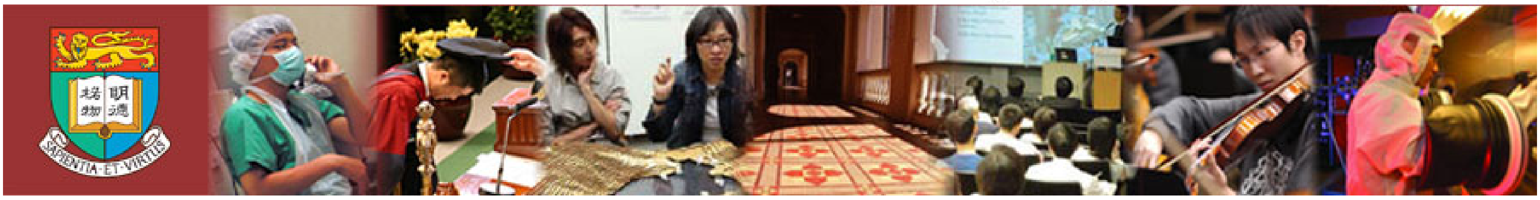
View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by HKU Scholars Hub

The HKU Scholars Hub The University of Hong Kong 香港大學學術庫



Title	Signal-to-noise ratio of intraoperative tibial nerve somatosensory-evoked potentials
Author(s)	Hu, Y; Liu, H; Luk, KDK
Citation	Journal Of Clinical Neurophysiology, 2010, v. 27 n. 1, p. 30-33
Issued Date	2010
URL	http://hdl.handle.net/10722/125185
Rights	This is a non-final version of an article published in final form in Journal of Clinical Neurophysiology, 2010, v. 27 n. 1, p. 30-33

*Manuscript (All Manuscript Text Pages in MS Word format, including Title Page, References and Figure Legends)

Signal-to-noise Ratio of Intraoperative Tibial Nerve Somatosensory Evoked Potentials

Yong Hu, HT. Liu, Keith D. K. Luk

Department of Orthopaedics and Traumatology, The University of Hong Kong, Pokfulam, Hong Kong

Correspondence to: Dr. Y. Hu

12 Sandy Bay Road, Hong Kong

Duchess of Kent Children's Hospital

Department of Orthopaedics and Truamatology,

The University of Hong Kong

Pokfulam, Hong Kong

Tel: (852) 29740359

Fax: (852) 29740335

E-mail: yhud@hkusua.hku.hk

Acknowledgements: This work was supported in part by Hong Kong Research Grants Council (RGC) Competitive Earmarked Research Grants (CERG HKU 7130/06E) and The University of Hong Kong CRCG Funds.

Running head: SNR of SEP

Abstract

To reveal the intrinsic signal to noise ratio (SNR) of somatosensory evoked potentials during spinal surgery, SEP was recorded by 13 scoliosis patients during intraoperative recording. The power of the SEP was estimated with least squares fitting in order to obtain the most realistic SNR of SEP. The SNR of cortical SEP from 13 cases presented individual difference among each other. According to the mean and standard deviation (SD), the coefficients of variation (CV) of cortical and sub-cortical SEP were 4.2% and 23%, respectively. The SNR of SEP were estimated to be -24±1dB in cortical SEP and -22±5dB in sub-cortical SEP. The lowest SNR of individual case was found to be -30dB in cortical SEP and -53 dB in sub-cortical SEP. The results showed that SNR of SEP varies considerably from person to person and it could be as low as -50dB. The results from this study can be used to understand the nature of SEP signals, which could guide researchers and designers on SEP denoising method selection, extraction and measurement as well as equipment development.

Keywords: Somatosensory evoked potentials (SEP), signal-to-noise ratio (SNR), intraoperative monitoring

Introduction

Somatosensory evoked potentials (SEP) are cortical or sub-cortical responses to repetitive electrical stimulation of a mixed peripheral nerve (Devlin et al. 2006). It has been widely used intraoperatively to minimize the possible risks during spinal surgery (Hu et al. 2005; MacLennan and Lovely 1995; Nuwer 1998). Unfortunately, when record via electrodes, the signal of interest is embedded in considerable noises, result in a low signal to noise ratio (SNR) (Lam et al. 2005; Hu et al. 2005). Ensemble averaging (EA) is the most commonly used method for SEP features detection. It averages the responses to repetitive stimulus in order to obtain SEP estimates with an acceptable SNR. Some other attempts tried to use various denoising techniques to improve SNR of SEP and minimize the demand of EA sweeps (Hu et al. 2005; Lam et al. 2005; Liu et al. 2007; Chan et al. 1995). However, these previous denoising method considered the “processed” signal as “cleaned” SEP signal, without knowing to what extent the intrinsic SNR of the original signal has actually been improved. Without the knowledge of the proportion of the SEP in the noised signal, i.e. the SNR, the improvement after the application of these denoising methods could possibly just be the result of signal processing. Hence, the understanding of intrinsic SNR of the original SEP signal is crucial in SEP detection and extraction.

As defined by Raz et al(Raz et al. 1988), SNR is defined as the ratio of unbiased estimators of signal and noise power, and it was used for constructing approximate confidence intervals for the Evoked Potential (EP). This method, while assuming the noise is stationary, seems not applicable in the case of SEP, as EEG, being the major source of noise in SEP, is non-stationary. Another report (Hongxuan et al. 2006) calculated the SNR by maximum amplitude ratio between SEP and noise and claimed the SNR of SEP to be about 1:10. However, the maximum amplitude ratio used in this work violates the conventional SNR formulation, which calculates the SNR based on power estimation, and thus, may lead to error. Recent reports (Jorge and Ozcan 2006; Ozcan and Jorge 2006) presented a SNR formulation in auditory evoked potential based on deconvolution averaging which could attenuate or amplify phase unlocked noise depending on the frequency characteristics of the arbitrary stimulus sequence. Although multiple sweeps were performed, the estimation of EP signal power produced may still be far from that of the true signal. Furthermore, most SNR were definited empirically. To the best of the authors' knowledge, there is so far no any study regarding the intrinsic SNR of intraoperative SEP or any feasible estimating method be reported previously.

The purpose of this study was to reveal the intrinsic SNR of SEP signals from a single sweep SEP recording. The knowledge of intrinsic SEP may benefits clinicians or researchers in selecting adequate signal processing methods on SEP signal detection and measurement.

Method

SIGNAL PROCESSING

EA, construct a more reliable SEP waveform by multiple sweeping of the signal, is the most general method in SEP detection from scalp recordings following a sensory stimulus. The i^{th} sweep SEP waveform, $x_i(t)$, is a continuous-time signal

$$x_i(t)= s_i(t)+ n_i(t), \quad i=1, 2,\ldots,M \tag{1}$$

where $s_i(t)$ and $n_i(t)$ are the signal and noise components in the i^{th} SEP waveform, and M is the number of sweeps. This model has widely been accepted in literature.

EA method assumes that $s_i(t)$ is deterministic and $n_i(t)$ is white noise with zero mean. Based on this assumption, the power of $x(t)$ after m ($m=1,2,3\ldots$) times averaging, $P_x(m)$, can be given by

$$P_x(m) = P_s + P_n \tag{2}$$

where P_s and P_n are the power of $s(t)$ and $n(t)$ after m-time averaging, and $P_x(m)$ is the power of m-time averaged signal with noises. EA consider $P_x \approx P_s$ after a large number of averaging, e.g. EA900. However, the EA900 signal estimates probably contained substantial residual noise contamination. Therefore, instead of EA900, least square fitting was employed to estimate P_s in this study.

Because P_n is inverse proportional to number of averaging performed, m, the estimate of P_s by EA can be obtained

$$P_s = \lim_{m\to\infty} P_x(m) = \lim_{m\to\infty}(P_s + \frac{\sigma^2}{m}) \tag{3}$$

where σ^2 is the power of filtered white noise.

By specifying values of m, the $P_x(m)$ can be calculated and the function can be described as

$$P_x(m) = P_s + \frac{\sigma^2}{m} \tag{4}$$

Therefore, we can denote a fitting function as:

$$f(x) = a + \frac{b}{x} \tag{5}$$

where x is the independent variable, a and b are constant. With enough values of x and $f(x)$, a and b can be estimated by the least squares fitting. In comparing equation (4) and (5), if we defined $P_x(m)$ as $f(x)$, it is obviously seen: $P_s = a$ and $\sigma^2 = b$.

Then SNR can be estimated by

$$SNR = 10\log_{10}\frac{P_s}{P_n} = 10\log_{10}\frac{P_s}{\sigma^2} \tag{6}$$

DATA COLLECTION

The data used in this study were obtained from 13 scoliosis patients who were undergoing surgical correction. They were 4 males and 9 females (ages 12-43 years, median 13 years). This study protocol was approved by the Institutional Review Board for Clinical Research Ethics. General anaesthesia with isoflurane and 100% Oxygen maintained below 1 MAC (between 0.6-1.2%) was used throughout the surgery (Hu et al. 2001; *Spinal cord monitoring : basic principles, regeneration, pathophysiology, and clinical aspects* 1998). The stimulation for SEP recording was applied on the posterior tibial nerve of the left lower limb with pulse duration of 0.2ms, at rate of 5.1Hz and constant current of 10 to 30mA. SEP signals were collected over Cz' (2cm posterior to Cz, 10-20 International system of electroencephalogram electrode placement), Cv (on the cervical spine over C2 process) versus the Fz of the 10-20 system. The signals were amplified 100,000 times. In consideration of commonly used optimal band filter for intraoperative SEP monitoring, the raw SEP signals were further filtered at 20-2000Hz (Hongxuan et al. 2006). All the SEP signals were acquired and recorded to a computer with 16-bit resolution and sampling rate of 5 kHz. A total of 900 sweeps were collected for each patient. But m was chosen from 500 to 900 in equation (4) since the averaged signals using previous 500 sweeps deviate the true one greatly. Though the length of entire sweep is 100ms, the meaningful information in the sweep or the potential of interest was considered in this study: the P37 for the cortical SEP and P31 for the sub-cortical. Therefore, signals within the window of 30~70ms in cortical SEP and the window of 15~55ms in sub-cortical SEP were used for SNR estimate.

DATA ANALYSIS

The SNR of every response from each patient was computed by the method mentioned above. The mean value and standard deviation (SD) were computed as well. To evaluate the variation, the coefficient of variation (CV), defined as the ratio of standard deviation to mean, was employed to measure the dispersion of a probability distribution.

Results

The SNR level of SEP was found to be very small from the results of this study. Fig. 1 shows an example of the entire single-sweep as well as 900 times averaged SEPs from one of the subjects. As showed in Fig. 1-(a) and 1-(b), SEP cannot be observed in single-sweep signal of both channels. After averaging, an obvious SEP was observed (Fig.1-(c) and (d)). Fig. 2 shows the relationship between the computed and estimated power of cortical SEPs and the increase of averaging number (that of sub-cortical SEPs was similar to this). The computed power was the signal power obtained by the traditional EA method ranging from 2 sweeps till 900 sweeps, while the estimated signal power was based on the least square fitting function. The correlation coefficient between the two curves was 0.98 and the estimated power showed a significant correlation with the computed one ($p<0.01$).

The estimated SNR of single-sweep SEP is presented in Table 1. The mean SNR values of cortical SEP and sub-cortical SEP from the 13 patients are -24±1dB and -22 ±5dB respectively. The variations of SNR in terms of the coefficient of variation (CV) are 4.2%(cortical) and 23%(sub-cortical). The intrinsic SNR estimated present a large inter-subject variability ranging from -53 dB to -5dB. The poorest SNR situation in cortical SEP was found to be as low as -30 dB, whereas the poorest SNR situation in sub-cortical SEP was -53 dB. From the comparison of the two channels, statistical significant differences could not be observed in single-sweep SEP signal ($p>0.05$).

Discussion

The present study was designed to figure out the SNR of single-sweep intraoperative SEP recorded in operation room. The true SEP signals can be obtained theoretically by EA when the number for averaging approaches infinity. This is not feasible in practice but the infinite-sweep-averaged SEP can be estimated with finite sweeps which was specified as 900 in this study once the fitting function was established. An estimated signal power of SEP, which is close to the true SEP, could be acquired by least square fitting function with 900 sweeps.

The results of this study indicate that the mean SNR of a single SEP signal were -24dB for cortical and -22dB for sub-cortical recording. This means the noise power was about 300 times greater than the SEP power, i.e. 17 times greater in amplitude. These results were in consistence with previous findings reporting a poor SNR in SEP(Lam et al. 2004; Iyer and Zouridakis 2007; Qiu et al. 1994; Xuan and Thakor 1996; Hu et al. 2005). Without the knowledge of the SNR of intraoperative SEP, a number of simulation studies based on experiences about multi-channel SEP extraction have been carried out using methods such as multi-adaptive filter (Lam et al. 2005) at -10, -15 and -20dB and second order blind identification at -10 and -20dB (Hu et al. 2005; Lam et al. 2005; Liu et al. 2007; Chan et al. 1995). However, the applicability of these technique is doubt when the SNR are much lower than -20dB (Table 1), This requires a further development on SEP extraction studies. Thus, our finding may provide insight in SEP processing method selection, even in methods combination at different SNR level.

Moreover, the inter-subject variability of the SNR of SEP is large as presented in the results. The intrinsic SNR ranged from -53 dB to -5dB while the coefficients of variation of single-sweep SEP from Cz'-Fz and Cv-Fz are 4.2% and 23%. This variation should reflect the true physiologic variance between subjects. Because the SEP was recorded in a controlled operation room setting, the corruption by the environmental and instrumental noises should be similar between patients.

Comparing cortical SEP with sub-cortical, although no statistical significant difference was found, it should be noted that the major sources of noise for cortical and sub-cortical SEP are different. Under anesthesia, EEG is the major source of noise for both channels (Lam et al. 2005). Nevertheless, since the sub-cortical is more susceptible to extraneous electrical artifacts, ECG is another source of noise caused by the longer inter-electrode distance and electrode location in SEP recording. Despite the difference of noise powers in cortical and sub-cortical recording, the resulting SNR in these two cases are similar.

It is noteworthy that intravenous anesthesia (Sloan and Heyer 2002) and an optimized recording derivation (MacDonald et al. 2005; MacDonald et al. 2004) may result in higher cortical SEP SNR. The inhalational anesthesia can produce a dose-related reduction in amplitude of cortically recorded SEP (Pajewski et al. 2007), therefore, isoflurane, being an inhalational agent, may also suppresses this potential. In another aspect, the optimized recording technique reporting a superior SNR (MacDonald et al. 2005; MacDonald et al. 2004) may reduce the number of sweeping during intra-operative monitioring. Using this technique, a higher SNR may be obtained.

Conclusion

The intrinsic SNR of intraoperative SEP varies from person to person with a broad range, from -53 to -5dB. Moreover, the SNR of SEP were -24±1dB in cortical SEP and -22±5dB in sub-cortical SEP. The findings of this study may enhance the understanding of the nature of SEP signals during intra-operative monitoring and guide researchers and designers on SEP denoising method selection, extraction and measurement as well as equipment development.

Captions of figure and table

Figure 1 A sample of SEP recording. (a) single-sweep cortical SEP (b) single-sweep sub-cortical SEP (c) EA900 cortical SEP (d) EA900 sub-cortical SEP

Figure 2 Illustration of the computed and estimated signal power of a sample cortical SEP

Table 1 SNR estimation of single-sweep SEP

References

Chan, F. H. Y., F. K. Lam, P. W. F. Poon, and W. Qiu. 1995. Detection of brainstem auditory evoked potential by adaptive filtering. *Medical and Biological Engineering and Computing* 33 (1):69-75.

Devlin, V. J., P. A. Anderson, D. M. Schwartz, and R. Vaughan. 2006. Intraoperative neurophysiologic monitoring: focus on cervical myelopathy and related issues. *Spine J* 6 (6 Suppl):212S-224S.

Hongxuan, Z., S. Venkatesha, R. Minahan, D. Sherman, Y. Oweis, A. Natarajan, and N. V. Thakor. 2006. Intraoperative neurological monitoring. *IEEE Engineering in Medicine and Biology Magazine* 25 (4):39-45.

Hu, Y., B. S. Lam, C. Q. Chang, F. H. Chan, W. W. Lu, and K. D. Luk. 2005. Adaptive signal enhancement of somatosensory evoked potential for spinal cord compression detection: an experimental study. *Comput Biol Med* 35 (9):814-828.

Hu, Y., K. D. Luk, Y. W. Wong, W. W. Lu, and J. C. Leong. 2001. Effect of stimulation parameters on intraoperative spinal cord evoked potential monitoring. *J Spinal Disord* 14 (5):449-452.

Iyer, D., and G. Zouridakis. 2007. Single-trial evoked potential estimation: Comparison between independent component analysis and wavelet denoising. *Clin Neurophysiol* 118 (3):495-504.

Jorge, B., and O. Ozcan. 2006. Signal to noise ratio analysis of maximum length sequence deconvolution of overlapping evoked potentials. *The Journal of the Acoustical Society of America* 119 (5):2881-2888.

Lam, B. S., Y. Hu, W. W. Lu, and K. D. Luk. 2004. Validation of an adaptive signal enhancer in intraoperative somatosensory evoked potentials monitoring. *J Clin Neurophysiol* 21 (6):409-417.

Lam, B. S. C., Y. Hu, W. W. Lu, K. D. K. Luk, C. Q. Chang, W. Qiu, and F. H. Y. Chan. 2005. Multi-adaptive filtering technique for surface somatosensory evoked potentials processing. *Med Eng Phys* 27 (3):257-266.

Liu, H., Y. Hu, C. Q. Chang, and K. D. K. Luk. 2007. Fast extraction of Somatosensory Evoked Potential based on Second Order Blind Identification. Paper read at Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE.

MacDonald, D. B., Z. Al Zayed, and B. Stigsby. 2005. Tibial somatosensory evoked potential intraoperative monitoring: recommendations based on signal to noise ratio analysis of popliteal fossa, optimized P37, standard P37, and P31 potentials. *Clin Neurophysiol* 116 (8):1858-1869.

MacDonald, D. B., B. Stigsby, and Z. Al Zayed. 2004. A comparison between derivation optimization and Cz'-FPz for posterior tibial P37 somatosensory evoked potential intraoperative monitoring. *Clin Neurophysiol* 115 (8):1925-1930.

MacLennan, A. R., and D. F. Lovely. 1995. Reduction of evoked potential measurement time by a TMS320 based adaptive matched filter. *Med Eng Phys* 17 (4):248-256.

Nuwer, M. R. 1998. Spinal cord monitoring with somatosensory techniques. *J Clin Neurophysiol* 15 (3):183-193.

Ozcan, O., and B. Jorge. 2006. Signal-to-noise ratio and frequency analysis of continuous loop averaging deconvolution (CLAD) of overlapping evoked potentials. *The Journal of the Acoustical Society of America* 119 (1):429-438.

Pajewski, T. N., V. Arlet, and L. H. Phillips. 2007. Current approach on spinal cord monitoring: the point of view of the neurologist, the anesthesiologist and the spine surgeon. *Eur Spine J* 16

Suppl 2:S115-129.

Qiu, W., F. H. Y. Chan, F. K. Lam, and P. W. F. Poon. 1994. Enhanced approach to adaptive processing of the brain steam auditory evoked potential. *Australasian Physical & Engineering Sciences in Medicine* 17 (3):131-135.

Raz, J., B. Turetsky, and G. Fein. 1988. Confidence intervals for the signal-to-noise ratio when a signal embedded in noise is observed over repeated trials. *IEEE Trans Biomed Eng* 35 (8):646-649.

Sloan, T. B., and E. J. Heyer. 2002. Anesthesia for intraoperative neurophysiologic monitoring of the spinal cord. *J Clin Neurophysiol* 19 (5):430-443.

Spinal cord monitoring : basic principles, regeneration, pathophysiology, and clinical aspects. 1998. Edited by E. Stalberg, H. S. Sharma and Y. Olsson. Wien :: Springer Verlag.

Xuan, K., and N. V. Thakor. 1996. Adaptive estimation of latency changes in evoked potentials. *IEEE Trans Biomed Eng* 43 (2):189-197.

Figure

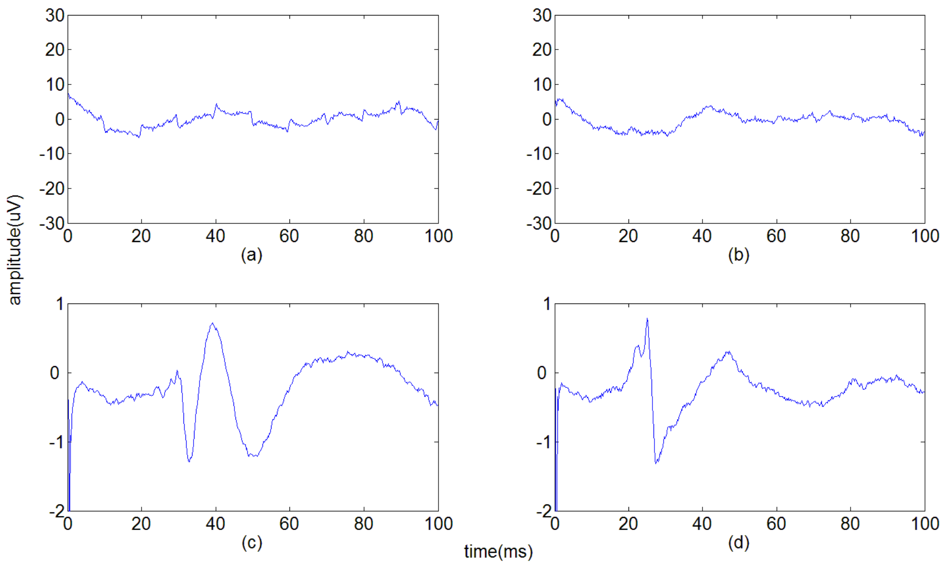


Figure 1 A sample of SEP recording. (a) single-sweep cortical SEP (b) single-sweep sub-cortical SEP (c) EA900 cortical SEP (d) EA900 sub-cortical SEP

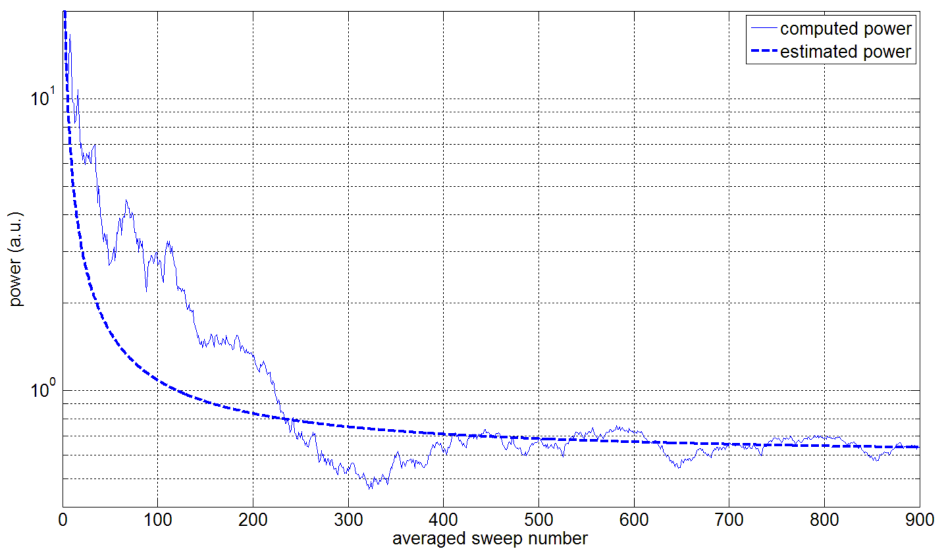


Figure 2 Illustration of the computed and estimated signal power of a sample cortical SEP

Table

Table 1 SNR estimation of single-sweep SEP

Case No.	Cz'-Fz (cortical SEP)	Cv-Fz (sub-cortical SEP)
1	-25 dB	-11 dB
2	-25 dB	-36 dB
3	-30 dB	-32 dB
4	-21dB	-53dB
5	-27 dB	-22 dB
6	-25 dB	-19 dB
7	-30 dB	-33 dB
8	-27 dB	-25 dB
9	-21 dB	-11 dB
10	-23 dB	-23 dB
11	-20 dB	-5 dB
12	-19 dB	-21 dB
13	-25 dB	-14dB
Mean(SD)*	-24±1 dB	-22±5dB

* The mean value and SD are not computed directly from the SNRs of 13 subjects. It is evident that substantial skewness to lower values exists in the single-sweep SNR results. Thus, mean, SD and variance calculations based on a normal distribution are not valid for this data. It must be transformed to a more normal distribution or analyzed in another way [20].