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ANALOG AND DIGITAL FILTERING OF THE BRAIN STEM AUDITORY EVOKED RESPONSE

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This study compared the filtering effects on the auditory evoked potential of zero and standard phase shift digital filters (the former was a mathematical approximation of a standard Butterworth filter). Conventional filters were found to decrease the height of the evoked response in the majority of waveforms compared to zero phase shift filters. A 36-dB/octave zero phase shift high pass filter with a cutoff frequency of 100 Hz produced a 16% reduction in wave amplitude compared to the unfiltered control. A 36-dB/octave, 100-Hz standard phase shift high pass filter produced a 41 % reduction, and a 12-dB/octave, 150-Hz standard phase shift high pass filter produced a 38 % reduction in wave amplitude compared to the unfiltered control. A decrease in the mean along with an increase in the variability of wave IV/V latency was also noted with conventional compared to zero phase shift filters. The increase in the variability of the latency measurement was due to the difficulty in waveform identification caused by the phase shift distortion of the conventional filter along with the variable decrease in wave latency caused by phase shifting responses with different spectral content. Our results indicated that a zero phase shift high pass filter of 100 Hz was the most desirable filter studied for the mitigation of spontaneous brain activity and random muscle artifact.

KEY WORDS - auditory brain stem response, auditory evoked potentials, auditory threshold testing, digital filtering.

INTRODUCTION

Significant spontaneous brain activity and random muscle artifact can distort the auditory evoked potential and make recording almost impossible. In neurodiagnosis and threshold testing it is often desirable and necessary to eliminate this artifact in order to record a clear response. The frequencies of spontaneous brain activity vary with the level of subject consciousness and overlap the response frequencies of auditory evoked potentials. The peak frequency of muscle potentials is approximately 60 Hz. This peak is broad based, with the majority of energy below 300 Hz.[1] The response frequency peaks of the early portion of the auditory evoked potential (auditory brain stem response) are located approximately at 100 Hz, 500 Hz, and 1,000 Hz.[2,3] The peak frequency of muscle artifact is less than an octave away from the frequency peak of the auditory brain stem response's slow component (100-Hz spectral peak) and there is considerable frequency overlap. Thus, a steep filter is needed in order to eliminate a substantial portion of the artifact. However, steep analog filters cause significant phase shift distortions of the auditory brain stem response.[4-6] Thus, shallow high pass filters (12 dB/octave or less) usually are used to mitigate the spontaneous brain activity and random muscle artifact. Often the cutoff frequency of the filter is raised to 150 Hz in order for these shallow filters to be effective and still allow the recording of the response.

This article will quantitate the effects of high pass analog and digital filtering on the first 15 ms of the auditory evoked potential. In contrast to previous studies, a digital filter was used with a resolution of 16.7 Hz, which was several octaves below the studied cutoff frequencies of 100 and 150 Hz.

The potentials studied in this paper were elicited by 35-dB normal hearing level (nHL) stimuli. Little research has been reported concerning the effect of filtering on auditory brain stem responses elicited by low intensity stimuli. In the more poorly defined, near-threshold waveforms (as also recorded with higher stimulus intensities in patients with hearing loss), phase shift distortions may make the identification of individual waveforms more difficult because the peaks of the high frequency component (waves I through V) are less well defined.

METHODS

Twenty-three audiometrically normal subjects were evaluated in this study. All subjects were tested in a soundproof room (Tracoustic model RS255A) while resting in a reclining chair. No sedation was used.

The Pathfinder II (Nicolet Corp) was used to generate the signals, average the responses, and digitally filter the waveforms. The presenting stimuli were 35-dB nHL, 0.1-ms rarefaction clicks presented at a rate of 9.7/s. All responses were recorded with open filters (0.2 to 8,000 Hz) by use of a 12-dB/octave Butterworth filter. Electrodes were placed on the vertex (+), ipsilateral mastoid (-), and contralateral mastoid (ground). Electrode impedance was less than 3 kHz.

All waveforms were recorded twice with 1,000 stimulus presentations each, to allow for verification of the data. The two averages were added

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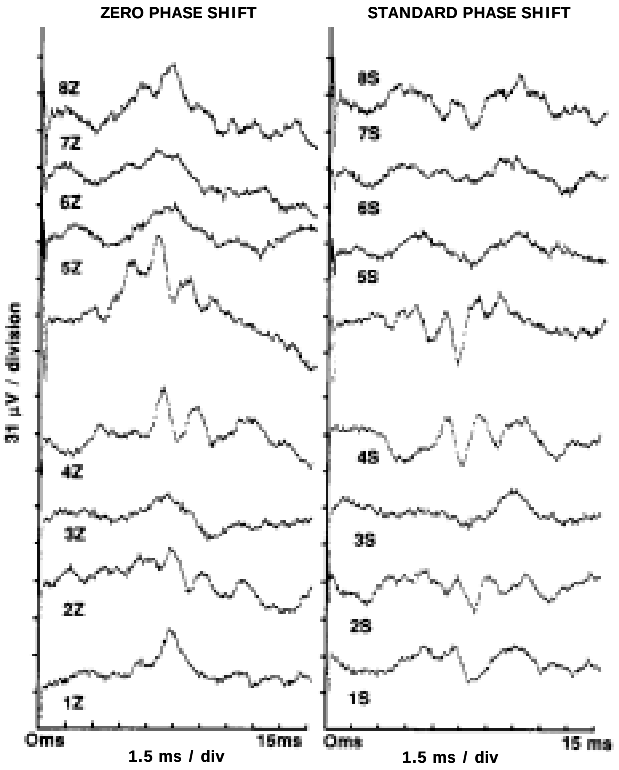

Zero and standard high pass digital filtering. High pass filter is 100 Hz, 36 dB/octave. Eight consecutively tested subjects (1 through 8) are shown.

together and baseline corrected. The waveforms, consisting of 2,000 averages each, were then digitally processed with a Fortran-based digital filter that mimicked a Butterworth filter with 12- and 36-dB/octave slopes and high pass cutoff frequencies of 100 and 150 Hz.[7] Both zero and standard phase shift conditions also were analyzed for all waveform sets. The filtering program implemented a discrete Fourier transform. The phase and power spectra were calculated for each waveform. The spectra then were weighted by use of the phase and power input/output functions of the desired filter. By use of these new spectral data the waveform was reconstructed.

The recording time base was 60 ms and consisted of 2,048 digitized points. The lowest discernible frequency of the digital filter was 16.7 Hz (1/time base). The highest discernible frequency is given by the Nyquist equation:

Highest discernible frequency =
1/[time base/(number of points digitized/2)]

and was equal to 17,067 Hz. After filtering, the first 256 points (15 ms) were segmented and displayed for waveform analysis.

The latency of the IV/V peak and IV/V-Na1 amplitude was measured on all waveforms. Waveform identification was performed in accordance with previous reports.[6-7] The slow component of the auditory brain stem response was defined as P0.[6-11] In many of the auditory brain stem responses studied in this report, the sharp IV and V peaks were absent and differentiation of these peaks from the slow component of the auditory brain stem response (P0) was impossible. Na1 was defined as the major trough that followed the IV/V peak and occurred within the 15-ms time window. Na was defined as the lowest trough between P0 (slow component of the auditory brain stem response) and Pa. The P wave was defined as the positive peak that divided Na into the two troughs Na1 and Na2[12]

The mean, standard deviation, and variance were calculated for all latencies and amplitudes. Statistical differences in mean latency and amplitude data were determined with a two-way analysis of variance (ANOVA). Analysis of the differences in latency and amplitude of all zero, standard, and unfiltered waveforms, regardless of the slope and cutoff frequency of the filter, was also performed by use of a two-way ANOVA with combined data groups. Statistical differences in variance data were determined with an F-max test.

RESULTS

Three of the 23 subjects had a large time-linked muscle potential. They were eliminated from the data analysis, since their responses were not primarily neurogenic but instead were neurogenic and myogenic. These subjects will have a response with a different phase and power spectral content than subjects with a primarily neurogenic response. Thus, the results of filtering will differ. The results of filtering waveforms with a large time-linked muscle potential are largely dependent upon the muscle potential's amplitude. Standard phase shift filtering can result in severe distortion of the waveform. Zero phase shift filtering may cause a deepening of the trough between wave IV/V and the potential, with the IV/V-Na1 amplitude obtaining a value of 2 to 3 uV[13] For this reason these subjects were eliminated from data analysis. Subjects with a large amount of spontaneous brain activity or random muscle artifact were not eliminated from data analysis.

The results of zero and standard phase shift digital filtering on the auditory brain stem response from the other 20 subjects are shown in the Figure and Tables 1 through 8. As expected, phase shifting high pass filters, compared to the zero phase shift condition, resulted in a decrease in wave latency. Paired t test analyses showed all three filter comparisons (100 Hz, 36 dB/octave; 100 Hz, 12 dB/octave; and 150 Hz, 12 dB/octave) to be significant ($p < .003$, $p < .02$, and $p < .015$, respectively). Since over 20 analyses were undertaken, there is an increased probability of a significant result due to chance alone (type I errors). Thus, a two-way ANOVA of the individual filter groups was performed. This analysis revealed that only the standard phase shift 36-dB/octave filter produced a

TABLE 1. WAVE IV/V LATENCY WITH ZERO AND STANDARD PHASE SHIFT HIGH PASS (100 HERTZ, 36 DECIBELS/OCTAVE) DIGITAL FILTERING

	Zero Phase Shift (ms)	*Standard Phase Shift (ms)*	*Significance*
Wave V latency	6.885	6.215	p < .0001*
Standard deviation	0.370	0.828	
Variance	0.137	0.685	p<.0l, (ratio = 5.0)[t]

	Unfiltered (ms)	*Zero Phase Shift (ms)*	*Significance*
Wave V latency	6.780	6.885	NS
Standard deviation	0.519	0.370	
Variance	0.270	0.137	NS (ratio= 1.97)[t]

	Unfiltered (ms)	*Standard Phase Shift (ms)*	*Significance*
Wave V latency	6.780	6.215	p < .0001*
Standard deviation	0.519	0.828	
Variance	0.270	0.685	p < .O5 (ratio = 2.53)[t]

NS - not significant.

* Two-way analysis of variance.

[t] F-max test (variance ratio for p < .O5 = 2.46; p < .0l = 3.32) .

Significant latency reduction. (This reduction was also significant when compared to all other filter conditions.) This analysis assumed that all measurements are independent of each other. Because the variances in the data groups were not equal the ANOVA was a very conservative test, creating type II errors. Also, the ANOVA probably underestimated the true significance in the differences because all three measurements, if studied by themselves, had significant paired t tests. For this reason a two-way ANOVA with combined data groups was per formed. When analyzed as a group, the filter conditions differed with a p value of less than .0001 (one chance in 10,000 that the results are due to chance alone). This significance was much higher than those found in any individual group and is a very strong argument that the latency reductions seen in the three phase shift filter conditions compared to the zero phase shift conditions are real and not due to chance. However, the changes were small for the 12-dB/octave filters (100 and 150 Hz), with wave IV/V having a similar mean latency and variance between the zero and standard phase shift conditions. This latency reduction was observed consistently in the majority of subjects studied. Zero phase shift filtering did not produce a significant shift in the IV/V wave latency compared to the unfiltered condition.

The response amplitude was larger with zero phase shift than standard phase shift filtering for all high pass conditions (Tables 2-4) . A two-way ANOVA with combined data groups compared all zero to all standard phase shift conditions and found this difference was significant at the $p < .0001$ level. A two-way ANOVA found these differences to be significant at the $p < .0001$, $p < .0553$, and $p < .0466$ levels for the 100-Hz, 36-dB/octave; 100-Hz, 12-dB/octave; and 150-Hz, 12-dB/octave filters, respectively. Increasing filter slope from 12 dB/octave to 36 dB/octave resulted in an amplitude reduction for only the phase shift condition. Little effect was noted with increasing the filter slope for the zero phase shift condition (Table 5). Increasing the filter's cutoff frequency from 100 to 150 Hz resulted in a further amplitude reduction (14%) for the zero shift condition. Phase shifting the waveform only reduced the response by an additional 2% over the zero phase shift (150 Hz) condition (Table 6) .

Phase shifting was responsible for the major decrease in amplitude with the 100-Hz, 36-dB/

TABLE 2. WAVE IV/V-Na1 AMPLITUDE WITH ZERO AND STANDARD PHASE SHIFT HIGH PASS (100 HERTZ 36 DECIBELS/OCTAVE) DIGITAL FILTERING

	Zero Phase Shift (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.420	0.295	p<.0001*	30
Standard deviation	0.138	0.112		
Variance	0.019	0.031	NS (ratio = 1.63)[t]	

	Unfiltered (uV)	*Zero Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.499	0.420	p < .0001*	16
Standard deviation	0.156	0.138		
Variance	0.024	0.019	NS (ratio= 1.26) [t]	

	Unfiltered (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.499	0.295	p < .0001*	41
Standard deviation	0.156	0.112		
Variance	0.024	0.031	NS (ratio= 1.29) [t]	

NS - not significant.

* Two-way analysis of variance.

[t] F-max test (variance ratio for p < .05 = 2.46; p < .01 = 3.32).

TABLE 3. WAVE IV/V-Na1 AMPLITUDE WITH ZERO AND STANDARD PHASE SHIFT HIGH PASS (100 HERTZ, 12 DECIBELS/OCTAVE) DIGITAL FILTERING

	Zero Phase Shift (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.407**	**0.368**	**p<.0553***	**10**
Standard deviation	**0.127**	**0.111**		
Variance	**0.016**	**0.012**	**NS (ratio = 1.33)[t]**	

	Unfiltered (uV)	*Zero Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.499**	**0.407**	**p < .0001 ***	**18**
Standard deviation	**0.156**	**0.127**		
Variance	**0.024**	**0.016**	**NS (ratio= 1.5)[t]**	

	Unfiltered (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.499**	**0.368**	**p<.0001***	**26**
Standard deviation	**0.156**	**0.111**		
Variance	**0.024**	**0.012**	**NS (ratio = 2.0)[t]**	

NS - not significant.

* Two-way analysis of variance.

t F-max test (variance ratio for p < .05 = 2.46; p < .0l = 3.32).

octave standard phase shift high pass filter, as response energy elimination was the major factor in the decrease of amplitude with the 150-Hz standard phase shift high pass filter.

Steep filters (36 dB/octave) produced severe response distortion (see Figure) that made waveform identification difficult. This distortion often caused the slow component of the auditory brain stem response to align itself with waves III and I (Table 8). In several cases, wave III had a latency greater than 5 ms and was the major response peak, with wave IV/V being smaller or absent (see Figure, waveforms 3S and 7S).

The amplitude reduction for the 100-Hz, 36-dB/octave zero phase shift filter was less than that for the 150-Hz, 12-dB/octave standard phase shift filter (Table 7). The larger waveforms in the zero phase shift condition were caused by a greater preservation of response energy (as shown by the two zero phase shift comparisons in the Figure) and by the lack of phase shift distortions.

The only significantly different latency variance was for the 36-dB/octave standard filter. This variance differed from all other filter settings. Analysis of the individual data revealed that six of the 20 data points would have to be discarded to eliminate this significance. It is unlikely that this finding is due to chance since over one quarter of the data points were responsible for this variance. The Figure also demonstrates that this variance was due

TABLE 4. WAVE IV/V-Na1 AMPLITUDE WITH ZERO AND STANDARD PHASE SHIFT HIGH PASS (150 HERTZ, 12 DECIBELS/OCTAVE) DIGITAL FILTERING

	Zero Phase Shift (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.351**	**0.310**	**p<.0466***	**12**
Standard deviation	**0.110**	**0.103**		
Variance	**0.012**	**0.011**	**NS (ratio = 1.09)[t]**	

	Unfiltered (uV)	*Zero Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.499**	**0.351**	**p < .0001 ***	**30**
Standard deviation	**0.156**	**0.110**		
Variance	**0.024**	**0.012**	**NS (ratio= 2.00)[t]**	

	Unfiltered (uV)	*Standard Phase Shift (uV)*	*Significance*	*% Reduction*
Wave V amplitude	**0.499**	**0.031**	**p<.001***	**38**
Standard deviation	**0.156**	**0.103**		
Variance	**0.024**	**0.011**	**NS (ratio= 2.18)[t]**	

NS - not significant.

* Two-way analysis of variance.

t F-max test (variance ratio for p < .05 = 2.46; p < .0l = 3.32).

TABLE 5. WAVE IV/V-Na1 AMPLITUDE COMPARISON BETWEEN HIGH PASS FILTERS OF 100 HERTZ (SLOPES OF 36 DECIBELS/OCTAVE AND 12 DECIBELS/OCTAVE)

	Zero Phase Shift 36 *dB/Octave (uV)*	*Zero Phase Shift 12 dB/Octave (uV)-*	*Significance*	*% Reduction*
Wave V amplitude	0.420	0.407	p<.5145*	3
Standard deviation	0.138	0.127		
Variance	0.019	0.016	NS (ratio= 1.19)[t]	

	Zero Phase Shift 36 *dB/Octave (uV)*	*Standard Phase Shift 12 dB/Octave (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.420	0.368	p<.0108*	12
Standard deviation	0.138	0.111		
Variance	0.019	0.012	NS (ratio= 1.58)[t]	

NS - not significant.

* Two-way analysis of variance.

[t] F-max test (variance ratio for p < .05 = 2.46; p < .0l = 3.32)

to the severe distortion produced by the filter and not by chance occurrence.

DISCUSSION

The digital filtering techniques used in this study differed from those of previous reports in that the filter's resolution was 16 Hz. Other authors have studied digital models of analog filters with much lower resolutions (from 83 to 111 Hz-estimated from the reciprocal of the time bases given in the Methods section or shown in the Figure).[14-17] A filter resolution of 16.7 Hz is several octaves below the cutoff frequencies of the studied filters, thus increasing the validity of the data reported in this study.

High pass analog filters (cutoff frequencies of 100 and 150 Hz) phase-shift and distort the auditory evoked potentials. It is the phase shifting of the 100-Hz energy in relation to the higher response energy (500- and 1,000-Hz spectral peaks) that causes the primary distortion. The high frequency component of the auditory brain stem response (500-Hz spectral peak) is more than an octave above the filter's cutoff frequency and is not phase shifted as much as the lower frequency energy. Also, the smaller wave period resulted in a much smaller latency shift per degree of phase shift.

Using steep analog filters to eliminate spontaneous brain activity and random muscle artifact is not desirable because of the severe response distortions caused by phase shifting. By comparing the data of the 100-Hz, 36-dB/octave high pass filter in Tables 1 and 2 the following conclusions can be reached. First, phase shifting caused a significant amplitude reduction in the recorded response in the majority of patients (16/20). With zero phase shift filtering the IV/V-Na1 amplitude was reduced by only 16% (p < .0001) as the phase-shifted response was reduced 41% (p < .0001) as compared to the unfiltered control. The difference in these two values was due to the phase characteristics of the filter and was significant at the p < .0001 level. The amplitude reduction in the phase-shifted waveform is caused by a nonalignment of the response energy peaks. This results in higher energy peaks being shifted into the troughs of lower energy peaks.[10]

Compared to previous studies,[14-16] the observed amplitude reduction with use of a zero phase shift

TABLE 6. WAVE IV/V-Na1 AMPLITUDE COMPARISON BETWEEN HIGH PASS FILTERS WITH SLOPE OF 12 DECIBELSIOCTAVE (CUTOFF FREQUENCIES OF 100 HERTZ AND 150 HERTZ)

	Zero Phase Shift 100 Hz (uV)	*Zero Phase Shift 150 Hz (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.407	0.351	p<.0057*	14
Standard deviation	0.127	0.110		
Variance	0.016	0.012	NS (ratio= 1.33)[t]	

	Zero Phase Shift 100 Hz (uV)	*Standard Phase Shift 150 Hz (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.368	0.310	p < .0001 *	16
Standard deviation	0.111	0.103		
Variance	0.012	0.011	NS (ratio= 1.09)[t]	

NS - not significant.

* Two-way analysis of variance.

[t] F-max test (variance ratio for p < .05 = 2.46; p < .0l = 3.32).

TABLE 7. WAVE IV/V-Na1 AMPLITUDE COMPARISON BETWEEN HIGH PASS FILTERS OF 100 HERTZ (36 DECIBELS/OCTAVE) AND 150 HERTZ (12 DECIBELS/OCTAVE)

	Zero Phase Shift 100 Hz, 36 dB/Octave (uV)	*Zero Phase Shift 150 Hz, 12 dB/Octave (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.420	0.351	p<.0007*	16
Standard deviation	0.138	0.110		
Variance	0.019	0.012	NS (ratio= 1.58)[t]	

	Zero Phase Shift 100 Hz, 36 dB/Octave (uV)	*Standard Phase Shift 150 Hz, 12 dB/Octave (uV)*	*Significance*	*% Reduction*
Wave V amplitude	0.420	0.310	p < .0001 *	26
Standard deviation	0.138	0.103		
Variance	0.019	0.011	NS (ratio= 1.73)[t]	

NS - not significant.
* Two-way analysis of variance.
t F-max test (variance ratio for p<.05=2.46; p<.01=3.32).

filter was slightly larger. This discrepancy is probably due to the higher resolution and steeper slope (36 dB/octave) of our digital filter, along with our use of a lower stimulus intensity. The lower stimulus intensity will not elicit well-defined high frequency components of the auditory brain stem response (the sharp peaks of waves IV and V) and can cause an increase in the latency of the Na1 trough out of proportion to the increase in latency of wave IV/V. This latter effect is caused by the P wave being positioned on the down shoulder of the slow component (P0) of the auditory brain stem response at high stimulus intensities and the up shoulder of wave Pa at low intensities.[6] The slow component of the auditory brain stem response widens and the frequency of the response is lowered. The 15-ms time base used in our study allowed the recording of the prolonged Na1, which can have a latency greater than 10 ms at low stimulus intensities.[13] The widening of the slow component along with the mitigation of high frequency components will produce a lowering of the mean spectral content of the response.

Besides significant amplitude effects, steep analog filters (36 dB/octave) can cause a large decrease in wave latency (0.67 ms; p<.0001) and an increase in wave latency variability (250%; p<.05) (Table 1). This increase in variability is caused by two factors. First, phase shifting can severely distort the response, making wave identification difficult (see Figure). This effect can cause the slow component of the auditory brain stem response to align itself with wave III. The sharp peaks of wave IV/V are often absent or markedly diminished in low intensity recordings. In all unfiltered and in 19 of 20 zero phase shift waveforms the peak of the auditory brain stem response was at wave IV/V. However, in the standard phase shift condition the slow component of the auditory brain stem response decreased in latency out of proportion to waves I through V. The peak of the auditory brain stem response varied between waves I, III, and IV/V (Table 8). Since a low intensity stimulus was used, all peaks were delayed and ill defined. Thus, confusion was created regarding waveform identification. This confusion led to the misreading of several of the waveforms. Wave III was often delayed past 5.0 ms and phase shifting can cause it to be the largest waveform of the response. Different observers may disagree on the location of wave IV/V (P0) in the analog-shifted waveforms. One cannot eliminate this confusion and thus it represents a confounding factor in latency determination of analog-filtered (phase-shifted) responses. This is especially evident in subjects 3S and 7S (see Figure). Second, because all auditory evoked potentials have a different spectral composition the degree of shift will differ and thus further the increase in variability of the latency measurement. Filtering the amplitude spectrum will cause a variability in wave latency for both standard and zero phase filters. However, the added change in the phase spectrum of waveforms modified by standard phase shift or analog filters will cause an increase in this variability. A small latency variability is very desirable in neurodiagnosis, in which small normative standard deviations and accurate latency

TABLE 8. LOCATION OF HIGHEST PEAK IN FIRST 8 MILLISECONDS OF RESPONSE

Filter Characteristics	*Wave I*	*Wave 111*	*Wave IV/V*
Unfiltered	0	0	20
36 dB/octave high pass 100 Hz			
Zero phase shift	0	1	19
Standard phase shift	5	10	5
12 dB/octave high pass 100 Hz			
Zero phase shift	0	1	19
Standard phase shift	0	5	15
12 dB/octave high pass 150 Hz			
Zero phase shift	0	0	20
Standard phase shift	0	6	14

Peak in standard recording was compared to zero phase-shifted recording in order to identify highest peak location (P0) .

measurements increase the reliability of the test.

The waveform distortions (amplitude reductions) from phase shifting 12-dB/octave filters were not as great as those found with 100-Hz, 36-dB/octave phase shifting filters ($p < .0003$) (Tables 2 and 3) . Also, the 12-dB/octave standard phase shift high pass filters of 100 and 150 Hz had similar wave latency variances and mean amplitude differences between the zero and standard phase shift conditions. Thus, the clinical use of shallowly sloping filters to avoid severe phase shift distortions appears to be valid.

However, one should be careful when using a high pass cutoff frequency to compensate for the shallower filter slope. The amplitude reduction of the auditory brain stem response filtered with a 150-Hz, 12-dB/octave standard phase shift high pass filter approximated that obtained with a 100-Hz, 36-dB/octave standard phase shift high pass filter (38% versus 41% ,respectively) (Tables 2 and 4) . At a cutoff frequency of 100 Hz, the 36-dB/octave standard phase shift filter produced a much smaller (30%) wave IV/V-Na1 amplitude than the zero phase shift condition (Table 2), as a cutoff frequency of 150 Hz produced little difference (12 %) between the two amplitudes (Table 4). It can be theorized that the amplitude reduction with the 150-Hz, 12-dB/octave standard phase shift filter is primarily due to the elimination of response energy and that seen in the 100-Hz, 36-dB/octave standard phase shift filter is primarily due to phase shifting (Tables 5 and 6) .

This is further confirmed by the finding that a shallow (12-dB/octave) zero phase shift filter with a cutoff frequency of 150 Hz eliminated significant response energy with a resultant 30% decrease in IV/V-Na1 amplitude compared to the unfiltered condition (Table 4) . This reduction is more than the 16% to 18% obtained with the 100-Hz, 36-dB/ octave and 12-dB/octave zero phase shift filter (Tables 2 and 3). It is apparent that high pass analog filtering at 150 Hz not only phase-shifts the response but also results in significant elimination of response energy.

Varying the slope of the zero phase shift filter at 100 Hz did not have a marked effect on the IV/VNa1 amplitude (Table 5). This finding can be attributed to the filtering of the 100-Hz spectral peak of the auditory brain stem response. A shallowly sloping filter will eliminate more energy above the cutoff frequency than a steeply sloping filter, as a steeply sloping filter will eliminate more energy below the filter's cutoff frequency than a shallowly sloping filter. When the filter's cutoff frequency approximates the response energy, the relative effects on amplitude cannot be predicted.

The amplitude reduction of a 12-dB/octave standard phase shift high pass filter at 150 Hz was 26% more than the reduction recorded with a 36-dB/ octave zero phase shift filter at 100 Hz (Table 7). This finding clearly demonstrates the advantages of zero phase shift digital filters in preservation of response amplitude. Unfortunately, digital filtering cannot be performed during signal averaging with commercially available evoked response units. It is hoped that with the falling price of computer components and the production of faster processors that this hardware will soon be available.

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REFERENCES

1. Hayes K. Wave analysis of tissue noise and muscle action potentials. J Appl Physiol 1960;15:749-52.

2. Suzuki T, Sakabe N, Miyashite Y. Power spectral analysis of auditory brainstem responses to pure tone stimuli. Scand Audiol 1982;11:25-30.

3. Boston JR. Spectra of auditory brainstem response and spontaneous EEG. IEEE Trans Biomed Eng 1981;28:334-41.

4. Laukh E, Mair IWS. Early auditory-evoked responses: filter effects. Audiology 1981;20:300-12.

5. Suzuki T, Horiuchi K. Effect of high pass filter on auditory brainstem responses to tone pips. Scand Audiol 1977;6:123-6.

6. Kavanagh KT, Harker LA, Tyler RS. Auditory brainstem and middle latency responses. I. Effects of response filtering and waveform identification. II. Threshold responses to a 500-Hz tone pip. Ann Otol Rhinol Laryngol 1984;93(suppl 108).

7. Kavanagh KT, Domico WD, Crews PL, McCormick VA. Comparison of the intrasubject repeatability of auditory brain stem and middle latency responses elicited in young children. Ann Otol Rhinol Laryngol 1988;97:264-71.

8. Oppenheim AV, Schafer RW. Digital signal processing. Englewood Cliffs, NJ: Prentice-Hall, 1975.

9. Rabiner LR, Schafer RW. Digital processing of speech signals. Englewood Cliffs, NJ: Prentice-Hall, 1978.

10. Kavanagh KT, Domico WD. High-pass digital filtration of the 40 Hz response and its relationship to the spectral content of the middle latency and 40 Hz responses. Ear Hear 1986;7:93-9.

11. Osterhammel P. The unsolved problems in analog filtering on the auditory brainstem responses. Scand Audiol [Suppl] 1981(suppl 13):69-74.

12. Mendel MI, Kupperman GL. Early components of the averaged electroencephalic response to constant level clicks during rapid eye movement sleep. Audiology 1974;13:23-32.

13. Kavanagh KT, Domico WD, Franks R, Han JC. Digital filtering and spectral analysis of the low intensity ABR. Ear Hear 1988;9:43-7.

14. Domico WD, Kavanagh KT. Analog and zero phase-shift digital filtering of the auditory brain stem response waveform. Ear Hear 1986;7:377-82.

15. Doyle DJ, Hyde ML. Analogue and digital filtering of auditory brainstem responses. Scand Audiol 1981;10:81-9.

16. Kevanishvili Z, Aphonchenko V. Frequency composition of brain-stem auditory evoked potentials. Scand Audiol 1979; 8:51-5.

17. Elton M, Scherg M, Cramon DV. Effects of high-pass filter frequency and slope on BAEP amplitude, latency and wave form. Electroencephalogr Clin Neurophysiol 1984;57:490-4.