Non-Invasive Fetal Heartbeat Detection Using Bispectral Contour Matching

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Abstract — A hybrid system using the mother and fetal ECG bispectral contours (BIC), which carry the signature imprints of their respective QRS-complexes, in the signal processing phase is described. The classification phase employs LMS-based single-hidden-layer classifiers. The mother's chest ECGs and the fetal scalp electrode ECGs have been used as templates or the HOS representatives in the classification. The bispectral contour matching technique is used to identify the signatures of both the maternal and fetal QRS-complexes. The highest achievable Fetal Heartbeat (FHB) classification rate using the BIC template matching technique is 90.12% with reduced false positives and negatives associated with the power spectrum-based FHB classification rate of 70%. The BIC has a marginally improved classification performance over and above the third-order cumulants (TOC) during episodes of overlapping fetal QRS-complexes and maternal T-waves. This is achieved at the expense of complexity and computation time.

Keywords — Bispectrum contour, ECG signal, neural network classifiers, non-invasive detection, fetal heartbeats

I. INTRODUCTION

The fetal heart rate is a useful tool in the assessment of the condition of the fetal before and during labour [1]. There are several non-invasive methods use for the measurement of the FHR: The ultrasound cardiotocography (CTG), Fetal Magnetocardiography (FMCG) [6], phonocardiography [9], and Fetal Electrocardiography (FECG) [1]. FECG uses non-invasive surface electrodes placed on the maternal abdomen is another tool for FHR recording. The fetal signal is weak relative to the maternal signal and to the competing noise. Widrow et al. [2] proposed an adaptive filtering and adaptive noise cancellation method to extract the FECG from the composite maternal ECG signal. A variant of the same approach was used by Longini et al. [3]. Auto-correlation and cross correlation techniques [4] and spatial filtering techniques [5] have been proposed. These methods require multiple maternal thoracic ECG signals. Other methods were proposed for the rejection of the disturbing maternal ECG signal [1]. The automated long-term evaluation of FECG is regarded as less robust than CTG. A failure rate of 30% is quoted as a norm [8]. The advantage of FECG is that it can be implemented in small and relatively low-cost devices [9].

A proposed technique employing wavelet transform [12] exploits the most distinct features of the signal, leading to more robustness with respect to signal perturbations. The algorithm is validated using data with high SNR. Dynamic modelling has been proposed [13]. The data has comparatively high SNR and the fetal heartbeats can be detected by an adaptive matched filter and requires much shorter data samples than dynamic modelling. The dynamic modelling apparent success at high SNR is offset by the required lengthy data. Due to the beat-to-beat fluctuations of the shape and duration of the ECG waveform, the normal ECG cannot be considered to be deterministic. Determinism is found in adult and fetal ECGs for data lengths of 10,000 samples [14]. The independent component analysis (ICA) has been carried out under assumptions [10], the validity of each has been challenged [11]. A third-order cumulants (TOCs) technique for non-invasive fetal heartbeat detection has been proposed [15]. The ECG signal is processed using a Volterra filter. To improve the performance of the Volterra filter, quadratic and cubic LMF Volterra filters have been proposed [16].

This paper proposes incorporating an adaptive cubic LMF Volterra and an artificial neural network classifier to improve the detection rate. The cubic Volterra filter has been shown to improve the performance of electromyographic signals during labour [17]. Cross validation has been done by comparing the results of the detection to QRS peaks of the fetal heartbeat extracted from the fetal scalp electrode which is the goldstandard. The paper is structured as follows; Section 2 offers a background Section 3 describes the proposed hybrid technique and the detection operation. Section 4 shows results using neural networks. Section 5 discusses the implementation of the hybrid technique and results for fetal ECG signals. Conclusions are drawn in Section 6.

II. BACKGROUND

This section describes a hybrid system using the mother and fetal ECG bispectral contours (BIC). The bispectral contour matching technique is an extension to the hybrid cumulant matching technique. The choice of the NN classifier is based on the general discussion presented in [21]. Prior information is exploited. It is the matching of the horizontal 2-d bispectral contours that has been used in the BIC template matching technique instead of the 1-d polar bispectral slices. Because in order to use the 1-d polar bispectral slices effectively, one needs to use a minimum of 24 polar slices to facilitate
capturing the most rapid changes in the bispectrum including null features that could be used as discriminant patterns. Whereas for BIC contours, provided that they are horizontally cut at a maximum number of 10 levels, a good quality discriminant picture can be made available for the neural network classifier. For example, it is very unlikely that maxima and troughs are missed because of any changes in their respective positions.

The same procedure in [21] is applied with the replacement of the third-order cumulant slices by the bispectral contours (usually 10 contours including the tip of the peak and are spaced by approximately 1 dB). The CPU time for the bispectrum computation is almost twice that for cumulants and 2000 times that for individual TOC slices. The Detection key operations are exactly the same as those in [21] except that the third-order cumulant slices are now going to be replaced by the bispectral contours. This operations are: 1) Creating ECG BIC database, 2) Detecting the maternal QRS-complexes, 3) Detecting the fetal cardiac cycles.

III. ECG BISPECTRUM

A. Background

The bispectrum, $n = 3$, is defined as [19]:

$$C_n^3(\omega_1, \omega_2) = \sum_{\tau_1=\infty}^{\infty} \sum_{\tau_2=\infty}^{\infty} c_n^3(\tau_1, \tau_2) e^{-j\omega_1 \tau_1 + j\omega_2 \tau_2} \quad (1)$$

where $c_n^3(\tau_1, \tau_2)$ is the third-order cumulant sequence. The computational complexity of the bispectrum is of the order of $N^3$.

IV. THE SINGLE-HIDDEN-LAYER PERCEPTRON

Single-hidden-layer perceptron classifiers are trained in a supervised manner with the back-propagation algorithm which is based on the error-correction learning rule. The back-propagation algorithm provides a computationally efficient method for the training of the classifiers. The back-propagation algorithm is a first-order approximation of the steepest descent technique. It depends on the gradient of the instantaneous error surface in weight space. The algorithm is stochastic in nature. It has a tendency to zigzag its way about the true direction to a minimum on the error surface. It suffers from a slow convergence property. A momentum term is employed to speed up the performance of the algorithm. The classifier is exactly the same as that used in [21].

A. Typical examples of bispectra and their contours

Linearisation is a key step in the signal processing phase and it is applied using an optimised third-order Volterra synthesiser. Fig. 1 depicts dual-band-pass filtered bispectra and their contours normalised to the maternal QRS-complex spectral peak for the transabdominally-measured ECG segments I, II, III, and IV. The dual-band-pass filter consists of two fifth-order Butterworth filters with cut-off frequencies of 10 - 20 Hz, and 25 - 40 Hz, respectively, a pass-band attenuation of 0.5 dB, and a stop-band attenuation larger than 70 dB. The sampling rate is 500 Hz. Optimised Kaiser weighting coefficients are used for the maternal and fetal ECGs to enhance their spectral peaks at 17 Hz and 30 Hz, respectively. The Kaiser windows are centred at frequencies of 15-19 Hz for the mother’s QRS-complex, and at frequencies of 28-38 Hz for the fetal heartbeat.

Fig. 1 (I) shows the maternal QRS-complex principal bispectral peaks and contours centred at the frequency pairs (18 Hz, 5 Hz) and (18 Hz, 16 Hz). These maternal frequency pairs with a frequency peak at 18 Hz slightly deviate from the actual frequency of 17 Hz [20], which is due to the BIC bias. The maternal optimised Kaiser window centred at 18 Hz will detect these peaks. Fig. 1 (II) shows the first fetal heartbeat principal bispectral peaks and contours at the frequency pairs (30 Hz, 5 Hz), (30 Hz, 18 Hz), and (30 Hz, 30 Hz). The fetal optimised Kaiser window centred at 30 Hz will detect these peaks. Note that these peaks are sharp. Fig. 1 (III) shows the QRS-free ECG bispectral peak and contours centred at the frequency pair (27 Hz, 15 Hz). The BIC of the QRS-free ECG is at approximately -12 dB which is 3 dB and 6 dB lower than that of the first and second fetal heartbeats, respectively. Fig. 1 (IV) shows the second fetal heartbeat principal bispectral peak and contours centred at the frequency pairs (30 Hz, 5 Hz), and (30 Hz, 28 Hz). The fetal optimised Kaiser window centred at 30 Hz will detect these peaks.

B. Classification rates

Table 1 shows a top classification rate of 100% for maternal QRS-complexes using bispectral contours for signal processing and single-hidden-layer perceptron classification. The 100% maternal QRS-complex classification rate has been achievable with or without linearization. A brief description of the optimised parameters required for the linearisation process is given. To calculate the maternal heart rate an auxiliary method to pinpoint the R-wave is needed. The results have been obtained using adaptive thresholding since all mothers’ ECGs exhibit normal-to-the-patient QRS-complexes. The instantaneous maternal heart rate is calculated by dividing 60 by the R-to-R interval (in seconds). The application of this auxiliary routine leads to a maternal heart rate with an accuracy of 99.85%. Parameter details are in [16].

Table 2 summarises the results of the fetal heartbeat detection using the power spectrum method and the bispectrum contour matching technique. Optimised adaptive LMF-based second- and third-order Volterra synthesisers are employed. The power spectrum method has a classification rate of 71.47%. Using the hybrid system, the classification rate increased to 87.72% without linearisation, and to 88.28% and 90.12% using second- and third-order Volterra synthesisers with LMF update, respectively. The hybrid method has an improvement of 19% and 4% in the classification rate.
Fig. 1: Dual-band-pass filtered bispectra, Kaiser shaped window, (l.h.s.) and their contour maps normalised to the maternal QRS spectral peak (r.h.s.) for the transabdominally-measured ECG segments. Segment I: predominantly maternal QRS-complex, Segment II: the first fetal heartbeat with maternal contribution; Segment III: QRS-free ECG; and Segment IV: the second fetal heartbeat with maternal contribution. The dual band-pass filter consists of two fifth-order Butterworth filters with cut-off frequencies of 10 - 20 Hz, and 25 - 40 Hz, respectively, a pass-band attenuation of 0.5 dB, and a stop-band attenuation larger than 50 dB.

Table 1: The classification rate for the maternal QRS-complex using maternal transabdominally-measured ECGs.

<table>
<thead>
<tr>
<th>Spectral matching template in conjunction with ANN classifiers</th>
<th>Power spectrum</th>
<th>The bispectrum contours</th>
</tr>
</thead>
<tbody>
<tr>
<td>Classification rate</td>
<td>99.84</td>
<td>100.00</td>
</tr>
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</table>

Table 2: Fetal heart detection classification rate using transabdominally-measured ECG with and without linearisation. The total number of fetal heartbeats is 120,000 and the total number of maternal ECG recordings is 30. The performance is assessed against synchronised fetal scalp heartbeats. All mothers were during the first stage of labour at 40 weeks of gestation.

<table>
<thead>
<tr>
<th>Spectral matching template type</th>
<th>Se (%)</th>
<th>Sp (%)</th>
<th>FP</th>
<th>FN</th>
<th>Classification Rate (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power spectrum with linearisation</td>
<td>71.29</td>
<td>71.44</td>
<td>34272</td>
<td>34537</td>
<td>71.37</td>
</tr>
<tr>
<td>Bispectral contour without linearisation</td>
<td>87.97</td>
<td>87.46</td>
<td>15048</td>
<td>14436</td>
<td>87.72</td>
</tr>
<tr>
<td>Linearised bispectral contour using 2nd order LMF Volterra synthesizer</td>
<td>88.53</td>
<td>88.04</td>
<td>14352</td>
<td>13764</td>
<td>88.28</td>
</tr>
<tr>
<td>Linearised bispectral contour using 3rd order LMF Volterra synthesizer</td>
<td>90.53</td>
<td>89.73</td>
<td>12324</td>
<td>11364</td>
<td>90.12</td>
</tr>
</tbody>
</table>
over and above that achieved with the second-order statistics and the TOC template matching technique, respectively. The classification rate of the coincident and non-coincident mother’s and fetal QRS-complexes is 0% and 99.21%, respectively. The second-order Volterra synthesiser parameters are: filter length = 6, step-size parameters = 0.005, and 0.0004 for linear and quadratic parts, respectively, delay = 5. The third-order Volterra synthesiser parameters are: filter length = 6, step-size parameters = 0.001, 0.0002, and 0.0004 for linear, quadratic and cubic parts, respectively, delay = 5 [22].

V. DISCUSSION

The bispectral contour matching technique is an extension to the cumulant matching technique. The choice of the NN classifier is based on the discussion presented in [21]. It is the matching of the horizontal 2-d bispectral contours that has been used in the BIC template matching. For BIC contours, a good quality discriminant picture can be made available for the neural network classifier. 50,000 maternal cardiac cycles have been included in the analysis. The numbers of bispectral contours compound templates are 10 for the maternal chest, 10 for the fetal scalp, and 140 for the transabdominally-measured 250 msec segments, respectively. Each bispectral compound template is made of 10 horizontal templates at different levels, starting from a normalised 0 dB and going down in steps of 1 dB each to a – 10 dB.

The maternal transabdominal ECG signal is linearised using an optimised LMF-based second- or third-order Volterra synthesiser. The transabdominal ECG signal is segmented into four segments containing: (I) The maternal QRS-complex, (II) the first fetal heartbeat with maternal contribution, (III) QRS-free ECG, and (IV) the second fetal heartbeat with maternal contribution. To segment the transabdominal ECG signals, the window length is carefully chosen to; (i) Yield an acceptable upper threshold of both the deterministic and stochastic noise types inherent in the higher-order statistics of the ECG signals encountered, and (ii) allow the detection of one, two, three, or four fetal heartbeats (FHBs) within one maternal transabdominal cardiac cycle. The classification procedure starts by matching the bispectral contours of the segments to those of the templates until the first and the second mother’s QRS-complexes are detected and their R-waves are pinpointed. The maternal heart rate is accurately calculated from the knowledge of the current and previous R-wave positions. Then, the search for the fetal heartbeat starts at 50 msec before the first maternal R-wave and continues until the second maternal R-wave is reached. The ECG bispectral contour template matching technique is effective in detecting the occurrence of the fetal heartbeats in the frequency domain even when it is completely buried in noise, it cannot locate the R-wave in the time domain over a window length of 250 msec. However, the maternal heartbeats can be measured fairly accurately and the instantaneous maternal heart rate can be calculated. By counting the number of fetal heartbeats that have occurred between two successive maternal R-waves, the averaged FHR within the maternal cardiac cycle can be calculated:

\[ \text{The average FHR} = \text{MHR} \times \frac{\text{Number of FHBs}}{\text{number of maternal heartbeats}} \]

The instantaneous maternal heart rate is previously known with some degree of accuracy, and the relative fetal to maternal heartbeat is also known within the maternal cardiac cycle. The averaged fetal heart rate can be calculated within each maternal cardiac cycle.

1. The effect of window length on the bispectral variance

The variance of the bispectrum for the optimum window length of 250 msec with FHB occurrence ranges from 0.47 to 3.3 with an average of 1.716. The variance of the bispectrum is smaller than that of the third-order cumulants. A further 15% increase in the variance of the bispectrum is due to an increase in the maternal heartbeat from 60 bpm to 100 bpm. The latter has resulted in a 30% decrease in segment size.

2. Parameters of the single-hidden layer perceptron

The network has been optimised in terms of its learning rate, momentum constant, and hidden layer size to achieve the minimum mean-squared error. The optimum learning rate and momentum constant are 0.2 and 0.2, respectively. The single-hidden-layer has a dimension of 6 x 6. The input to the first layer is the bispectral contours of the four transabdominally-measured ECG segments. The network is trained using the BIC templates. During the training phase, the input to the network is four template patterns. These are the BIC of four segments from one transabdominal cardiac cycle. For example the first is the maternal QRS-complex BIC, the second is the first fetal heartbeat BIC, the third is the QRS-free ECG BIC, and the fourth is the second fetal heartbeat BIC. The network is trained over ten templates of each of the four segments. The training terminates when the worst error in all patterns in one pass is less than 0.1. Typically the average error will be in the range of 0.001.

VI. CONCLUSIONS

Results obtained for the hybrid system from 30 cases using the non-invasive transabdominally-measured ECG signal, with the simultaneous fetal scalp electrode ECG signal as a reference, show that the method has a classification rate of 100% for normal, healthy maternal QRS-complexes and 90.12% for fetal heartbeats. An improvement of 1% to 3% is attainable with ECG signal linearisation employing second- and third-order Volterra synthesisers, respectively. Power spectrum-based methods of fetal heartbeat detection have a success rate in the range of 70%. The hybrid system has a higher classification rate than second-order based methods. The classification rate of fetal heartbeats for non-coincident and coincident mother’s and fetal QRS-complexes is 99.21% and 0%, respectively. This means that the bispectral contours technique fails to resolve the fetal beat when both the mother and fetal QRS-complexes are synchronised. The bispectral contour template matching technique improved the
classification rate by approximately 4% over and above that of the third-order cumulant template matching technique. The difference in performance is not due to better resolvability of the latter over the former in the case of coincident mother’s and fetal QRS-complexes, as both techniques fail in this respect. But, it is due to the fact that the BIC template matching technique can resolve a few of the fetal QRS-complexes occurring within the T-wave region of the mother.

VII. REFERENCES