COMPARISON OF TEMPORAL AND SPECTRAL PROPERTIES OF EMFi AND SCSB SIGNALS

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ABSTRACT

In this paper we describe methods developed and applied for comparing temporal and spectral properties of signal from an Electromechanical Film (EMFi) sensor and signal from a Static Charge Sensitive Bed (SCSB) mattress in order to evaluate the different properties of these sensors and their suitability for sleep studies. The SCSB mattress has been used earlier in sleep research for simultaneous recordings of respiration, BCG (ballistocardiogram) and movements in order to detect different sleep disorders like apneas and for sleep scoring. Nowadays also the EMFi sheet has shown potential in sleep recordings.

For this study a single simultaneous recording was made from one person with SCSB mattress and EMFi sheet and three signal analysis methods were developed in order to compare obtained signals in suppressed respiration and in normal respiration. Measures of amplitude similarity, correlation degree and spectral similarity were studied. Comparisons between EMFi and SCSB signals produced high similarity with all three comparison methods. During both suppressed and unsuppressed respiration, amplitude similarity and correlation were quite close to each other.

In spectral comparison the EMFi and SCSB signals were very similar in the frequency range 6–16 Hz during both suppressed and unsuppressed respiration. In 0-16 Hz frequency range the similarity was higher during suppressed respiration.

KEY WORDS
EMFi, SCSB, BCG, apnea, sleep research

1. Introduction

Static charge sensitive bed (SCSB) [1] and Electromechanical Film [2,3] (EMFi) as non-invasive sensors have shown their potential in monitoring different physiological functions of a human. They have been used in recording cardiorespiratory functions, called ballistocardiography [4] together with the respective regulatory mechanics and different motor activities especially in sleep studies. When placed below the mattress of a bed these sensors do not disturb the sleep of a patient.

Traditionally the SCSB mattress has been used in sleep studies and thus the purpose of this study was to make previous studies made with SCSB mattress comparable with those made with the EMFi sensor. In this work we developed and applied methods for comparing temporal and spectral properties of EMFi and SCSB mattress signal waveforms in order to evaluate their similarity.

2. Methods

2.1 Obtained data

For the purpose of this preliminary study, we made a single simultaneous recording half an hour of EMFi and SCSB signals at the Sleep Laboratory of the Department of Clinical Neurophysiology in Tampere University Hospital in Finland. The channels included in this study were an EMFi channel and a SCSB channel. In the measurement below the mattress there was a small EMFi sheet and below that the SCSB sensor.

The recording was made in such a way that periods of holding breath and normal respiration alternated. Sections of normal respiration alternated with the sections of suppressed respiration. Respiration induced a slow
fluctuating movement into the signals. Artefact and movement free signal sections were chosen for the study by visual inspection. Other sections included movement and other artefacts and thus were excluded from this study. The sampling rate used was 200 Hz.

2.2 Signal comparison methods

The comparison methods were developed to quantify the level of similarity in amplitude, correlation and spectral properties. The mean value of the processed signal segments was first removed. After that the signals were filtered with a 401-tap FIR band pass filter with a pass band 6-16 Hz (-3 dB points at 5.7 and 16.3 Hz). In addition, in the second spectral similarity comparison no filtering was used. The amplitudes of all analyzed signal segments were normalized by their standard deviations. By that it was assured that the powers of the signals under comparison were 1 mV².

2.21 Amplitude similarity

First, the amplitude deviation $e[k]$, where $k$ is the current second, was calculated between the EMFi and SCSB signal segments of length of 1s:

$$e[k] = \sum_{i=1}^{200} |EMF[i] - SCSB[i]|,$$  \hspace{1cm} (1)

where $i$ is the index of the signal sample.

At each second $e[k]$ was calculated considering possible timing difference in the heart cycle between the EMFi and SCSB signal segments. This was done in following way: EMFi segment included remained intact and SCSB segment was moved at one sample steps (0.005 s) so that beginning of the SCSB segment ranged from -0.5 s to 0.5 s compared to EMFi segment. This produced 200 corresponding $e[k]$ values. Then the minimum of the $e[k]$ values, denoted as $e_{\text{min}}[k]$, was used to indicate best similarity at that second $k$. The corresponding timing difference between the two signals was obtained based on the best similarity.

An amplitude similarity measure, denoted as $s_{\text{corr}}[k]$, was designed to describe similarity in percents, being high, when the EMFi and SCSB signal segments resemble each other. Theoretically the maximum value was 100 % and the minimum value 0 %. The measure $s_{\text{corr}}[k]$ was obtained as:

$$s_{\text{corr}}[k] = \{100 - (e_{\text{min}}[k] / e_{\text{max}})\} \times 100 \%,$$  \hspace{1cm} (2)

where the constant $e_{\text{max}}$ (maximum amplitude deviation) was calculated using two step functions in equation 1. The first one consisted of amplitude 1 during 0.5 s and -1 during the next 0.5 s and the other one had phase reversed as compared to the first one. This provided $e_{\text{max}} = 400$.

2.22 Correlation degree

First, the correlation coefficient was calculated between the EMFi and SCSB signal segments in 1.0 s window as follows:

$$\rho(EMF,SCSB) = \frac{c(EMF,SCSB)}{\sigma_{\text{EMF}} \cdot \sigma_{\text{SCSB}}},$$  \hspace{1cm} (3)

where the covariance function was:

$$c(EMF,SCSB) = \sum_{i=1}^{200} \{EMF[i] \cdot SCSB[i]\}.$$  \hspace{1cm} (4)

The time difference between the compared signals was dealt with in the same way like in section 2.21. The maximum (best value) of the correlation coefficient $\rho$ was selected and expressed in percents:

$$\text{cor}_{\text{corr}}[k] = \{\rho(EMF,SCSB)_{\text{MAX}}\} \times 100 \%.$$  \hspace{1cm} (5)

The value of $\text{cor}_{\text{corr}}[k]$ was large when the signal segments resembled each other. Theoretically the maximum value would be 100% corresponding to perfect match and the minimum value would be 0% corresponding to the worst case.

2.23 Spectral similarity

Spectral comparison between EMFi and SCSB signals in the frequency ranges 0-16 Hz and 6-16 Hz was done using 5 second windowing centred at current second $k$. By using such a windowing, multiple (typically 5-6) heart cycles were included at every step. Both of the signal segments of 1000 samples were windowed with a Hanning window, then a 1024 point FFT was computed and scaled to amplitude spectrums, denoted as $S_{\text{EMF}}[f]$ and $S_{\text{SCSB}}[f]$, (where $f$ is the frequency) by taking into account the influence of the Hanning window.

First the spectra were compared by computing sums of absolute differences at chosen frequency ranges of 0-16 Hz and 6-16 Hz:

$$e_{\text{SPEC}(0-16)}[k] = \sum_{j=0}^{16} |S_{\text{EMF}}[f] - S_{\text{SCSB}}[f]|,$$  \hspace{1cm} (6)

$$e_{\text{SPEC}(6-16)}[k] = \sum_{j=6}^{16} |S_{\text{EMF}}[f] - S_{\text{SCSB}}[f]|.$$  \hspace{1cm} (7)

The area occupied by EMFi and SCSB spectra was calculated in the chosen frequency ranges:

$$A_{\text{SPEC}(0-16)} = \sum_{j=0}^{16} S_{\text{EMF}}[f] + S_{\text{SCSB}}[f],$$  \hspace{1cm} (8)

$$A_{\text{SPEC}(6-16)} = \sum_{j=6}^{16} S_{\text{EMF}}[f] + S_{\text{SCSB}}[f].$$  \hspace{1cm} (9)
Then spectral similarity measures were calculated in percents:

\[ SPEC(0-16)_i[k] = 100\% - \left( e_{SPEC(0-16)} / A_{SPEC(0-16)} \right) \times 100\% \]  \hspace{1cm} (10)

\[ SPEC(6-16)_i[k] = 100\% - \left( e_{SPEC(6-16)} / A_{SPEC(6-16)} \right) \times 100\% \]  \hspace{1cm} (11)

The values of \( SPEC(0-16)_i[k] \) and \( SPEC(6-16)_i[k] \) were large when the spectra of EMFi and SCSB segments resembled each other. Theoretically the maximum value would be 100% corresponding identical spectra and the minimum value would be 0% corresponding to totally different spectra.

3. Results

In this study there were six sections of suppressed and normal respiration, as seen in the tables 1 and 2. The results of the comparison of EMFi and SCSB signals are presented in tables 1 and 2, respectively. An example of EMFi and SCSB waveforms is shown in Figure 1.

Table 1 shows that the EMFi and SCSB signal waveforms were quite similar during suppressed respiration. The median values of amplitude similarity \( s_{n_i}[k] \) ranged from 63.1% to 69.9%. The median values of timing differences between the EMFi and SCSB signal segments ranged from -0.01 to 0.13 seconds. The median of correlation degree \( cor_{n_i}[k] \) values ranged from 59.6% to 92.3%.

The spectral similarity measure \( SPEC(6-16Hz)_{n_i}[k] \) produced median values ranging from 64.2% to 82.9%, indicating high similarity. For comparison, the median values of \( SPEC(0-16Hz)_{n_i}[k] \) ranged from 40.7% to 55.3% indicating lower overall similarity.

Table 1. Outcome of the signal comparison during suppressed respiration sections.

<table>
<thead>
<tr>
<th>Method</th>
<th>Duration (s)</th>
<th>( s_{n_i}[k] )</th>
<th>Timing difference (s)</th>
<th>( cor_{n_i}[k] )</th>
<th>( SPEC(6-16Hz)_{n_i}[k] )</th>
<th>( SPEC(0-16Hz)_{n_i}[k] )</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.21</td>
<td>54</td>
<td>63.7</td>
<td>(60.7-66.9)</td>
<td>61.5</td>
<td>(39.3-77.6)</td>
<td>51.6</td>
</tr>
<tr>
<td>2.22</td>
<td>47</td>
<td>63.8</td>
<td>(61.8-66.8)</td>
<td>74.0</td>
<td>(60.3-71.9)</td>
<td>(25.3-58.2)</td>
</tr>
<tr>
<td>2.23</td>
<td>40</td>
<td>63.6</td>
<td>(60.0-66.3)</td>
<td>-0.01</td>
<td>(0.0-6-0.4)</td>
<td>(24.7-52.2)</td>
</tr>
<tr>
<td>2.23</td>
<td>34</td>
<td>69.9</td>
<td>(54.9-84.9)</td>
<td>0.01</td>
<td>(0.1-0.1)</td>
<td>(27.9-51.7)</td>
</tr>
<tr>
<td>2.23</td>
<td>34</td>
<td>63.1</td>
<td>(59.6-73.4)</td>
<td>0.11</td>
<td>(0.9-0.4)</td>
<td>(19.4-51.9)</td>
</tr>
</tbody>
</table>

Figure 1. EMFi and SCSB signal segments of one second (bandpass filtered 6–16 Hz) during suppressed respiration. The signal comparison measures were in this case the following: \( s_{n_i}[k] = 74.0\% \), \( cor_{n_i}[k] = 80.9\% \) and \( SPEC(6-16Hz)_{n_i}[k] = 82.7\% \), indicating quite similar signal waveforms.
Table 2. Outcome of the signal comparison during normal respiration sections.

<table>
<thead>
<tr>
<th>Method</th>
<th>Duration (s)</th>
<th>§\text{median} \text{(min-max)}</th>
<th>§\text{median} \text{(min-max)}</th>
<th>§\text{median} \text{(min-max)}</th>
<th>§\text{median} \text{(min-max)}</th>
<th>§\text{median} \text{(min-max)}</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.21</td>
<td>s_0[k]</td>
<td>65.8 (63.0-70.6)</td>
<td>62.9 (59.7-68.2)</td>
<td>64.0 (60.1-67.7)</td>
<td>63.5 (60.3-68.3)</td>
<td>63.7 (61.3-70.8)</td>
</tr>
<tr>
<td>2.21</td>
<td>Timing difference (s)</td>
<td>0.01 (-0.50-0.45)</td>
<td>0.01 (-0.45-0.46)</td>
<td>0.02 (-0.47-0.48)</td>
<td>0.01 (-0.48-0.49)</td>
<td>0.02 (-0.49-0.46)</td>
</tr>
<tr>
<td>2.22</td>
<td>cor_0[k]</td>
<td>76.0 (36.8-88.6)</td>
<td>75.3 (52.6-89.2)</td>
<td>63.8 (45.6-83.9)</td>
<td>78.0 (52.2-89.6)</td>
<td>70.0 (43.5-89.1)</td>
</tr>
<tr>
<td>2.23</td>
<td>SPEC(6-16Hz)_0[k]</td>
<td>71.2 (64.5-79.7)</td>
<td>70.1 (59.2-75.1)</td>
<td>60.8 (50.7-75.8)</td>
<td>70.6 (62.0-78.4)</td>
<td>68.3 (61.0-76.1)</td>
</tr>
<tr>
<td>2.23</td>
<td>SPEC(0-16Hz)_0[k]</td>
<td>25.0 (19.4-35.1)</td>
<td>28.1 (19.4-33.3)</td>
<td>25.0 (9.8-32.2)</td>
<td>24.4 (12.2-35.1)</td>
<td>27.5 (17.3-42.9)</td>
</tr>
</tbody>
</table>

The signal waveforms resembled each other also during normal respiration quite well, as seen in Table 2. The median values of amplitude similarity $s_0[k]$ ranged from 62.3% to 65.8%. Correlation degree $\text{cor}_0[k]$ the median values ranged from 63.8% to 78.0 %. The spectral similarity $\text{SPEC}(6-16\text{Hz})_0[k]$ produced median values ranging from 60.8% to 72.4% and $\text{SPEC}(0-16\text{Hz})_0[k]$ median values ranged from 24.4% to 45.0%. The median values of timing differences between the EMFi and SCSB signal segments ranged from -0.19 to 0.02 seconds.

4. Conclusion

To give some preliminary insights into the similarities and differences of EMFi and SCSB signals we developed various comparison methods and applied them in one test recording containing simultaneous traces of EMFi and SCSB signals. Comparisons between the signals in suppressed respiration and normal respiration were made in six sections. The outcome produced high similarity with all three different comparison methods.

Amplitude similarity and correlation degree measures were quite high suggesting that the time-domain signal waveforms resemble each other quite well.

The suppression of respiration has influence on the ballistocardiographic signal so that the slow respiratory signal components are diminished. This can be seen in our two spectral similarity measures so that in the 0–16 Hz frequency range during suppressed respiration the results were higher than during normal respiration.

It can also be assumed that the small time period between sections of suppressed and unsuppressed respiration may have influenced the results, because the body regulatory system needs some time to restore the reduced blood oxygen saturation and it takes some time to adapt to the normal situation.

It should keep in mind that the structure and operation of EMFi and SCSB sensors have their own characteristics. Also the properties of the mattress (material and thickness) in the bed and the used measurement methods (placement of the sensors in the bed, size of the sensors and properties of the bed [1]) may have an effect on the measured signals besides the pre-amplifier of EMFi sheet and SCSB mattress.

Traditionally SCSB mattress has been used in sleep studies and the purpose of this study was to make previous studies made with SCSB mattress comparable with those made with the EMFi sensor. Based on this study both of these sensors can be used in sleep studies although there are differences in the results. Further studies will provide additional information about these topics.

References