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Comparisons of EEG Waveform Distortions Caused by the Signal Conditioning Filters

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Abstract

This paper investigates the EEG waveform distortions caused by the transient responses of various types of signal conditioning filters, which are generally introduced for automated analysis of EEG. This study explicitly simulates the filter responses to the typical EEG waveform models, and compares the distortions. The filter distortion effects are also illustrated with the experiments on real EEG signals.

1. Introduction

EEG (electroencephalogram) waveform detection is believed to form the core part of the human EEGer's visual inspection process. Therefore, the establishment of a correct set of waveform criteria is crucial for the success of automated EEG analysis. Most of the EEG waveforms are short-time existing sinusoidal bursts. Waveforms of this type are generally called as "spindles" and further distinguished as alpha, beta, delta, sigma, and theta, according to their intra-waveform periodicities. Some of the EEG waveforms such as delta are described by the half-wave periodicity. A sample set of waveform definitions including the periodicity windows are shown in [1][2].

The EEG waveforms are always superimposed on the background noise activity. Therefore, some type of signal conditioning filters are invariably involved in the processing. The purpose of the filters is to remove unwanted frequency components (or noise in a more general term) and to enhance the frequency components of interest from the signal. Besides the involvement of a signal conditioning filter in the analysis, various other types of filters are often introduced in the data acquisition procedure. The AC coupled recording of EEG machine is an example of the introduction of a highpass filter. The AC coupling is to reject the high potential DC voltage. A notch filter is often included in the machine to reject the power line interference.

It must be stressed that the filters not only remove the unwanted components of the signal but also distort the signals of interest (waveforms). Especially, since the EEG waveforms are short-time existing transient phenomena, the filter transient response may significantly distort the waveform shapes.

The effects of filter transients are investigated by explicitly simulating the responses to the typical EEG waveform models, i.e., the sigma spindle and the delta wave. A spike-type input model is also used in the simulation to illustrate the ringing effect of the filters which may cause a false positive detection of the spindle waveforms. The filters designed for the simulation study are also applied to the real EEG signal to illustrate the distortion effects of the filters.

2. Filter Transient Responses

Various types of bandpass filters are designed and the effects of the filter transients are investigated with the sigma spindle waveform model, i.e., a 13.5Hz sinusoidal burst with 0.5 seconds of duration, and with the sharp spike-wave model. The sigma spindle and the spike-wave model are illustrated in Fig. 1. A full cycle of 0.5Hz sinusoidal wave is used to investigate the effect of the filter transients to the delta wave.

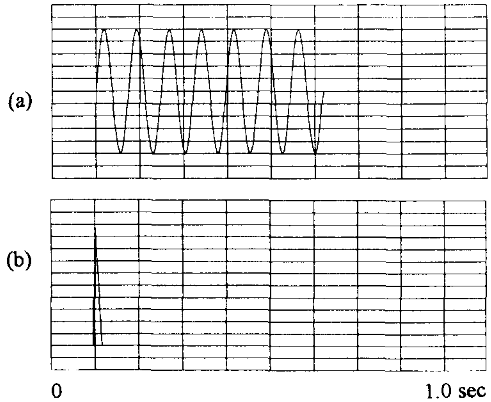

Fig 1. (a) A modle of sigma spindle waveform, i.e., 13.5Hz sinusoidal burst of 0.5 second duration. (b) A model of a spike-wave; 0.0167 seconds of triangular pulse.

The 2nd-order and the 4th-order Butterworth bandpass filters are designed with the narrow bandwidth (12 - 16Hz) specification. This bandwidth conforms that of the intra-sigma spindle periodicity [2]. The 2nd-order and the 4th-order Butterworth bandpass filters are also designed with the wider bandwidth (12 - 36Hz) specification. To investigate the delta wave distortion, the 2nd-order Butterworth bandpass filters are designed with the two different bandwidth specifications; 0.1 - 2.0Hz and 0.1 - 10.0 Hz. The designed analog filters are transformed to the digital counterpart filters by using the bilinear transform technique [3]. The sampling frequencies of the digital filters are 240Hz for the sigma conditioning filters and 70Hz for the delta conditioning filters, respectively.

The effect of the transient response of the linear phase FIR (finite impulse response) filter, which is designed for the sigma spindle detection in the automated EEG analysis [2], is also compared with those of the other IIR (infinite impulse response) filters.

Table 1 shows the lists of the designed digital filters.

Table 1. (a) Summary of the designed digital filters for sigma spindle waveform detection. Sampling frequency is 240Hz.

Digital Filter H(z)	Band-width (Hz)	Remark
$\frac{0.2454-0.2454z^{-2}}{1-1.2834z^{-1}+0.5092z^{-2}}$	12-16	2nd-order BWBP IIR
$\frac{0.0675-0.1351z^{-2}+0.0675z^{-4}}{1-2.6723z^{-1}+2.9900z^{-2}-1.6731z^{-3}+0.4125z^{-4}}$	12-16	4th-order BWBP IIR
$\frac{0.0498-0.0498z^{-2}}{1-1.7763z^{-1}+0.9003z^{-2}}$	12-36	2nd-order BWBP IIR
$\frac{0.0675-0.1351z^{-2}+0.0675z^{-4}}{1-3.6007z^{-1}+5.0975z^{-2}-3.3432z^{-3}+0.8622z^{-4}}$	12-36	4th-order BWBP IIR
$(z^{-5}-1)(z^{-2}+0.5z^{-1}+1)(z^{-1}+1)$	12-36	Linear Phase FIR

Table 1. (b) Summary of the designed digital filters for delta waveform detection. Sampling frequency is 70Hz.

Digital Filter H(z)	Band-width (Hz)	Remark
$\frac{0.0788-0.0788z^{-2}}{1-1.8410z^{-1}+0.8452z^{-2}}$	0.1-2.0	2nd-order BWBP IIR
$\frac{0.3226-0.3226z^{-2}}{1-1.3490z^{-1}+0.3548z^{-2}}$	0.1-10	2nd-order BWBP IIR

3. Experiments and results

The response of the 2nd-order Butterworth filter to a full period of 0.5Hz sinusoidal wave is illustrated in Fig. 2. The delta conditioning filter shows the significant amount of waveform distortions. The half wave shows the reduction of 28% in its peak amplitude level and the reduction of 16% in its half-wave period.

The outputs of three different types of the filters to the input signal of 13.5Hz sinusoidal burst are shown in Fig. 3. As is illustrated, the distortion gets bigger as the order of the filter is increased.

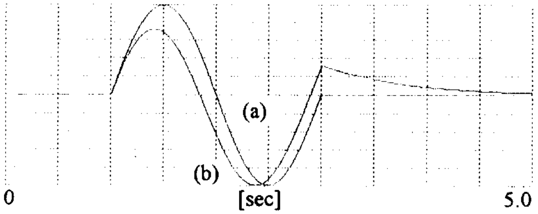

Fig 2. Response of the 2nd-order Butterworth filter(0.1-10Hz). (a) 0.5 Hz sinusoidal input. (b) Output of the filter.

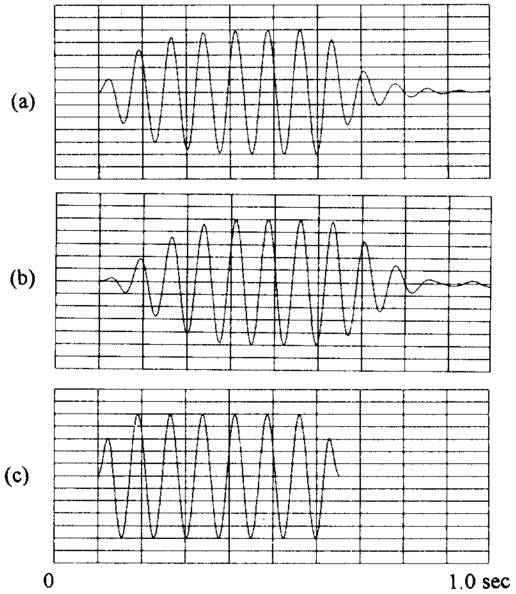

Fig 3. Responses of the filters to the sigma spindle model. (a) Output of the 2nd-order Butterworth filter(12-16Hz). (b) Output of the 4th-order Butterworth filter(12-16Hz). (c) Output of the linear phase FIR filter(12-36Hz).

The narrowband 4th-order Butterworth filter shows the worst distortion. In this case, the first peak of the output is reduced to only about 5% of the input peak. More than 5% of the reduction is still shown at the 7th half-wave peak. The wideband filters show the less distortions compared to the narrowband filters. The linear phase FIR filter shows the smallest distortion. The first peak of the output shows about 38% amplitude reduction and there does not exist any further amplitude distortion from the second peak. The filter magnitude distortions are summarized and shown in Fig. 4.

The filter responses to the spike-wave input are shown in Fig. 5. A spindle-like transient response is observed for the narrowband IIR filters. As mentioned before, this results from the ringing effect of the narrowband filters. Therefore, the narrowband IIR filters are susceptible to the spike-like noisy waves causing a false positive detection of the spindle.

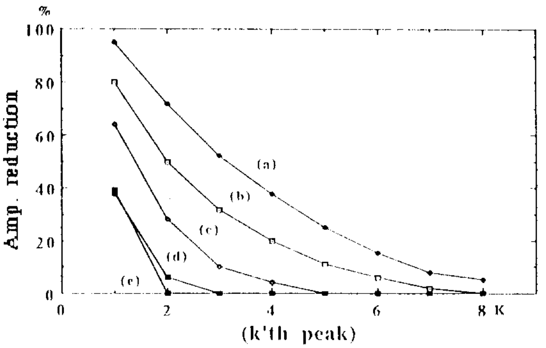

Fig 4. Summary of distortions in terms of peak amplitude reduction. (a) 4th-order BWBP filter (12-16Hz). (b) 2nd-order BWBP filter (12-16Hz). (c) 4th-order BWBP filter (12-36Hz). (d) 2nd-order BWBP filter (12-36Hz). (e) Linear phase FIR filter(12-36Hz).

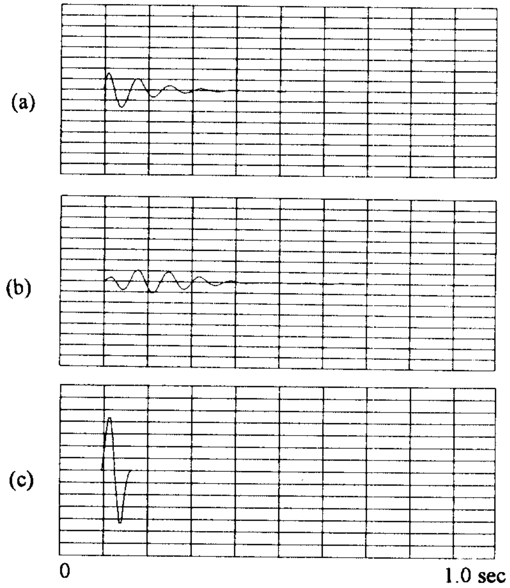

Fig 5. Responses of the filters to the spike wave model. (a) Output of the 2nd-order Butterworth filter(12-16Hz). (b) Output of the 4th-order Butterworth filter(12-16Hz). (c) Output of the linear phase FIR filter(12-36Hz).

Multichannel EEG signals are acquired using the acquisition system which is designed based on the Intel 8097 microcontroller chip with a 10bit A/D converter [4]. Microvolts(μV) level EEG/EOG signals are amplified by the Nihon Coden 8 channel EEG machine and interfaced to the acquisition system through an interfacing circuit. The acquisition system is also connected to an Intel 80386 type host computer through the RS232 communication interface. The signals are sampled with a 250 Hz rate for each channel. Detailed hardware descriptions of the system is shown in [4].

The filters' responses to a segment of central channel (C3-A2) EEG are illustrated in Figs. 6, 7, and 8. The response of the narrowband IIR filters shows the erroneous sigma spindle for the inputs of noisy spike and large amplitude delta wave. This results from the excessive ringing effect of the filter. On the other hand, the widerband FIR filter does not show any significant ringing effect. It just makes the appearance of the sigma spindle more discernable reducing the effect of the large amplitude wave and high frequency noise. This is the required characteristics of the signal conditioning filter for the successful detection of the waveforms.

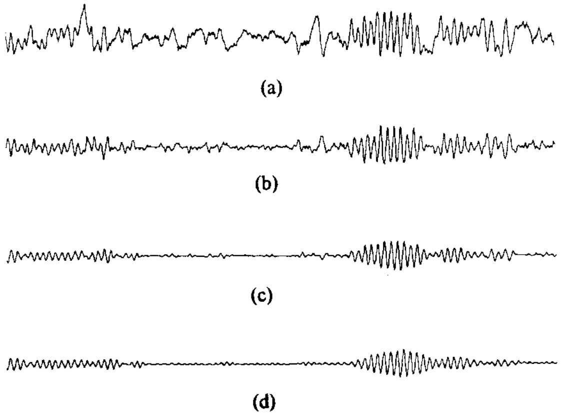

Fig 6. (a) Example of real EEG signal which contains a typical sigma spindle. (b) Conditioned signal by the linear phase FIR filter(12-36Hz). (c) Conditioned signal by the 2nd-order BWBP filter (12-16Hz). (d) Conditioned signal by the 2nd-order BWBP filter (12-16Hz). Note that ringing efects are observed in the output of the filters (c) & (d).

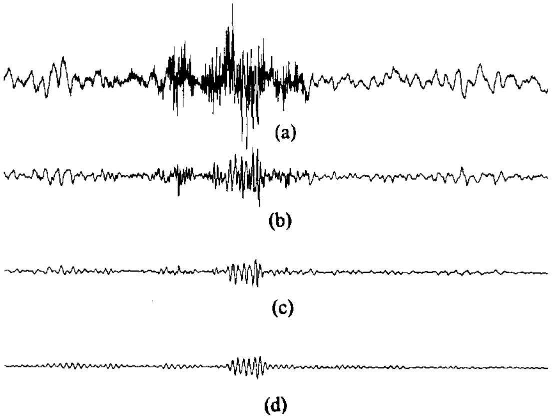

Fig 7. (a) Example of real EEG signal which contains a lot of noisy spikes(muscle artifacts). (b) Conditioned signal by the linear phase FIR filter(12-36Hz). (c) Conditioned signal by the 2nd-order BWBP filter (12-16Hz). (d) Conditioned signal by the 2nd-order BWBP filter(12-16Hz). Ringing effects of the filters (c) & (d) produce spurious sigma spindles when they are excited by the noisy spikes.

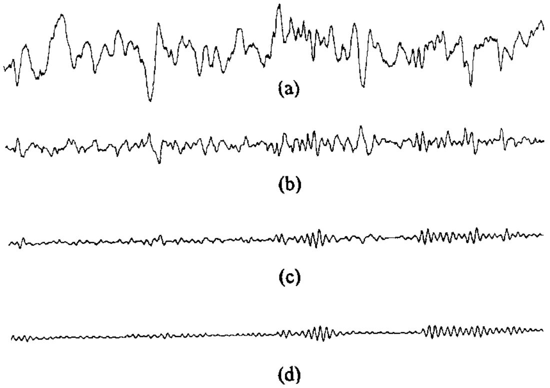

Fig 8. (a) Example of real EEG signal which contains large amplitude delta waves. (b) Conditioned signal by the linear phase FIR filter(12-36Hz). (c) Conditioned signal by the 2nd-order BWBP filter (12-16Hz). (d) Conditioned signal by the 2nd-order BWBP filter(12-16Hz). Spurious sigma spindles also occur when the filters (c) & (d) are excited by the large amplitude waves.

4. Discussions and Conclusion

The distortions resulting from the effects of the transient responses of the various types of the filters are investigated by explicitly simulating the filter responses to the typical EEG waveforms as well as to the spike-wave. It is illustrated that the signal conditioning filters generally produce the amplitude and period distortions because of the filter transients. The filters with wider bandwidth generally produce less waveform distortion and the lower order filters give less distortions. The linear phase FIR filters are generally more robust to the waveform distortion. Such an explicit analysis of the waveform distortions can provide a very much useful information for the definition of the waveform criteria as well as for the design of signal conditioning filters needed for the automated analysis of EEG data.

References

[1] J.R. Smith, Automated Analysis of Sleep EEG Data, Handbook of Electroencephalo-graphy and Clinical Neurophysiology, Vol. 2, Elsevier Science Publishing Co., Inc., New York 1986, 131-147.

[2] T.G. Chang, J.R. Smith, and J.C. Principe, "An expert system for multichannel sleep EEG/EOG signal analysis," ISA Transactions, Vol. 28, No.1, 1989, pp.45-51.

[3] A.V. Oppenheim and R.W. Schafer, Digital Signal Processing, Prentice- Hall Inc., 1975.

[4] J.H. Cho, T.G. Chang, and W.Y. Yang, "A study on the automated analysis of multichannel EEG signal," Proc. of KIEE Conf., July 1922, pp. 293-295.