Hz, or about 3.7 Hz) and 60 frequencies below the response frequency, excluding frequency bins at which other modulation frequencies occurred, were used. The response amplitudes were compared with the EEG noise estimates using an F-ratio with 2 and 240 degrees of freedom (df) (John & Picton, 2000a). An overall noise-level estimate for each recording was also computed by averaging together the EEG noise-level estimates for each of the 4 stimuli presented to a test ear and multiplying this represents the 95% confidence limits of the noise. Any recording that contained a final overall noise-level estimate above 30 nanovolts (nV) was excluded from the analysis, since this represented the top 10% of noise levels for the population.

Experimental Design

All infants provided responses to AM, MM, and AM^2 stimuli. These experimental conditions occurred in random order across subjects. In six infants from the newborn group, eight stimuli were presented simultaneously, four to each ear. However, since it was difficult to keep infants asleep while maintaining both insert phones in place, the remaining 40 infants were tested monaurally. The ear tested was randomly determined by which side the infant slept on. Where time permitted, we also collected responses to FM tones in a subgroup of six newborn infants.

Data Analyses

Two data sets were evaluated using the amplitude data of the newborn group. The first analysis used data from all 46 subjects—624 responses (46 infants × 3 conditions × 4 responses with 6 binaural recordings having 8 responses). A second “selected” data set used a subset of 30 subjects in which the EEG noise levels were similar across the three types of stimuli; only subjects whose recordings within the three conditions had noise estimates within 50–200% of each other were included. For the older group, all data were included in their data set, since the noise levels of all recordings met this criteria.

In addition to evaluating differences in response amplitude, an analysis of EEG noise levels was also necessary to ensure that these were similar across the three stimulus conditions and across the two subject groups. Differences in the ability to detect response between the older and younger infants could have been due to differences in the response amplitudes or in the background EEG noise levels since both contribute to the SNR estimates used to evaluate the responses.

Comparisons were made between the amplitudes of the responses for both groups using a three-way analysis of variance (ANOVA; group × carrier frequency × stimulus type) with repeated measures on the latter two factors. Post hoc evaluations of the amplitudes were assessed using two-way repeated measures ANOVAs (stimulus type × carrier frequency) within each group of infants. Because only six newborn infants had binaural data, their responses for left and right ears were arithmetically averaged (disregarding phase) prior to the ANOVA. The noise estimates were analyzed similarly except that there was only one noise estimate for all responses and the ANOVAs did not have a carrier frequency factor. Any missing cells in the data matrix (for example, those rejected due to excessive EEG noise level), were handled by the statistical software that automatically reduced the degrees of freedom of the calculations. Greenhouse-Geisser corrections for the probability levels were used where appropriate. Post hoc comparisons relied on the Fisher Least Significant Difference test. Differences were considered significant at $p < 0.05$. The phase results were not evaluated beyond the means and circular standard deviations due to the different modulation rates in the stimuli presented to the two ears.

RESULTS

Noise Estimates

Figure 2 shows the distribution of background noise levels in the newborn group (all 50 subjects) for the three types of stimuli. In four infants (three male), the noise estimates for the AM, MM, and AM^2 recordings were all above 30 nV, and these subjects were excluded from further analysis. The ANOVA

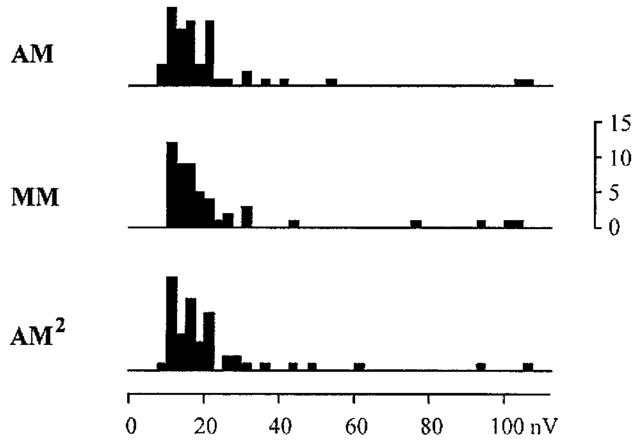

Fig. 2. Histograms showing the distribution of the overall noise levels (nV) across recordings collected during presentation of the three types stimuli to the newborn group of subjects (noise levels were measured at the end of the 12-minute recording). The 10% of recordings which contained noise levels over 30 nV were not used in the analysis. EEG noise levels of 14 nV or lower occurred in 50% of the recordings.

for the newborn group showed no effect of stimulus type ($F = 0.073$; df = 2,72; $p = 0.9$) with the average noise levels in the AM, MM, and AM^2 recordings being 13.7, 13.9, and 14.0 nV, respectively. The ANOVA for the older group also showed no effect of stimulus type ($F = 2.26$; df = 2,36; $p = 0.13$), with the average noise levels in the AM, MM, and AM^2 recordings being 11.9, 13.9, and 12.7 nV, respectively. The ANOVA comparing the noise levels between the newborn and the older group also failed to show any differences ($F = 0.9$; df = 2,108; $p = 0.4$), with the average values for the newborn and older groups being 13.9 and 13.0 nV, respectively. There was again no effect of stimulus type and no interaction between group and stimulus type.

Responses in Newborn Infants

The responses to MM and AM^2 stimuli were larger than those evoked by AM stimuli. Results for two newborn infants are shown in Figure 3. The infant on the right has greater EEG noise levels than the one on the left. In this infant, only the larger responses obtained with the MM and AM^2 stimuli allow the 500 Hz response to become significant. The grandmeans of the vector-averaged responses from all infants are shown separately for each ear in Figure 4.

The mean data for the newborn group are shown in Figure 5. The upper half of the figure shows the average amplitudes of the responses evoked by AM, MM, and AM^2 stimuli. The percentage plots in the lower half of the figure were based on the average

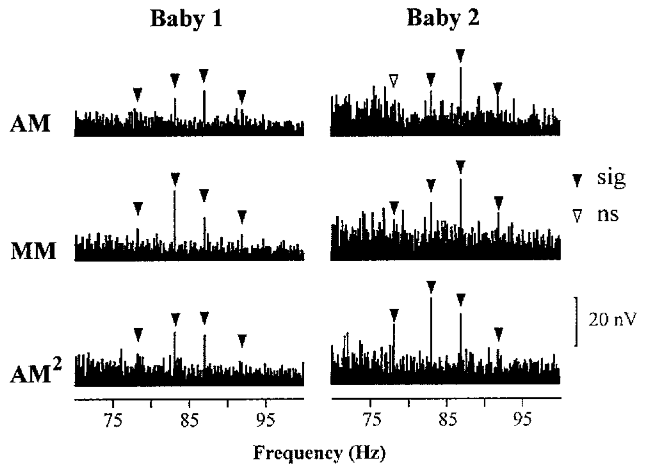

Fig. 3. Response to AM, MM, and AM^2 stimuli recorded from two newborn babies. For both babies the stimuli were presented to the right ear. The amplitudes are generally larger for the MM and AM^2 responses than for the AM responses. The noise levels for Baby 2 are higher and the 500 Hz response is not significantly different (ns) from the background noise for the AM response. All responses become significant (sig) in the MM and AM^2 responses.

data. In relation to the AM response, the average amplitude of the responses across all carrier frequencies increased by 13% and 16% for the MM and AM^2, respectively. An ANOVA of the amplitude data on the left side of the figure (with all cases) showed significant main effects for stimulus type ($F = 5.18$; df = 2,72; $p < 0.05$) and carrier frequency ($F = 11.6$; df = 3,108, $p < 0.001$). An ANOVA of the selected

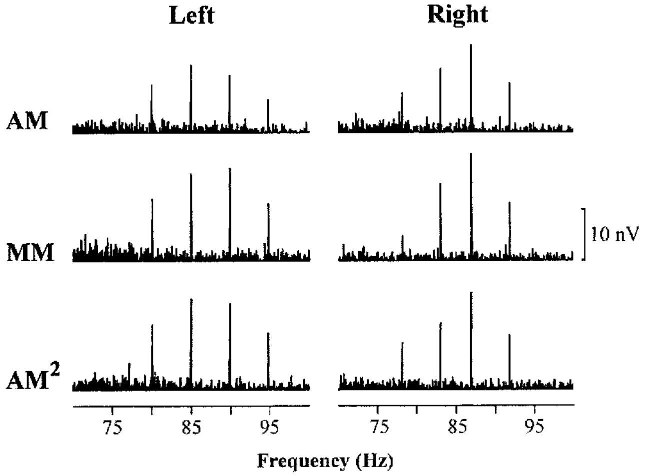

Fig. 4. Grandmean spectra for the responses to the AM, MM, and AM^2 stimuli. These plots show separate vector-averaged spectra for the subjects simulated in the left or right ear. The subjects who were stimulated binaurally were included in the average data, but the responses to the stimuli in the other ear were arbitrarily zeroed prior to averaging. The background EEG noise levels are very low because of the averaging across the 26 subjects.

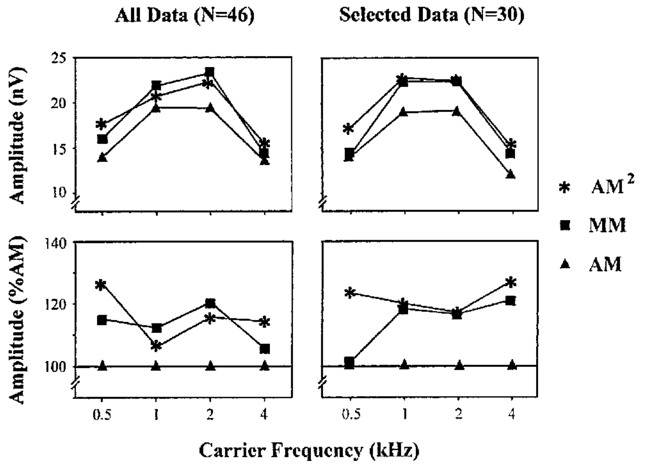

Fig. 5. Average amplitudes for the newborn group. This figure plots the arithmetic average of the amplitudes across the individual infants in the newborn group for the AM, MM, and AM^2 responses. The left side of the graph plots data for all 46 subjects. The right side shows data from 30 subjects where all three conditions had similar noise levels. The upper graphs plot the absolute amplitudes and the lower half of the figure displays these amplitudes as a percentage of the value for the AM responses. The values in this graph are higher than the values in the grandmean spectra plotted in Figure 4 because the phase variability across subjects attenuated the vector-averaged responses.

data (on the right side of Fig. 5) also showed significant main effects for stimulus type ($F = 10.04$; df = 2,58; $p < 0.001$) and carrier frequency ($F = 11.89$; df = 3,87, $p < 0.001$). Neither ANOVA showed any significant interactions between stimulus type and carrier frequency. Post hoc comparisons in both ANOVAs indicated that the MM and AM^2 responses were both statistically larger than the AM responses, with no statistically significant difference between the MM and AM^2 responses. However, for all types of stimuli, the intersubject amplitudes varied greatly, with the variance increasing as carrier frequency decreased. There was no significant difference in the variance of response amplitudes elicited by the three stimulus types (which were almost identical); results for the AM^2 responses are shown in Table 3.

As we have done previously in adults (John, Dimitrijevic & Picton, 2002), an analysis of the amplitude data was conducted for individual subjects to see how many individual responses increased when MM and AM^2 stimuli were used compared with when AM was used. Table 4 shows the number of responses that became significant using MM or AM^2 rather than AM stimuli. Additionally, comparisons between responses that were enhanced by using MM or AM^2 were evaluated by creating a matrix of ones and zeros for each stimulus type. In the case of the MM stimuli, for each subject, the responses to each the carrier frequencies was evaluated as 1 if the response was greater using MM than AM, and 0 if the reverse was true. A similar matrix was also made for the AM^2 compared with the AM data. The correlation between the two matrices was $r = 0.43$.

Although only the first harmonic responses are shown in Figures 3 and 4, second harmonic responses were also evident in the recordings. The second harmonics were larger for the AM^2 stimuli

TABLE 3. Variability of the response amplitudes

Measurement	500 Hz	1000 Hz	2000 Hz	4000 Hz
Mean	17.5	20.6	22.4	15.3
Standard Deviation	13.7	11.2	9.3	5.6
Coefficient of Variation	0.8	0.5	0.4	0.4
Minimum	1.0	4.0	5.0	3.0
Maximum	58.0	49.0	52.0	34.0

Data are for the exponentially modulated responses in the selected newborn group and are reported in nanovolts.

TABLE 4. Changes in amplitude of steady-state responses (%)

Stimulus (Hz)	AM < MM		AM > MM		AM < AM^2		AM > AM^2	
	Newborn	Older	Newborn	Older	Newborn	Older	Newborn	Older
500	53	50	42	44	52	50	43	44
1000	63	83*	28	11	61	67	30	33
2000	72	67	23	33	70	78*	27	17
4000	67	83*	30	11	70	78*	30	11
Overall	64	71*	31	25	64	68*	32	26

The incidences are percentages of the total number of responses that had similar levels of background noise, using 43 and 44 responses for the mixed-modulated (MM) and exponentially modulated (AM^2), respectively, and using 18 and 18 responses for the MM and AM^2, respectively, in the older group. For the amplitude-modulated (AM) and MM stimuli, 5% (4% for older) of the responses were of equal amplitude, whereas for the AM and AM^2 stimuli, 4% (6% for older) of the responses were equal for the two types of stimuli. McNemar test for significance of improvement due to stimulus type was computed using number of cases (although table expresses percentages). * = $P < 0.05$.

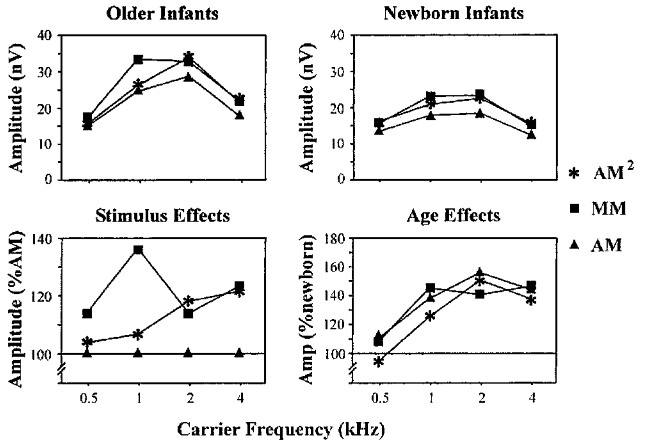

Fig. 6. Arithmetic average amplitudes for the older group. The left side of the figure shows the absolute and relative amplitudes for the older group. The graph in the upper right plots the newborn data from the upper left of Figure 5 (using a different scale) so that it may be readily compared with the data for the older group. The lower right graph shows the relative change in the amplitudes between the newborn group and the older group.

than for the AM stimuli. This was not due simply to the first harmonics being larger, but also because the second harmonics were larger relative to the first harmonic (9.5% versus 13.4% for AM and AM^2, respectively).

To determine whether the responses decreased in size over the recording period, we examined the size of the steady-state responses from the first and second halves of the recordings in 12 newborn infants who demonstrated relatively robust responses and low levels of background EEG noise. The amplitudes of all four stimuli were analyzed, both separately and in combination. There were no significant differences in the amplitudes, noise estimates, or signal-to-noise ratios between the 0–6 minutes and 6–12 minutes of the recording. The average response amplitude measured in the second half was slightly but not significantly greater than in the first half (26 nV compared with 25 nV).

Responses in Older Infants

The grandmean data for the group of older infants are shown in the upper left of Figure 6. The ANOVA on these data showed main effects of stimulus-type ($F = 7.99$; df = 2,36; $p < 0.01$) and carrier frequency ($F = 13.98$; df = 3,54; $p < 0.001$). Post hoc testing showed that the responses to MM and AM^2 stimuli were both larger than those evoked by AM stimuli, and that the midfrequency responses were larger than the 500 or 4000 Hz responses. A just-significant interaction between carrier frequency and stimulus type ($F = 2.6$; df = 6,108, $p < 0.05$) was due to the particularly large response at 1000 Hz for the MM stimulus. The lower left of Figure 6 shows the percent increase of the MM and AM^2 responses compared with the AM responses. The average response amplitude across all carrier frequencies increased by 22% and 13% for the MM and AM^2, respectively.

The amplitudes of the responses in the older group were larger than those recorded in the newborn group. The data from the newborn group are replotted for comparison, using a similar scale for amplitude of the response, in the upper right of Figure 6. The lower right of Figure 6 shows the percent change between the newborn and the older group. The overall three-way ANOVA showed a significant between-group effect with larger amplitudes in the older group ($F = 367.3$; df = 1,18; $p < 0.001$). There were no interactions of stimulus type with the group factor. However, there was a significant interaction of the carrier frequency with the group factor ($F = 3.2$; df = 2, 108; $p < 0.05$) caused by the group effect being smaller at 500 Hz than at the other frequencies, as is evident in the top row of Figure 6. Post hoc *t*-tests indicated the difference between older and younger infants was not significant at 500 Hz, but was significant at 1000, 2000, and 4000 Hz ($p < 0.01$).

Incidence of Significant Responses

The incidence of responses deemed significantly different from the residual background noise is shown in Table 5. These incidence values followed the same pattern as the amplitudes. Simple Chi-square tests were used to compare incidences using data combined across the two subgroups of the data. The incidence of significant responses was lower at 500 Hz than at the other three carrier frequencies (Chi-square = 93.5; df = 1; $p < 0.001$), and was higher for the older group of infants than for the newborns (Chi-square = 10.5; df = 1; $p < 0.01$). The incidence of significant responses was larger for the MM and AM^2 responses than the AM responses, but this did not reach statistical significance (Chi-square = 2.93; df = 1; $0.05 < p < 0.10$).

Phase

The effects of stimulus type on the phases of the steady-state responses for the newborn group are shown in Table 6. The onset phase generally decreased (and the phase delay increased) for the MM and AM^2 stimuli compared with the AM stimuli.

FM Responses

Figure 7 shows the average responses for the AM, FM, and MM stimuli for six newborn infants. The

TABLE 5. Incidence of significant steady-state responses (%)

Stimulus (Hz)	AM		MM		AM^2	
	Newborn	Older	Newborn	Older	Newborn	Older
500	45	52	56	50	51	55
1000	84	91	82	96	72	86
2000	80	95	92	100	98	100
4000	61	91	65	82	82	96
Overall	67	82	73	82	76	84

The incidences are expressed as percentages of the total number of responses within each group that had background noise levels under 30 nV. The newborn group contained 49 responses (37 monaural + 6 binaural) for each of the 500, 1000, 2000, and 4000 Hz stimuli. The older group contained 22 responses (18 monaural + 2 binaural). The incidence of significance of the 500 Hz response was considerably lower than the other responses.
AM = amplitude-modulated; MM = mixed-modulated; AM^2 = exponentially modulated.

stimuli were binaural in one, right only for three, and left only for two. Of the seven total responses for each frequency, the number of significant responses evoked by the FM stimuli were three, seven, five, and three for the 500, 1000, 2000, and 4000 Hz tones, respectively. The number of FM responses that were significant was 18 (64%), which was only slightly less than the 22 (79%) significant responses for the AM responses of that group. We compared the MM response to what would have occurred if the AM and FM components of the response were completely independent and additive ("predicted" data in the figure). The actual MM amplitudes were, on average, 84% of the predicted amplitudes.

DISCUSSION

Effects of Stimulus Type

The results clearly show that MM and AM^2 stimuli increase response amplitudes in infants compared with AM stimuli of the same carrier frequency and modulation rate. Significant enhancements were found for both stimuli. The average increases found in this paper were 13% (MM) and 16% (AM^2) in the newborn infants (all data) and 22% (MM) and 13% (AM^2) for the older group. These values are slightly less than the increases of 20% found using MM stimuli (John, Dimitrijevic, van Roon & Picton, 2001) and 21% found using AM^2 stimuli (John, Dimitrijevic & Picton, 2002) in adults.

The increase in the amplitude of the responses should shorten the time needed to recognize a signal that is significantly different from the background EEG noise levels of the recording. If we assume that the noise levels are constant, an increase in amplitude means that the time required to reach the same SNR changes by $1/X^2$, where X is the ratio of the amplitudes. This calculation derives from the principle that averaging decreases the noise levels according to square root rule. Increases in amplitude of about 13–22% translates into requiring only about 75% of the time needed to reach an equivalent signal-to-noise level.

Using MM or AM^2 rather than AM may slightly decrease the frequency specificity of the response since the spectra for the MM and AM^2 spread more widely than the spectrum of the AM tone. However, this increased acoustic spread contains relatively little energy and the overall frequency specificity of the stimulus is likely within the band-pass of the responding system, as has been determined using AM stimuli in derived-band masking studies (Herdman, Picton & Stapells, 2002).

Sturzebecher, Cebulla, and Pschirrer (2001) have described a different type of stimulus ("AM2FM2") that can increase the amplitude of the response without greatly altering its frequency-specificity. This stimulus increases the SNR by 27%, an effect that is similar to that obtained with the exponential envelopes.

We used MM stimuli with the relative phases of the AM and FM adjusted so that the maximum

TABLE 6. Phase values for AM, MM, and AM^2 responses

Carrier (Hz)	Modulation		AM		MM		AM^2	
	L	R	L	R	L	R	L	R
500	80	78	207 ± 27	255 ± 58	181 ± 44	278 ± 69	196 ± 36	248 ± 35
1000	85	83	146 ± 38	178 ± 36	120 ± 40	160 ± 35	135 ± 32	170 ± 39
2000	90	87	89 ± 42	148 ± 31	85 ± 25	145 ± 27	78 ± 38	137 ± 36
4000	95	92	8 ± 51	89 ± 45	9 ± 14	73 ± 25	11 ± 41	55 ± 37

Mean onset phase values (and circular standard deviations) in degrees for three types of stimuli for left (L) and right (R) ears. The phase delay could be obtained by subtracting these values from 360.
AM = amplitude-modulated; MM = mixed-modulated; AM^2 = exponentially modulated.

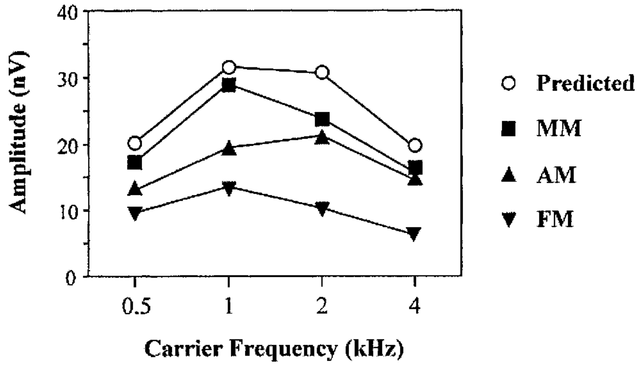

Fig. 7. Grandmean data for the AM, FM, and MM responses in six newborn subjects. The "predicted" data represent what would have occurred if the responses the AM and FM were vector averaged. The actual MM data is a little smaller than this predicted value.

frequency occurred at the same time as the maximum amplitude (Cohen et al., 1991). This is similar to the relative phase that creates the largest combined response in both adults (John, Dimitrijevic, van Roon & Picton, 2001) and young infants (Brennan et al., Reference Note 1). The AM and FM components of the response likely evoke independent responses that add together with only a small loss in amplitude (John, Dimitrijevic, van Roon & Picton, 2001). The results in newborn infants (Fig. 7) are similar to those found in adults, with the MM response being 84% of the vector sum of the AM and FM responses. The size of the AM responses compared with the FM responses, with respect to each carrier, are similar to adults, suggesting that these ratios change little with maturation.

AM^2 stimuli are easier to use than MM stimuli since there does not need to be any adjustment of the relative phase and there is no worry that in certain subjects the optimum relative phases of the AM and FM components may differ from normal values. Importantly, AM^2 stimuli have spectra with slightly better acoustic frequency specificity than MM stimuli created with AM of 100% and FM of 20% (Fig. 1). The larger second harmonics in the AM^2 response may also be helpful when detection of responses are based on algorithms that use both first and second harmonic responses (Cohen et al., 1991; Sturzebecher, Cebulla & Neumann, 2003).

The significant increase in amplitudes reported in this paper did not result in significant increases in the number of significant responses when Table 5 was submitted to a Chi-square analysis. In part, this is because the main increases in amplitude occur for the 1000 and 2000 Hz responses, which are already large enough to become significant. For example, the 2000 Hz response, which increased for both younger and older subjects and increased from 80 to 92% (or 98% for AM^2) in the younger subjects, only increased from 95% to 100% in the older population because of a ceiling effect. Alternatively, the more modest gains at 500 and 4000 Hz apparently were not large enough to generally increase the chance of the response becoming significant because the amplitude was relatively low to start with. Further, although the average response amplitude increased, there will be intersubject variability in terms of the increases that the MM and AM^2 stimuli produce.

Individual Effects

Although both of the approaches that we used to examine individual results included variance due to the state of the subject and background EEG noise levels, they provide a general approximation of the effects of stimulus type. An analysis of the number of individual responses that increased in amplitude across the three stimulus types indicated that 64% (MM) and 62% (AM^2) of responses showed increase in response amplitude, compared with those evoked by AM stimuli. This result is similar to the proportion of improvements elicited by exponential envelopes (61%) found in adults at a similar intensity level (John, Dimitrijevic & Picton, 2002).

The correlation between the enhancements produced by the MM and the AM^2 was relatively low at $r = 0.43$. This indicates that AM responses that were enhanced by using MM were not necessarily increased by using AM^2, and vice versa. It may therefore be useful to use both MM and AM^2 in the same stimulus. Responses might then be independently enhanced by both mechanisms, leading to a larger response than either alone. Furthermore, since the two types of modulation may act to enhance responses in different individuals, the proportion of increased responses may be larger across the population. Additionally, whereas the MM stimuli tended to preferentially increase the 1000 and 2000 Hz responses, the exponential stimuli enhanced the lower and higher frequencies (e.g., the left side of Fig. 4). The MASTER instrument marketed by Biologic Systems Corp. can present MM stimuli with exponential modulation envelopes. Formal studies should be carried out to evaluate the effectiveness of these stimuli. At the physiological level, the enhancements obtained by using MM stimuli are likely due to different mechanisms (i.e., the addition of AM and FM responses) than the enhancements produced by using exponential envelopes (e.g., increases in the phase synchrony of the responses).

Incidence of Significant Responses

The incidence of significant responses was lower than we had anticipated. On the basis of tone-ABR results in neonates (Sininger, Abdala & Cone-Wesson, 1997), we had believed that the 50 dB SPL stimuli would be 10–20 dB above the threshold intensity required for detecting the ASSR. Of course, we believed that this would only be true if the EEG noise levels were low and if we averaged the data for a reasonable length of time. The noise levels in the recording after the elimination of several outliers above 30 nV were only slightly higher than the levels we find in adults. The 12-minute recording duration and the use of weighted averaging reduced the noise levels to 10–20 nV. The main obstacle, therefore, was not the level of background noise but rather the low amplitude of the neonates' responses. The average amplitude of the AM^2 response at about 50 dB SPL in an adult is about 35 nV (John, Dimitrijevic & Picton, 2002), whereas the average amplitude is about one-half this value in the newborn infants (Fig. 5). In clinical situations, testing is sometimes halted after the ASSRs reach significance. In this study, we relied on a fixed 12-minute period. In the case of repeated testing, the criterion value for reaching significance should be increased to account for the number of tests. Because the infant ASSR responses are so small, this would likely lead to an even lower percentage of significant responses than are reported here. Accordingly, in clinical environments, either fixed testing durations should be used or, when using a "stop when significant" rule, a criterion should be used such as "the response must stay significant for a specified number of sweeps" rather than increasing the probability criteria.

The incidence of significant responses rose substantially when the infants were tested at the age of 1–3 mo rather than within 3 days of birth. There were no differences in the EEG noise levels of the recordings of these two groups, but the responses became significantly larger in the older infants. This increased amplitude could be attributed to the fact that the older infants were tested in a sound-attenuated chamber rather than in a quiet room on the nursing unit. However, the change in the acoustic environment was probably not the main factor, particularly since the stimuli were presented using insert phones. The maturation of the auditory system in the first few months of life was probably a main cause of the larger responses in the older infants.

The amplitude of the ASSR was lower at 500 Hz than at the higher frequencies. Rance et al. (1995) suggest that this might be explained by poorer neural synchronization. Another factor might be the decreased effective stimulus intensity reaching the infant's inner ear at 500 Hz. Vernix in the ear canal of the infant (Chang, Vohr, Norton & Lekas, 1993) and variations in the middle ear pressure (Naeve, Margolis, Levine & Fournier, 1992) may decrease the intensity of the stimulus reaching the infant's inner ear. Maturational changes in the external and middle ear (Keefe, Bulen, Arehart & Burns, 1993; Keefe & Levi, 1996; Kruger & Ruben, 1987) suggest that there is a loss of power transfer into the infant middle ear when compared with the adult. All these factors might decrease the effective stimulus intensity in a frequency dependent manner, resulting in a smaller response at 500 Hz. Real ear measurement of the ASSR stimuli in the infant ear canal would be necessary to quantify any changes to the signal that may enhance or diminish the physiological response.

The advantage of using a longer recording duration (12 minutes) than used in most previous studies may have been lessened if there had been adaptation of the amplitude of the steady-state response over that period. We have seen adaptation of the amplitude of the steady-state responses in adults, but this was over a prolonged period of recording (about an hour) and only amounted to a decrease of about 15% (Picton, John, Purcell & Plourde, 2003). We had wondered whether infants might be more susceptible to adaptation, but found no change in amplitude with duration of the recording.

Threshold Estimation

The estimation of thresholds was not the goal of this study. However, the data provide important information concerning how accurately thresholds might be estimated in newborn infants using the ASSRs. The incidence of significant responses at 50 dB SPL for the 500 Hz data was close to 50% in the newborn infants. This indicates that the average thresholds for the 500 Hz tones in the few days after birth are about 40 dB HL. The average thresholds at the other frequencies might be some 10 or 15 dB better (depending on the actual shape of the cumulative incidence function), but there would be a range of thresholds that would cause some proportion, for example 20%, of thresholds at 2000 Hz to be greater than 50 dB SPL (or approximately 40 dB HL). The data from the older infant group suggest that the thresholds improve by about 10 dB in the first few months of life, except at 500 Hz. These findings are similar to those presented by Savio et al. (2001), although their data are higher in terms of SPL levels, probably because the environment in which the infants were tested had higher levels of background acoustic noise.

In this context, it should be noted that our estimated thresholds are probably not elevated because of insufficient averaging. When using 90 sec recording times, Rance and Rickards (2002) found that the

TABLE 7. Estimated test duration for different amounts of background noise

Noise Levels (nV)		Times Needed at Each Carrier Frequency (minutes)			
At 12 Minutes	Estimated at 16 sec	500 Hz (15.4 nV)	1000 Hz (26.2 nV)	2000 Hz (34.0 nV)	4000 Hz (21.4 nV)
10	67	5.1	1.7	1.0	2.6
15	101	11.4	3.9	2.3	5.9
20	134	20.3	7.0	4.2	10.4
25	168	31.7	10.9	6.5	16.3
30	201	45.7	15.7	9.4	23.5

The table shows estimated time, in minutes, for responses to become significant in an average newborn subject. The average amplitudes of the responses for 500, 1000, 2000, and 4000 Hz stimuli were taken from the older age group data (upper left of Fig. 6), and time was calculated using the equation $T = S(B/N)^2$, which is derived from an equation discussed in John, Purcell, et al. (2002), where S is the sweep duration, B is the background noise level in a single sweep, and N is the amplitude of the noise required to identify a response (i.e., the 95% confidence limits of the noise). The estimated noise in a single 16-sec sweep (second column) was calculated as the noise level at 12 minutes (after 45 sweeps) multiplied by the square root of 45. As shown in Figure 2, EEG noise levels for 14 nV or lower occurred in 50% of the recordings.

ASSRs thresholds were about 30 dB higher than the behavioral thresholds in normal-hearing subjects. Using longer recording times (up to 17 minutes), Dimitrijevic et al. (2002) found that the ASSR thresholds were only 10–15 dB higher than behavioral thresholds. The difference is likely related to the fact that the longer recording times made it possible to recognize the small responses close to threshold (discussed more extensively in Picton, John, Dimitrijevic & Purcell, 2003). We used recording times of 12 minutes in the present study. Table 7 presents some estimates of how long it might have taken to recognize the average AM^2 responses at the average amplitudes recorded for the older group. The estimates used equations presented in John, Purcell, Dimitrijevic, and Picton (2002). These equations were based on the assumption that the background EEG noise is normally distributed and follows a square root rule of averaging. If the noise levels in the recording become high or if one is looking for very small responses, the test could take an inordinate amount of time. When ASSR testing is performed using only 90 sec recording times, thresholds that are close to normal will often not be accurately detected in younger infants.

Our results suggest that frequency specific threshold testing using ASSRs should probably not be done in the neonatal period (<3 days). Testing might be more reasonable at 1–3 mo, although further data are clearly needed to assess the accuracy of threshold estimation in this period. Although the ASSR thresholds might be elevated compared with the assumed behavioral thresholds of a young infant, these might still be useful in demonstrating the pattern of frequency-specific hearing loss during the adjustment of hearing aids. Further, it may be possible to estimate behavioral thresholds by subtracting a set value from the ASSR thresholds or by using regression analyses. As discussed in Picton, John, Dimitrijevic, and Purcell (2003), these compensations need to be done with caution. An additional factor that must be considered in the estimation of infant thresholds is the increased intensity levels that are recorded in the infant ear canal when using insert phones calibrated for adult ear canals (see Sininger et al., 1997).

The ASSR thresholds that our data suggest for the newborn infants are 10–20 dB higher than the tone-ABR thresholds reported in newborn infants by Sininger et al. (1997). This difference is less in older infants (data reviewed in Picton, John, Dimintrijevic & Purcell, 2003) and close to zero in adults (Dimitrijevic et al., 2002), provided of course that averaging time has been sufficient. Three factors might be considered as possible causes for the ASSR threshold to be relatively high compared with the tone-ABR threshold in infants. First is the difference in stimulus envelope. Brief tones with relatively rapid rise times may be better able to synchronize the response in infants than modulated pure tones. Second is the difference in stimulus presentation rates. Tone-ABRs are recorded at slower rates (e.g., 20/sec in Sininger et al., 1997) than the modulation frequencies used for ASSRs. Infants may be less able than adults to follow the more rapid rates. However, Sturzebecher et al. (2003) has recently reported that, at least for click stimuli, steady-state responses are largest at about 90 Hz (their study only examined rates between 60–200 Hz and did not examine slower rates such as 20 Hz). A third factor to consider is the peak intensity of the stimuli. Modulated tones have a peak intensity that is 3–10 dB more than the RMS intensity (depending on the envelope). The normal-hearing level values for the brief tones used to evoke the ABR have peak levels about 20 dB higher than hearing level values, although these numbers vary with the couplers used and the rate of stimulation. Stimuli with lower peak intensities may be less able to evoke responses in infants than in adults. Exponential stimuli which are defined with exponents raised to the power of, for example, 12 rather than the squared envelope used in this study would make the ASSR stimuli approximate tone-burst stimuli. To draw firm conclusions concerning the differences between thresholds obtained with tone-ABR and ASSR methods, these two techniques should be evaluated on the same newborns.

Phase Measurements

The phases of the steady-state responses demonstrated larger variability than that which occurs in adults. This variability may preclude using population normative data, when using phase biasing (Picton et al., 2001) to improve the detection of the responses. Possibly, intrasubject phase values may be more stable and will allow phase biasing to occur based on earlier segments of the recording or on responses that are already detected for other carrier frequencies, but we have not yet evaluated these procedures based on our data. The mean phase data behave regularly but are difficult to understand in terms of latencies. One problem is that the stimuli may be of variable intensity relative to the infant's threshold and, since the latency of the response changes with intensity (John & Picton, 2000b), this may distort the data. As was reported by Lins et al. (1996), the onset phase for the 500 Hz response was greater than those found in adults. This means that the phase delay is shorter. Because of the ambiguity in estimating latency from phase (reviewed in John & Picton, 2000b), it is impossible, without obtaining a more comprehensive set of data, to attempt to determine if latency of the response is shorter or longer than that found in adults. Nevertheless, the onset phase for the AM^2 response is generally less than for the AM responses. This would fit with the later latency for the AM^2 response, likely related to the changes in the timing of the maximum slope in the stimulus cycle (discussed in John & Picton, 2002b).

Clinical Implications and Future Directions

The enhancement of response amplitude obtained by using AM^2, MM & AM2FM2 stimuli is important when using auditory steady-state responses to estimate hearing thresholds. The larger responses will be recognized as significant both more rapidly and at lower intensity levels.

We recommend that, when possible, longer recording sessions be used to assess the ASSRs when responses cannot be detected quickly. Longer sessions are not necessary if the responses are detected quickly, but are necessary to determine whether a small response is present at near-threshold intensities. Shorter recording times are sufficient to detect response only at higher intensities, and even then not consistently (e.g., Cone-Wesson, Parker, Swiderski & Rickards, 2002).

Our data suggest that frequency-specific audiometry will be more accurate in infants 1–3 mo of age than in the neonatal period. The ASSRs may not provide a rapid test of frequency-specific thresholds in the neonatal period. However, the testing will likely be reasonably accurate in babies older than 1 mo. The test may therefore be appropriate as a follow-up procedure after a screening procedure that uses stimuli that are not frequency-specific, such as click ABRs or steady-state responses to modulated white noise (Picton , John, Dimitrijevic & Purcell, 2003). Currently, tone-ABR tests are recommended to follow up on subjects who have been referred because of results of their screening tests (Stapells, 2002). Although it is hard to compare the two techniques, due, in part, to differences between the two types of stimuli (and the current lack of clinical data for ASSR), there are some advantages of ASSR tests (Cone-Wesson, Dowell, Tomlin, Rance & Ming, 2002). ASSRs should provide a more rapid testing procedure than tone-ABRs in infants of age 1–3 mo, but this will have to be formally evaluated.

Lastly, ASSR testing such as that provided by the MASTER system should always be used as part of a larger test battery and interpreted intelligently. A click-ABR and OAE test should be recorded in addition to MASTER, in the case where MASTER test indicates elevated thresholds. Click-ABR provides latency information (e.g., peaks I-V), which can be important for detecting neurological problems or developmental delays. OAEs can provide information about cochlear function even when the ASSRs and ABRs are absent, as occurs in auditory neuropathy. Immittance testing and behavioral testing (even if not always accurate) also provide information. The cross-check principle in pediatric audiology (Jerger & Hayes, 1976), where the MASTER results are evaluated in the context of the other results of a test battery, is essential in evaluating infants in the first few months of age (Gravel, 2002; Sininger, 2003).

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REFERENCE NOTE

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