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Citation for published version (APA):

DOI:
10.1109/IEMBS.2008.4649751

Document status and date:
Published: 01/01/2010

Document Version:
Publisher’s PDF, also known as Version of Record (includes final page, issue and volume numbers)

Please check the document version of this publication:

• A submitted manuscript is the version of the article upon submission and before peer-review. There can be important differences between the submitted version and the official published version of record. People interested in the research are advised to contact the author for the final version of the publication, or visit the DOI to the publisher's website.
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The Effect of Artifact Correction on Spectral Estimates of Heart Rate Variability

Chris Peters, Rik Vullings, Jan Bergmans, Guid Oei, Pieter Wijn

Abstract— Spectral analysis of fetal heart rate variability might offer additional information that can be used for assessing the fetal condition more reliably. Clinical recordings of fetal heart rate are usually contaminated by artifacts. These artifacts can be detected and corrected or removed, but this can affect the spectral estimates obtained from the heart rate data. To determine what level of artifact correction is still acceptable for reliable calculation of spectral heart rate variability parameters, artifact correction is simulated on neonatal and fetal data that did originally not contain artifacts. 2000 data segments with various levels of artifact correction are analyzed spectrally, and calculated spectral estimates are compared to the values obtained from the original, artifact free data. In the very low (< 0.04 Hz) and low (0.04 – 0.15 Hz) frequency range, powers can be calculated reliably when up to 25% of the data are missing due to artifact correction. Powers in the high frequency range (0.15 – 0.4 Hz for adults, 0.4 – 1.5 Hz for newborns) cannot be calculated reliably when data are missing due to artifact correction. This is a major limitation for application in clinical practice, which might be solved by calculating power in the high frequency range at a shorter time scale than power in the low frequency range. Short segments of heart rate data that are free of artifacts can then be used to calculate powers in the high frequency range reliably, while segments that contain artifacts are excluded.

I. INTRODUCTION

SPECTRAL analysis of heart rate variability (HRV) can provide valuable insight in cardiovascular regulation by the autonomic nervous system, as sympathetic and parasympathetic nervous activity make frequency specific contributions to the power spectrum of the heart rate [1]. Currently, spectral analysis of heart rate variability is widely used in clinical research, but direct application in medical devices is scarce. Partially, this is caused by the complexity of the control mechanisms that coordinate the total pattern of activity in a subject. As changes in activity may demand alterations of the heart rate, information on this total activity is required for correct interpretation of heart rate variability [2]. In clinical practice, this information may not be available or may not be taken into account sufficiently.

Additional limitations arise from the sensitivity of spectral HRV parameters to artifacts that may be present in heart rate data. Methods used for automated spectral analysis of heart rate data should be insensitive to these artifacts [3].

The worldwide used standard method for fetal monitoring, cardiotocography (CTG), is based on visual evaluation of patterns of fetal heart rate and maternal uterine activity. The specificity of cardiotocography is however poor, which is reported to result in increased rates of unnecessary operative delivery without noticeable improvement of fetal outcome [4]. Therefore, continuous need exists for additional information that can be used to assess the fetal condition more reliably. Spectral analysis of fetal heart rate variability might offer additional information that can be used for fetal monitoring [5]. To a certain extent, spectral analysis of fetal heart rate variability reflects fetal compromise during delivery, offers the potential to predict severe fetal acidose [6,7] and may be used to monitor the development of the autonomic nervous system in fetuses [8].

Fetal heart rate data obtained in clinical practice are often corrupted by artifacts, for example due to patient movement, especially when fetal data are obtained non-invasively from the maternal abdomen. Generally, in fetal heart rate data, artifacts can easily be detected and removed or corrected. Single ectopic or falsely detected heart beats can be corrected by phantom beat replacement [3]. When artifacts corrupt multiple heart beats, the corresponding part is usually removed from the dataset. Both single beat and multiple beat artifact corrections can affect the spectral estimates obtained from heart rate variability data. However, it remains unclear what level of artifact correction is still acceptable for reliable calculation of spectral HRV parameters. To provide insight in the effect of artifact correction on spectral estimates of heart rate variability, in this paper artifact correction is simulated using heart rate variability data that were originally free of artifacts. Datasets with varying levels of corrected artifacts are generated and analyzed spectrally. The resulting spectral estimates are compared to the results calculated from the original heart rate variability data.

II. METHODOLOGY

A. Datasets

1) Neonatal data: Neonatal heart rate data are obtained from 3-leads ECG recordings in a neonatal intensive care unit (NICU). The ECG signals are recorded at a sample rate of 240 Hz using a General Electric Solar 8000M patient
monitor. From these ECG signals, R-peak occurrences are detected and, because of the relatively low sample rate, a quadratic fit is used to reduce sampling errors. This results in a dataset containing time stamps for all R-peak occurrences that were detected in the recorded signal. From this dataset five segments of 192 s that are completely free of artifacts, are selected for analysis. Fig. 1a shows the R-R interval series for one of the segments of 192 s.

2) Fetal data: Fetal heart rate data are obtained from a single lead scalp ECG recording in a delivery room. The ECG signal is recorded at a sample rate of 500 Hz using a Neoventa STAN s31 fetal monitor. R-peak occurrences are detected without the use of a quadratic fit. This results in a dataset containing time stamps for all R-peak occurrences that were detected in the recorded signal. From this dataset five segments of 192 s that are completely free of artifacts, are selected for analysis. Fig. 1b shows the R-R interval series for one of the segments of 192 s.

![Fig. 1a. R-R interval series of neonatal data segment III](image)

![Fig. 1b. R-R interval series of fetal data segment III](image)

B. Simulation of artifact correction

For each of the 10 segments of 192 s (5 segments from the neonatal dataset and 5 segments from the fetal dataset), timestamps are deleted at random positions in the segment. In this way both single beat artifacts and multiple beat artifacts are simulated. Timestamps are deleted until the desired level of corrected artifacts is achieved. For each of the original segments, artifact corrected segments are generated at 10 different levels (5 to 50% of the segment length, steps of 5%). For each level of corrected artifacts, 20 different data segments are generated from each original data segment, resulting in a total of 2000 data segments to be analyzed.

C. Spectral analysis

The timestamps in each of the data segments are used to calculate R-R interval series. For spectral analysis of these R-R interval series, the fast Fourier transform (FFT) is used. Each of the segments of 192 s is divided in 5 subsets of 64 s that overlap for 50%. Each subset of 64 s is analyzed separately, after which the resulting power spectra are averaged to obtain one power spectrum with reduced variance. The R-R intervals in the data segments are not equidistantly distributed in time. To be able to calculate the Fourier transform, the R-R intervals must be transformed into an equidistant set of data. This data set is created by resampling the R-R intervals at a frequency of 4 Hz, after using a sample & hold technique and convoluting the data with a square wave that has a width of 0.5 seconds and a surface equal to 1. Next, the resampled dataset is multiplied with a Parzen window, to reduce spectral leakage, and after subtraction of the mean R-R interval value to remove DC offset, the power spectrum is calculated. Finally, the energies in the calculated power spectrum are corrected for the application of the Parzen-window and the spectrum is divided by the squared Fourier transform of the square window, to correct for the convolution prior to resampling.

After calculating the power spectra of the R-R interval series, the power in various frequency bands is calculated. Table I contains an overview of the spectral estimates that are calculated.

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Frequency range</th>
</tr>
</thead>
<tbody>
<tr>
<td>VLF</td>
<td>power in very low frequency range</td>
<td>&lt; 0.04 Hz</td>
</tr>
<tr>
<td>LF</td>
<td>power in low frequency range</td>
<td>0.04 – 0.15 Hz</td>
</tr>
<tr>
<td>HF&lt;sub&gt;a&lt;/sub&gt;</td>
<td>power in high frequency range for adults</td>
<td>0.15 – 0.4 Hz</td>
</tr>
<tr>
<td>HF&lt;sub&gt;n&lt;/sub&gt;</td>
<td>power in high frequency range for newborns</td>
<td>0.4 – 1.5 Hz</td>
</tr>
<tr>
<td>TP</td>
<td>total power (outside VLF)</td>
<td>0.04 – 1.5 Hz</td>
</tr>
<tr>
<td>LFn</td>
<td>LF power in normalized units</td>
<td></td>
</tr>
<tr>
<td>HFn</td>
<td>HF power in normalized units</td>
<td></td>
</tr>
<tr>
<td>LF/HF</td>
<td>LF/HF ratio</td>
<td></td>
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</tbody>
</table>

III. RESULTS

Fig. 2a to 2c show the powers in the LF and HF band and the total power calculated for the neonatal heart rate data for each of the levels of artifact correction. Fig. 3a to 3c show the powers in the LF and HF band and the total power for the fetal heart rate data. The HF power that is shown, is the power in the HF band as defined for newborns, which ranges from 0.4 to 1.5 Hz. For all calculated spectral estimates, the relative deviation from their theoretical value is determined. Table II shows the mean relative deviation and the corresponding standard deviation for all datasets (both neonatal and fetal).
IV. DISCUSSION

Fig. 2a and 3a show that even when relatively large parts (up to 25%) of heart rate data are missing due to the correction of artifacts, calculated powers in the low frequency range only slightly deviate from their theoretical values (values at 0% corrected artifacts). At higher levels of artifact correction, the standard deviation of the calculated values rapidly increases. For powers in the very low frequency range results are similar and even higher levels of artifact correction may be acceptable. Interestingly, in the very low frequency range powers are slightly overestimated, while in the low frequency range, powers are slightly underestimated.

Fig. 2b and 3b show that already at very low levels of artifact correction, calculated powers in the high frequency range for newborns significantly deviate from their theoretical values. For the averaged relative deviation in HF power as presented in Table II, a linear inverse relationship exists between the averaged relative deviation and the level of artifact correction ($y = -1.024 \times x$, $R = 0.99$, $p < 0.001$). However, a large number of datasets was used for these calculations. In general, HF power will not be constant throughout a dataset and the actual deviation will strongly depend on which part of the dataset contains the artifacts.

Powers in the high frequency range for adults also show a significant deviation from their theoretical values, but the averaged relative deviation is smaller than for the high frequency range for newborns. The total power calculated in the range between 0.04 and 1.5 Hz (Fig. 2c and 3c) shows an underestimation of the theoretical value. This underestimation is smaller than the underestimation in the high frequency range for adults and newborns, which is due to the relatively large power in the low frequency range.

V. CONCLUSION

For neonatal and fetal heart rate data, the power in the very low frequency and low frequency range can be calculated reliably for datasets in which up to 25% of the heart rate data are missing due to artifact correction. Powers in the high frequency range, for both adults and newborns, cannot be calculated reliably when heart rate data are missing due to artifact correction. For spectral analysis of fetal heart rate data in clinical practice, this is a major limitation, as these data will virtually always be corrupted by artifacts. A possible solution for this limitation is the use of alternative methods for spectral analysis. Wavelet analysis for example, enables analysis of powers in the high frequency range at a shorter time scale than the analysis of powers in the low frequency range. Short segments of heart rate data that are free of artifacts can then be used to calculate powers in the high frequency range reliably, while segments that contain artifacts are excluded. In future work, the application of a wavelet-based method of analysis will be explored.

Spectral estimates in the low frequency range of the fetal heart rate appear to be clinically most relevant for fetal monitoring [5]. For clinically obtained fetal heart rate data, the power within this range can be calculated reliably after artifact correction, as long as the corrected data do not exceed 25% of the length of the segment to be analyzed. However, if normalized powers are used ($LFn = LF/Total power$), the total power should also be calculated reliably. Total power contains the power in the high frequency range, and therefore, for normalized powers the same limitations exist as for spectral estimates in the high frequency range.

REFERENCES