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The effects of digital filtering on feline auditory brain-stem evoked potentials

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Summary   The power spectrum of the feline auditory brain-stem evoked potentials (ABEPs) consists of 3 frequency bands, similar to the human wave form, but differing in range. The frequency bands in the feline spectra were separated by notches at 326 Hz and 732 Hz. Click-evoked ABEP from 15 cats were digitally filtered in 3 passbands: (1) below 326 Hz ('slow filter'), (2) between 326 and 732 Hz ('medium filter'); and (3) between 732 and 1790 Hz ('fast filter'). Filtering in each of these bands differentially affected the ABEP components. The vertex positive components are labeled by their order of appearance, i.e., 1, 2,... 5. Peak 1 is subdivided into 2 subcomponents labeled 1a and 1b. The slow filter was associated with the loss of all components leaving a slow potential shift, i.e., the 'pedestal' peaking at the latency of peak 4. The medium filter was associated with the loss of components 1a, 1b and 2, sparing 3 and 4. The fast filter was associated with the loss of 1b and a diminution of 2.

Comparing cat and human ABEP, feline components 2, 3 and 4 behaved precisely the same as the human II, III and V. In contrast to the human I, the feline first component (1a) was not detected with the medium filter. No feline component, following peak 1 in the unfiltered wave form, disappeared with the slow and medium filters, and reemerged with the fast filter (as human IV does). Thus, based on the effects of digital filters on ABEP wave form, the human peak IV did not have a feline counterpart, and the feline bifid peak 1 differed compared to its human I counterpart. Some of these conclusions run counter to homologues suggested from lesion and depth recording experiments. Factors related to differences in the dimensions, composition, and orientation (relative to the recording electrodes) of the auditory pathway of humans and cats could affect the definition of homologues between the two species using filters as well as lesion and depth recordings.

Key words: Auditory brain-stem evoked potentials; Finite impulse response; Digital filter; (Cat)

Spectral analysis of averaged human auditory brain-stem evoked potentials (ABEPs) have described 2 frequency bands corresponding to the slow potential shift and to the transient components (Fridman et al. 1982; Møller 1983; Takagi et al. 1983). However, careful examination of the spectra provided in these and other reports (Boston 1981; Boston and Møller 1985; Aoyagi and Harada 1988), and results from our laboratory (Urbach and Pratt 1986), reveal 3 frequency bands separated by notches at 240 Hz and 484 Hz. Filters for each of the frequency bands in the ABEP frequency spectrum of humans (Urbach and Pratt 1986) differentially affected components, depending on the band. The slow filter (up to 240 Hz) left only the 'pedestal' and peak V. The medium filter (240–483 Hz) spared components I, III and V, while II and IV were abolished. The fast filter (above 483 Hz) revealed all 5 peaks. This passband selectivity for components has been verified over a wide range of stimulus intensities and rates, and has been successfully employed in clinical cases (Pratt et al. 1989).

The purpose of this study on the feline ABEP was to apply digital filtering to try to differentially affect components of the wave forms. A comparison of these effects with those reported for the human wave forms may be useful in suggesting interspecies homology of components.

Methods

Potentials were recorded from 15 awake cats in a restraining bag. Body temperature was maintained with a homeothermic blanket and infrared lamp. Subdermal needle electrodes were arranged in a differential derivation between vertex and midline under the mandible and a grounding screw was placed in the left frontal sinus. The interelectrode impedance was 5 kΩ or less. Potentials were differentially amplified ($\times$100,000) with an analog band pass of 30–3000 Hz (−3 dB points, 6 dB/octave slopes). The amplified potentials were averaged using 512 addresses and a dwell time of 20 μsec/channel.

Stimuli were clicks generated by transducing 100 μsec square electric pulses in Sony MDR-E225 dynamic earphones. Clicks were presented to each ear in

FELINE AUDITORY BRAINSTEM EVOKED POTENTIALS
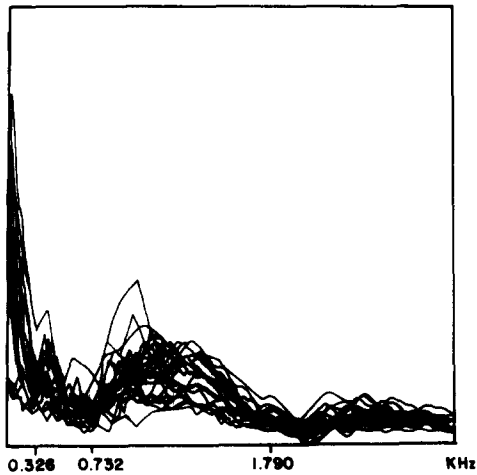POWER SPECTRUM ESTIMATION

80 dBnHL clicks, 15 CATS (30 EARS)

Fig. 1. Superimposed spectra of unfiltered ABEP wave forms from 15 cats (30 ears). Potentials were evoked by averaging responses to 4000, 80 dB nHL, 10.6/sec condensation clicks. Note the 3-lobed spectrum with notches at 326, 732 and 1790 Hz.

turn, as well as binaurally. Potentials following 4000, 80 dB nHL (re human listeners), condensation clicks presented at a rate of 10.6/sec were averaged to produce each trace. The large number of trials averaged for each wave form was acquired to negate any possible residual noise from muscle activity of the awake cats. The averaged data were magnetically stored for further analysis.

The power spectra of the ABEP wave forms (Fig. 1) showed 3 lobes. The averaged wave forms were further filtered digitally in 3 passbands, based on the lobes in the power spectra: (1) below 326 Hz ('slow filter'), (2) between 326 and 732 Hz ('medium filter'); and (3) between 732 and 1790 Hz ('fast filter'). The filtering procedure was the direct form realization of FIR filter (Oppenheim and Schafer 1975) with 64 filter coefficients. In order to avoid boundary effects of the 64 point filters on the wave forms, which included 512 points, the first and last 32 points of the wave forms were mirror-imaged to the beginning and ending points, respectively.

The vertex positive components were labeled by their order of appearance, i.e., 1, 2, ... 5. Peak 1 was further subdivided into 2 subcomponents labeled 1a and 1b. Peak latencies, of the digitally unfiltered wave forms, as well as of the digitally filtered wave forms, were determined manually, using cursors on the computer screen. The correlation between peak latencies in the passbands studied was assessed by linear regression, and its significance determined using Student's t

test for a slope of 0. The coincidence of peaks was determined by their latency differences across passbands. The significance of these differences was assessed by the paired Student's t value. Because 6 comparisons were conducted (6 peak correlations or 6 latency differences), only probabilities that were smaller than 0.01 were considered significant.

Results

The unfiltered evoked potentials, as well as the wave forms obtained after filtering in the specific bands used in this study, are presented in Fig. 2. The slow filter defined the pedestal and peaks 4 and 5. With the medium filter peaks 3, 4 and 5 appeared, whereas 1a, 1b and 2 were absent. With the fast filter there was a loss of 1b, a diminution of 1a and 2, while peaks 3, 4 and 5 were clearly defined. The pedestal was lost with the fast filter.

FELINE AUDITORY BRAINSTEM EVOKED POTENTIALS
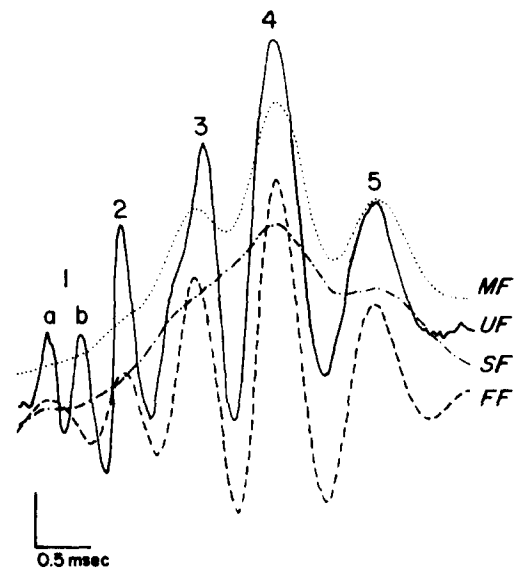DIGITAL FILTERING

80 dBnHL GRAND AVERAGE (30 EARS)

Fig. 2. The unfiltered feline ABEP wave form, as well as the wave forms obtained after its FIR digital filtering using the slow, medium and fast filters. UF represents the unfiltered wave forms, SF signifies the slow filtered, MF stands for the medium filtered while FF marks the fast filtered wave forms. The amplitude calibration bar represents 0.5 μV for the UF wave form, 0.4 μV for SF and MF and only 0.2 μV for the FF wave form. Potentials were evoked by 80 dB nHL, 10.6/sec condensation clicks. The amplitude scale is the same for all wave forms. Note the coincidence of peak 4 in all wave forms, and the coincidence of peaks 1, 3, 4 and 5 in the unfiltered, medium and fast filtered wave forms, as well as the relative diminution of peak 2 in the fast filtered wave form.

TABLE I

Average latencies (mean, in msec) and standard deviations (S.D.), across 30 ears of 15 cats, for peaks 1, 3 and 4, in response to 10.6/sec 80 dB nHL clicks, in the 3 passbands examined. In the unfiltered data, peak 1b is listed. UF represents the unfiltered wave forms, SF signifies the slow filtered, MF stands for the medium filtered while FF marks the fast filtered wave forms. Note the coincidence of respective peak latencies in the different passbands and the smaller S.D. in the data from the filtered wave forms.

	1		3		4	
	Mean	S.D.	Mean	S.D.	Mean	S.D.
UF	1.07	0.27	2.39	0.10	3.18	0.19
FF	1.02	0.26	2.36	0.07	3.14	0.09
MF			2.31	0.06	3.14	0.09
SF					3.12	0.09

Peak latencies across passbands were very similar, with the filtered wave form latencies having smaller standard deviations than those of unfiltered wave forms (Table I). The correspondence of respective peaks defined in the unfiltered, slow, medium and fast filtered wave forms are detailed in Table II. All correlations had slopes of close to 1, and, with the exception of peak 4, all were significant. The low correlation coeffi-

cients and significance levels for the fourth peak's latency are surprising because peak 4 was the most prominent and reproducible across passbands. This lower correlation of peak 4 may be attributed to the small latency differences between passbands (Table I), resulting in a small and random, rather than a linear distribution of values in the correlation matrix.

The differences between peak latencies determined manually from unfiltered wave forms and the respective peaks in the fast, medium and slow filtered wave forms are included in Table III. All differences were very small, though significant for peaks 1a and 3. The insignificant differences in peak 4 latency support a random distribution within a small range, as suggested to explain the non-significant correlations in Table II.

Discussion

Comparative studies of human and animal ABEPs have used analog filters, or smoothing algorithms that simulate the effects of analog filters (e.g., Fullerton et al. 1987). Digital filters improve the recording of ABEPs and their superiority over analog filters with respect to

TABLE II

Correlations between respective peak latencies of feline ABEP, in the unfiltered (UF) and in the slow (SF), medium (MF) and fast (FF) filtered wave forms evoked by 10.6/sec, 80 dB nHL clicks. Peak 1b was analyzed in the unfiltered data. a stands for the regression slope, r for the correlation coefficient, P represents Student's t test probability for a slope of 0. Note that all slopes were close to 1 and the regressions significant.

		UF								
		1			3			4		
		a	r	P <	a	r	P <	a	r	P
FF	1	0.97	0.92	0.0001						
	3				0.86	0.56	0.001			
	4							1.01	0.42	N.S.
MF	3				0.81	0.50	0.006			
	4							1.01	0.42	N.S.
SF	4							0.87	0.42	N.S.

TABLE III

Differences between peak latencies determined manually from unfiltered wave forms (UF) and the respective peaks in the fast (FF), medium (MF) and slow (SF) filtered wave forms, evoked by 10.6/sec 80 dB nHL clicks. Peak 1b was analyzed in the unfiltered data. Mean differences (mean, in msec) across 30 ears of the cats, as well as significance levels according to Student's paired t tests (P) are listed. All differences were very small and those of 4 were the least, or non-significant.

		UF					
		1		3		4	
		Mean	P <	Mean	P <	Mean	P
FF	1	0.05	0.005				
	3			0.03	0.01		
	4					0.03	N.S.
MF	3			0.06	0.0005		
	4					0.03	N.S.
SF	4					0.05	N.S.

latency distortions has been repeatedly demonstrated (Boston and Ainslie 1980; Møller 1980, 1983; Doyle and Hyde 1981; Fridman et al. 1982; John et al. 1982; Boston 1983; Takagi et al. 1983; Suzuki et al. 1986). However, even when digital filters are used, ABEP peak latencies depend on the type and characteristics of the filter (Møller 1983). Because peak latencies are important in comparative wave form studies, phase must be kept linear when filters are used. For example, a linear phase filter will cause an input signal, which falls entirely in the passband, to be accurately copied to the output with a constant delay. A symmetric causal finite impulse response (FIR) system (Oppenheim and Schafer 1975) has such a precisely linear phase.

The results of this study indicate that, similar to the human ABEP, the feline wave form consists of 3 frequency bands. Although the shapes of the spectra are similar for human and feline ABEP, the actual frequencies in the cat wave forms are higher, correlating with the shorter duration of individual feline components and their smaller interpeak temporal separation (Fig. 2) compared to human potentials (Urbach and Pratt 1986; Fig. 3 this report). The bases for such differences between animal and human ABEP have

been related to: (1) the smaller dimensions of the animal auditory nerve (Møller et al. 1988) and brain-stem (Fullerton et al. 1987); and (2) differences in the relative sizes of auditory brain-stem nuclei and their orientation relative to the surface recording sites between animals and humans (Moore 1987).

Selective filters for each of the power spectrum frequency bands resulted in the selective disappearance of components, depending on the band. Peaks 1a, 1b, 2 and 3 were lost with the slow filter, sparing only the 'pedestal' and peaks 4 and 5. Peaks 1a, 1b and 2 were lost with the medium filter, leaving only components 3, 4 and 5. Only 1b and the pedestal were lost with the fast filter.

The first component in both animals (1a) and humans (I) is generally agreed to reflect activity in the distal portion of the VIIIth nerve (Sohmer and Feinmesser 1967; Lev and Sohmer 1972; Buchwald and Huang 1975; Allen and Starr 1978; Achor and Starr 1980; Legatt et al. 1986; Fullerton et al. 1987; Starr and Zaaroor 1991). The second component of humans (II) has been suggested to be homologous to an oft overlooked second component in cats (1b) peaking approximately 400 μsec after 1a, and which has been related to activity of the VIIIth nerve as it enters the cochlear
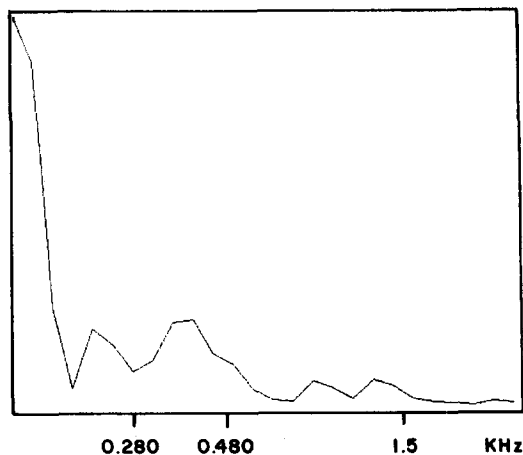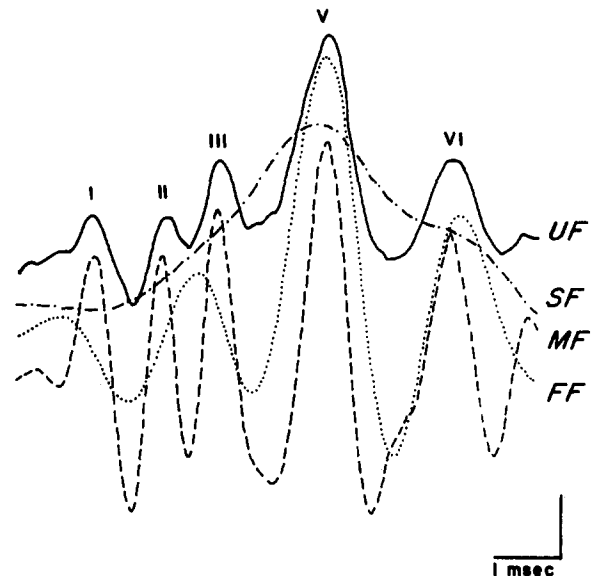

Fig. 3. The unfiltered wave form, as well as the wave forms obtained after its FIR digital filtering using slow, medium and fast filters for human ABEP. UF represents the unfiltered wave forms, SF signifies the slow filtered, MF stands for the medium filtered while FF marks the fast filtered wave forms. The amplitude calibration bar represents 0.2 μV for the UF wave form, 0.15 μV for SF, 0.1 μV for MF and only 0.06 μV for the FF wave form. Potentials were evoked by 75 dB nHL, 10/sec alternating polarity clicks. Note the coincidence of peak V in all wave forms, the coincidence of peaks I, III and V in the unfiltered, medium and fast filtered wave forms, and the diminution of peaks II and IV in the medium filtered wave form.

nucleus (P0.8 and P1.2: Achor and Starr 1980; P1a and P1b: Starr and Zaaroor 1990). In contrast, the first peak and the one immediately following it in monkeys have been considered as sub-peaks of the animal equivalent of the human first component (1a and 1b: Legatt et al. 1986). The second (II), third (III), fifth (V) and sixth (VI) vertex positive components of humans have been suggested to correspond to the respective vertex positive second, third, fourth and fifth components of animals (2, 3, 4 and 5 in cat: Lev and Sohmer 1972; 3, 5, 7 and 8 in monkey: Legatt et al. 1986). The simian wave form has been suggested to include the homologue of the human IV (6: Legatt et al. 1986) while the feline wave form has been described as lacking in a peak equivalent to the human IV (Fullerton et al. 1987).

The results of this study, on cats, compared with an earlier study on humans (Urbach and Pratt 1986) add a new line of evidence to the homology between animal and human ABEP components. The effects of slow, medium and fast filters on feline component 5 were precisely the same as on human VI which was not lost with any of the filters (Figs. 2 and 3).

The effects of filters on feline 4 and human V were also the same: both can be identified using all 3 filters and their peaks coincide with the peaks of their respective pedestals (Figs. 2 and 3). The homology of the cat 4 and the human V components has seemed likely based on other types of experimental evidence. They both show similar changes in amplitude and latency with alterations in stimulus intensity and rate (Fullerton et al. 1987). Moreover, binaural interaction components of the ABEP first appear at the time of the feline fourth and the human fifth components (Hosford et al. 1979; Huang 1980; Fullerton et al. 1987; Wada and Starr 1989).

None of the components of the feline ABEP behaved like the human IV; disappearing only with the slow and medium filters and persisting with the fast filter (Fig. 3). This result supports Fullerton's suggestion that the cat ABEP does not contain a component homologous to the human IV.

The effect of filters on cat 3 (Fig. 2) was the same as that observed on human III (Fig. 3) and is in agreement with earlier thoughts as to the relationship of the cat and human ABEP (Lev and Sohmer 1972). However recent evidence from both recording and lesion studies does not support this proposed homology. Wave III in human has been attributed to activity ipsilateral to the stimulated ear involving both the cochlear nucleus and its efferents traveling in the trapezoid body (Scherg and Von Cramon 1985) whereas the feline third component is prinicipally generated bilaterally in the brain-stem by the neurons of the superior olivary complex (SOC) (Wada and Starr 1989; Zaaroor and Starr 1991a) with contributions from axons in the trapezoid body. There is a marked interspecies difference in the composition of the superior olivary complex. In particular, the lateral superior olivary nucleus in humans is rudimentary (Moore 1987) while this component is a major contributor to ABEP in cats (Zaaroor and Starr 1991a).

The lack of concordance between the homologies proposed for cat and human ABEP components using the results from selective filters and the results of experimental recording and lesion studies is even more striking with component 2 in cat and wave II in humans. Both of these components behave similarly with regard to the selective filters; being lost with the slow and medium filters and appearing again with the fast filter, a finding that suggests that these components are homologous. However, depth recording and lesion experiments suggest that cat 2 and human II are principally generated by different structures. From recording experiments in human, wave II is coincident with activity of the proximal portion of the VIIIth nerve adjacent to the brain-stem (Møller et al. 1981; Scherg and Von Cramon 1985; Curio et al. 1987) whereas component 2 of the cat is lost following lesions of the cochlear nucleus (Buchwald and Huang 1975; Pratt et al. 1991; Zaaroor and Starr 1991b), suggesting it is generated centrally in the brain-stem. Using only the data from lesion and depth recording experiments, feline 2 would appear to be homologous to the human III, and feline 3 would appear to be homologous to human IV.

Explanations to account for the differences of the homologies suggested from selective filtering and from lesion and recording studies are not immediately apparent. In the extreme case one (or both) type of experiments may be inappropriate for deriving homologies between cat and human ABEP components. A more likely possibility is that there are limitations to one or both of these methods that must be taken into consideration in realizing homologies. For instance, the dimensions of the brain-stem auditory pathway differ between cat and man (Fullerton et al. 1987; Moore 1987) resulting in shorter conduction times within the auditory pathway (Allen and Starr 1978; Fullerton et al. 1987) and a higher frequency spectrum of the ABEP in cat versus man (Fullerton et al. 1987; this study).

Such spectral and anatomical differences probably contribute to differences in the effects of filtering on feline and human ABEP components that are generally agreed to be homologous. For instance, the feline 1a and the human I are both coincident with activity of the VIIIth nerve within the cochlea (Sohmer and Feinmesser 1967) yet they behave differently with selective filters. Human I is lost only with the slow filter whereas the cat 1a is lost with both the slow and medium filters. The length of the VIIIth nerve in humans and cats is considerably different, being 25 mm in man and only 3 mm in cat (Lang 1981), while conduction velocities are

similar (13–25 m/sec in humans: Hashimoto et al. 1981; Møller et al. 1981; Spire et al. 1982; 10 m/sec in cats: Starr and Zaaroor 1990). The resulting disparity of conduction times along the nerve is associated with differences in the early portions of the ABEP in the two species. In the human, waves I and II are separated by a prominent negativity lasting approximately 1 msec whereas the negativity separating components 1a and 1b in the cat is brief, lasting less than 0.4 msec. Moreover, the pedestal, on which the ABEP components ride, begins close to wave II in man (Urbach and Pratt 1986; Fullerton et al. 1987; Fig. 3, this report) whereas in cat the pedestal begins earlier, at the time of 1a (Fullerton et al. 1987; Fig. 2, this report). Thus, different frequency domains are contained in the spectra of the early portions of the cat and human ABEPs which would account for the different effects of selective filtering on 1a and 1b in the cat and I and II in humans.

In conclusion, the differential effects of digital filtering on components of the cat ABEP would indicate that components 2, 3, 4 and 5 of cat are homologous to human components II, III, V and VI; cats lack a homologue of the human component IV; and the initial components of feline (1a, 1b) and human (I) ABEPs are different. However, significant anatomical differences between both the length and the composition of the auditory brain-stem pathways in cat and human probably contribute to a lack of correspondence between homologies based on selective filtering, as outlined in this paper, when compared to the homologies derived from lesion and depth recording studies.

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