Using Spectral Coherence for the Detection and Monitoring of Spinal Cord Injury

Angelo All[1], Noreen Fatoo[2], Nabil Mirza[2], Rabi Ahmed[2], Hasan Al-Nashash[2] and Nitish Thakor[1]

[1] Johns Hopkins University, Baltimore, USA
[2] American University of Sharjah, Sharjah, UAE

***Abstract* — Somatosensory evoked potentials (SEPs) were obtained from 15 rats that were inflected with graded injury using the NYU Impactor. SEPs, in response to stimuli to the nerves in the limbs, were recorded from the cranium. Spectral coherence was used to analyze these signals. Results obtained from the investigation show that this technique is capable of providing a quantitative measure of spinal cord injury (SCI).**

***INDEX TERMS* — Bioelectric phenomena, Bioelectric potentials, Biomedical engineering, Biomedical signal processing, Limbs, Neural networks, Spectral analysis.**

I. INTRODUCTION

United States alone has about 14,000 cases of spinal cord injury every year. Moreover, all over the world, millions of SCI patients are living with the devastating effects of spinal cord injuries [1]. A steady improvement in life expectancy without analogous enhancement in the quality of life has led to a rising number of SCI patients.

Research in the area of spine injury is becoming even more important as the number of accidents and misfortunate incidents is increasing.

The Basso, Breathe and Breshnahan (BBB) technique is a conventional method to assess SCI. It involves an observation of a rat for four minutes in an open field by a trained examiner [2]. A score between 0-21, where 0 and 21 stand for the lowest and highest possible scores respectively represents the condition of the rat. This technique is well-accepted and easy to execute. Nevertheless, it does not show distinguished recovery for mild injuries [3]. Moreover, BBB results are not concurrent between two examiners. It also does not control for the non-willingness of the rodent to move due to swelling, anesthesia, pain, etc. Another disadvantage of BBB is that the examiner needs to have a trained eye. BBB, inherently, is a method to evaluate motor function and confers no information about the state of the sensory pathways of the rat.

In this research work, rodents were used to validate a potential method to provide a quantitative measure of SCI. An Evoked Potential (EP) is an electrophysiological response of a neural system to an external stimulus. Somatosensory evoked potentials (SEPs) are generally obtained by electrical stimulation of the median nerve at the wrist or the posterior tibial nerve at the ankle [4]. This mechanism was applied to evaluate ongoing neuropsychological changes throughout the recovery period after SCI.

Previous studies using SEP data for SCI detection have used changes in latency and peak amplitude of SEP signals as seen in Fig. 1. The inherent disadvantage of time analysis is that spectral changes can not be detected. Moreover, some SEP signals, like in Fig. 2, do not have a detectable latency or peak amplitude. Other methods which have been used to analyze SEP signals include autoregressive algorithms, adaptive latency measurement, kinematic measures, etc. [5-7].

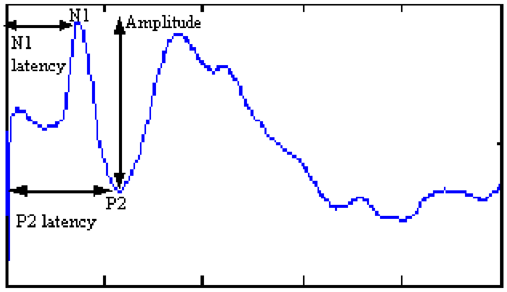

Fig. 1. Latency and peak amplitude measurement in an SEP signal.

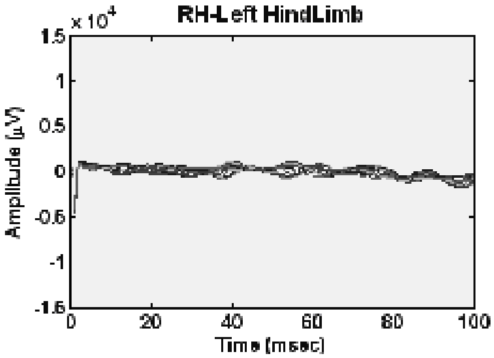

Fig. 2. Overlapped SEP signals that have been taken from one of the experimental rats. The signal has no detectable latency and peak amplitude.

Coherence analysis will give a quantitative measure that can be used for the detection and monitoring of SCI. Recent work also shows that there is a very sharp drop in the magnitude coherence estimation during hypoxic brain injury [8].

An assessment method was developed via signal processing and event-related neurological monitoring. This will enable researchers, in the area of SCI recovery and rehabilitation, to assess more accurately and objectively any possible therapeutic mechanisms to reverse or prevent the devastating effects of SCI.

The paper is organized as follows. In section II, the injury protocol and spectral coherence are introduced. Section III presents some results of the spectral coherence assessment method. Finally, conclusions and suggestions for future work are included in section IV.

II. METHODOLOGY

A. Injury Protocol

Female adult Fischer rats were used as the experimental samples. Five burr holes were drilled into the cranium at the forelimb and hindlimb somatosensory cortex area on the right and left hemispheres. The four screw electrodes made very light contact with the duramater, but did not compress the dura or brain structures. The fifth screw electrode, on the anterior of the cranium, was used as a reference electrode. These skull electrodes were used to obtain the SEP signals.

After implanting skull electrodes, a 30-60 minute *baseline* SEP was recorded. This was followed by laminectomy which takes around 20 minutes. Right after the laminectomy, *post-lamin baseline* SEP was recorded for 30-60 minutes. The rat was then removed from SEP set-up and put under NY-impactor to induce an injury in the T-8 region. The graded levels of SCI were produced by dropping a 10 g rod with a flat circular impact surface from heights of 6.25, 12.5, 25 or 50 mm for the mild, moderate, severe and very severe injury groups respectively. This process takes around 10 minutes. The rat was returned for *post-injury* SEP recording for 60 minutes.

To generate stimulation for SEP, subcutaneous needle electrodes are used for left and right median and tibial nerves (1 Hz frequency, 3.5 mA amplitude, 200 ms duration, 50 % duty cycle) without direct contact with the nerve bundle.

Contralateral SEP recordings were used for the left and right forelimbs, as well as the hindlimbs. Averaging of the recorded evoked potentials was performed to enhance the signal-to-noise ratio.

Biologically, the left hemisphere controls the right side of our bodies and vice versa. Therefore, it is reasonable to use signals from the left hemisphere to analyze right forelimbs and hindlimbs. In this report, all the analysis is done baring this in mind and the results focus on the right limbs.

B. Spectral Coherence Analysis

The coherence function gives a measure of similarity between signals and is related to cross correlation function. The magnitude-squared spectral coherence function Γ_{xy}^2 of two signals X and Y is a normalized version of the cross power spectral density between X and Y and is defined as

$$\Gamma_{xy}^2(\omega) = \frac{\left|P_{xy}(\omega)\right|^2}{P_{xx}(\omega)P_{yy}(\omega)} \qquad (1)$$

$P_{xy}(\omega)$ is the cross power spectrum between X and Y signals, $P_{xx}(\omega)$ and $P_{yy}(\omega)$ are the power spectrums of the X and Y signals respectively.

Assume that the 1 Hz input stimulus signal S is the same for all limbs. X, in Fig. 3, is the SEP signal recorded at the cortex which results from stimulating the left forelimb, right forelimb, left hindlimb or right hindlimb. Similarly, Y is the SEP signal recorded at the cortex which results from stimulating the left Forelimb, right forelimb, left hindlimb or right hindlimb. Assume that X and Y are related to S through linear systems H_1 or H_2 but they also contain additive independent noise n_1 and n_2. H_1 or H_2 is used to model the transfer function of the biological system or network from the stimulation site to the recording site at the cortex.

For a normal healthy spinal cord transmission system, H_1 and H_2 are expected to have a relatively fixed frequency transfer characteristics. However, following SCI, H_1 or H_2 or both will be modified and hence their frequency transfer characteristics will also be modified. Therefore, the spectral coherence function will also be modified.

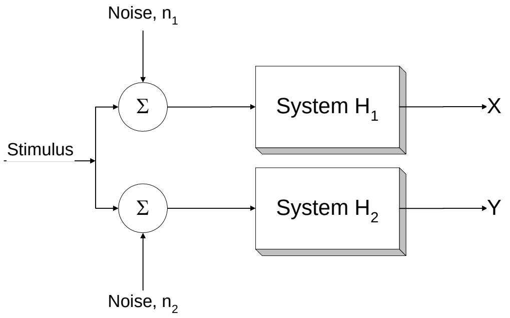

Fig. 3. Stimulus source signal passing through two networks H_1 and H_2, which represent the biological system from the simulation site to the recording site.

Under normal conditions, we expect Γ_{xy}^2 to approach 1. However, Γ_{xy}^2 may decrease down to zero under SCI conditions. In this work, Γ_{xy}^2 is computed for N epochs averaged, with a spectral coherence given by:

$$\overline{\Gamma}^2(\omega) = \frac{1}{N}\sum_{i=1}^{N}\Gamma_i^2(\omega) \quad (2)$$

The SEP data size controls the selection of N. The available data enabled us to select N between 20 and 50. N was selected to be around 20 for all average spectral coherence values. Average coherence was performed for a band that concentrated on the region with the highest baseline spectral coherence. This is called the *global coherence*.

III. RESULTS

The following results are obtained for a cohort of 15 rats. Each of the four groups mentioned in the previous section had three rats. Additionally, a group of three rats was used as control. The spectral coherence was taken against the baseline right forelimb SEP signal which is used as a control signal throughout the process of data analysis. It can be assumed that the effect of injury on the forelimb is insignificant. Hence, any right forelimb signal can be used instead of its baseline (before injury SEP signal) for analysis of rats injured by the NY-impactor [9].

Figure 4 shows the global spectral coherence between the baseline right forelimb and the right hindlimb signals over time for two of the control rats. The control rats have a high global spectral coherence relative to their baseline spectral coherence. A show of consistently high spectral coherence for all days of measurement relates to non-injury.

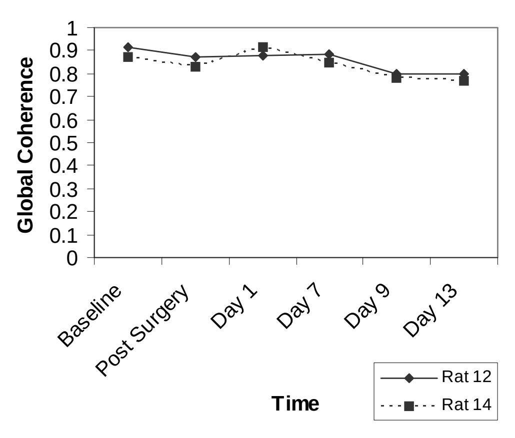

Fig. 4. Global spectral coherence between baseline right forelimb and right hindlimb over time for Rat 12 and Rat 14 from the control group.

A visual inspection of the averaged time domain signals, as seen in Figure 5, of the right hindlimb before and 13 days after surgery for any one of the two rats can also support the findings of no injury. The shape of the time domain signal is the same after 13 days of surgery as it was before the surgery.

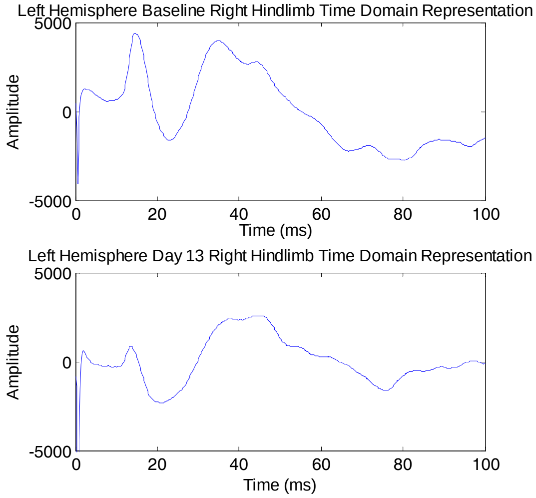

Fig. 5. The averaged time domain signals of the right hindlimb before and 13 days after surgery for Rat 12.

Figure 6 shows the global spectral coherence between the baseline right forelimb and the right hindlimb signals over time for two of the rats from the 6.25 mm injury level group.

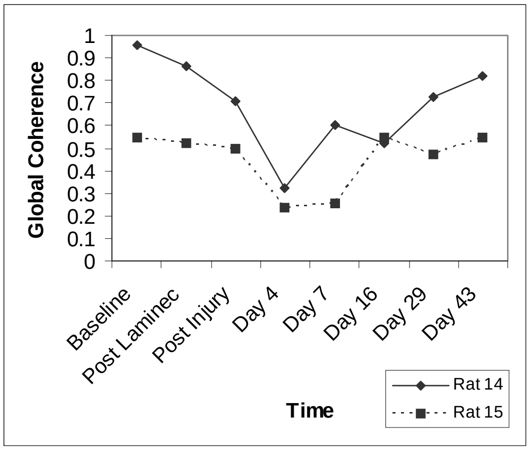

Fig. 6. Global spectral coherence between baseline right forelimb and right hindlimb over time for Rat 14 and Rat 15 from the 6.25 mm injury level group.

It can be observed, from Figure 6, that the rats recover with different degrees relative to the same level of coherence before injury due to the variability of the extent and location of injury. A visual inspection of the averaged time domain signals, as seen in Figure 7, of the right hindlimb of Rat 14 support the findings of recovery as the shape of the signal after 44 days is close to the shape of the signal before injury.

Spectral coherence reflects the level of injury and severity of injury. Our conclusions about the right hindlimb should not be confused with overall health of the rat. A recovery in the shape of the waveform of the right hindlimb tells us of the health of the right hindlimb only. There are cases in further levels of injuries wherein the left hindlimb signal had not shown the same improvement as the right hindlimb did. This report includes results based on right hindlimb only.

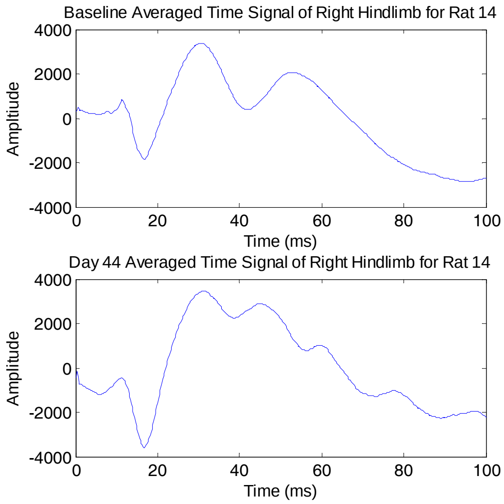

Fig. 7. The averaged time domain signals of the right hindlimb before and 44 days after injury for Rat 14.

The global coherence for two rats with an injury level of 50 mm, as seen in Figure 8, shows no recovery or improvement in the right hindlimb after the injury had taken place. The baseline and Day 85 time signals are plotted in Figure 9 for one of the rats. It can be visually confirmed that no similarity between the waveform shapes and therefore, we can conclude that the injury was persistent.

Spectral coherence reveals information specific to each rat that is missing in conventional methods of assessing spinal cord injury.

IV. CONCLUSION

Spectral coherence analysis was tested on experimental data obtained from rats. Some of the advantages of this method are that it: a) is a normalized quantitative measure; b) does not require a trained examiner; c) does not necessarily require the baseline signals; and d) is an objective method. This method can show improvements in a particular hindlimb. Such information is missed when other techniques are used.

Every rat has a different frequency band of interest. In this research, we have assumed that averaged peak coherence before injury coincides for all rats.

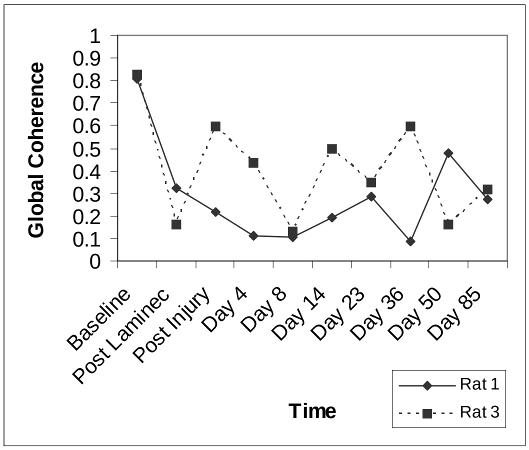

Fig. 8. Global spectral coherence between baseline right forelimb and right hindlimb over time for Rat 1 and Rat 3 from the 50 mm injury level group.

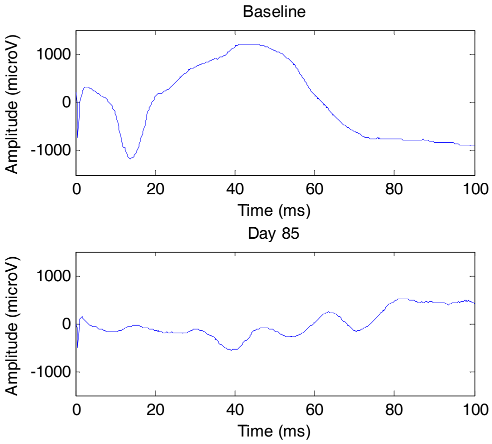

Fig. 9. The averaged time domain signals of the right hindlimb before and 85 days after injury for Rat 3.

As the time domain SEP signal is non-stationary, our future work will focus on the development and testing of a method that incorporates time with spectral coherence.

REFERENCES

[1] D. Schreiber, “Spinal Cord Injuries,” in *emedicine-Instant Access to the Minds of Medicine*, vol. 2004, D. J. Dire, F. Talavera, T. Scaletta, J. Halamka, and C. V. Pollack, Eds., 2002. Available: http://www.emedicine.com/emerg/byname/spinal-cord-injuries.htm.

[2] All, Angelo H., Sherman, David L., Eaton, Mary J. and Thakor, Nitish V., “Somatosensory Evoked Potential as a Complement to Motor Behavioral Assessment of Spinal Cord Injury Outcome,” unpublished.

[3] Aggarwal, Manisha, “Assessment of Spinal Cord Injury in a Rodent Model using Somatosensory Evoked Potentials and Magnetic Resonance Imaging,” May 2006, unpublished.

[4] M. Nuwer, "Fundamentals of evoked potentials and common clinical applications today," Electroencephalography and Clinical Neurophysiology, vol. 106, pp. 142-148, 1998.

[5] C. Sergio, C. Giuseppe, L. Deigo, M. Paolo and P. Giorgio, “A Parametric Method Of Identification of Single-Trial-Event-Related Potentials in the Brain,” *IEEE Trans. Biomedical Engineering*, VOL. 35, NO. 9, September 1988.

[6] K. Xuan and T.V. Nitish, “Adaptive Estimation of Latency Changes in Evoked Potentials,” *IEEE Trans.Biomedical Engineering*, Vol. 43, No. 2, February 1996.

[7] R. Jung, E.A. Knapp, A.K. Thota, B.T. Thompson, S. Mulligan, N. Ravi and A. Quick, “Quantitative Outcome Measures for Assessing Motor Control in a Rodent Model of Spinal Contusion Injury,” in *Conf. EMBS/BMES,* Houston, TX, USA, October 23-26, 2002.

[8] Gerovichev, O., Naeini, H. M., Sherman, D. L., Al-Hatib, F., Venkatesha, S., Geocadin, R., Hanley, D., Thakor, N., “Detection of brain herniation with spectral coherence analysis of somatosensory evoked potentials,” in *Proceedings of the Second Joint EMBS/BMES Conference*, 2002.

[9] Fatoo, N., Mirza, N., Ahmed, R., Al-Nashash, H., All, A., Thakor, N., “Detection and Assessment of Spinal Cord Injury Using Spectral Coherence,” in *the 29th IEEE EMBS Annual International Conference*, 2007.