PhysioNet/CinC Challenge 2013: A Novel Noninvasive Technique to Recognize Fetal QRS Complexes from Noninvasive Fetal Electrocardiogram Signals

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Abstract

The aim of this study is the intelligent recognition of the fetal heart rate and its R-R intervals from noninvasive fetal electrocardiogram signals. The non-value data was first eliminated and the missing data were regenerated based on the statistical distribution of the data. Then, the power line noise and baseline noise are removed. At the next step, a variable threshold criterion was designed to detect the maternal R-waves. By eliminating the specific ranges of the maternal R waves from signal, the remaining data describe merely the fetal QRS complexes. Next, a window with a specific length was slid on D_1 signals and the envelope curves were extracted. The locations of each local maximum on the envelope curve represent the fetal R waves. Finally, in order to improve both the performance of the proposed method and the robustness of the algorithm to noise, an amendment technique with respect to the fetal and maternal R-R intervals was implemented

*The algorithm was applied on the test data set B consequently as the preliminary challenge scores. The average scores **108.766** and **15.480** were achieved as the best scores for the events 4 and 5, respectively, on phase 1, and **63.750** and **11.198** on phase 2.*

1. Introduction

Heart defects are among the most common birth defects and the leading cause of birth defect-related deaths [1,2]. Every year, about one out of 125 babies are born with some form of congenital heart defects [3]. The defect may be so slight that the baby appears healthy for many years after birth, or so severe that its life is in immediate danger. Congenital heart defects originate in early stages of pregnancy when the heart is forming and they can affect any of the parts or functions of the heart. Cardiac anomalies may occur due to a genetic syndrome, inherited disorder, or environmental factors such as infections or drug misuse [4, 1]. The electrocardiogram signal (ECG) is an effective non-invasive tool for knowing the condition of the heart. With examining the ECG signal in detail, it is possible to derive a number of informative measurements from the characteristic ECG wave form [5]. Fetal monitoring today is based entirely on the fetal heart rate and does not incorporate characteristics of the fetal ECG (fECG) waveform characteristics that are the cornerstone of cardiac evaluation of both children and adults [6]. However, fetal electrocardiography currently is not an effective way for detecting structural defects [7].

In this paper we propose an approach to detect the fetal QRS complex that is robust to noise. Although the structure of fECG depends on fetus age, the proposed approach has acceptable accuracy in all kind of maternal and fetal ECG mixtures. The stochastic methods are used to select the appropriate lead, and in this study not only one of the leads but also the other leads may be used if they can give help.

2. Material and method

2.1. Discrete wavelet transform (DWT)

The Specific structure of wavelet bases may be appreciated by considering generation of an orthonormal wavelet basis for function $g \in 1^2(R)$ (the space of square integral real functions). The approach of Daubechies is the most often adopted in applications of wavelets in statistics, mutually orthonormal, functions or parent wavelets: the scaling function, φ (sometimes referred to as the father wavelet), and the mother wavelet, ψ :

$$\varphi_{j0k}(t) = 2^{j_0/2}\varphi(2^{j_0}t - k)$$
$$\varphi_{jk}(t) = 2^{j/2}\varphi(2^{j}t - k) \quad (1)$$
$$j = j_0, j_0 + 1, ..., k \in Z$$

For some fixed $j_0 \in Z$, where Z is set of integers. The $2^{j/2}$ term maintains unity norm of the basis function at various scales and j and k are the scaling and translation parameters, respectively. A unit increase in j in (1) has no effect on scaling function (φ_{j0k} has a fixed width), but packs oscillations of ψ_{jk} into half the width (doubles its scale or resolution). A unit increase in k in (1) shifts the location of both φ_{j0k} and ψ_{jk}, the former by a fixed amount (2^{-j0}) and the latter by an amount proportional to its width (2^{-j}). Given the wavelet basis, a function $g \in 1^2(R)$ is then represented in a corresponding wavelet series as

$$g(t) = \sum_{k\in Z} c_{j0k}\varphi_{j0k}(t) + \sum_{j=j_0}^{\infty}\sum_{k\in Z} w_{jk}\psi_{jk}(t) \quad (2)$$

with $c_{j0k} = < g, \phi_{j0k} >$ and $w_{jk} = < g, \psi_{jk} >$ (where $< .,. >$ isthe standard l^2 inner product of two functions: $< g_1, g_2 >= \int_R g_1(t)g_2(t)dt$

The wavelet expansion (2) represents the function g as a series of successive approximations.Given a vector of function value $g = [g(t_1), g(t_2), ..., g(t_n)]^T$ of equally spaced points t_i, the DWT of g is given by:

$$d = Wg \quad (3)$$

where d is an $n \times 1$ vector comprising both discrete scaling coefficients $u_{j0,k}$ and discrete wavelet coefficients $d_{j,k}$ and W is an orthogonal n×n matrix associated with orthonormal wavelet basis chosen. Both $u_{j0,k}$ and $d_{j,k}$ are related to their continuous counterparts $c_{j0,k}$ and $w_{j,k}$ via the relation ships $c_{j0,k} \approx u_{j0,k} / \sqrt{n}$ and $w_{j,k} \approx d_{j,k} / \sqrt{n}$ .The factor $\sqrt{n}$ arises because of the difference between continuous and discrete orthonormality conditions [1-2]. Figure 1 illustrates sturcture of DWT in high and low frequency and the red rectangle related to the approximation part.

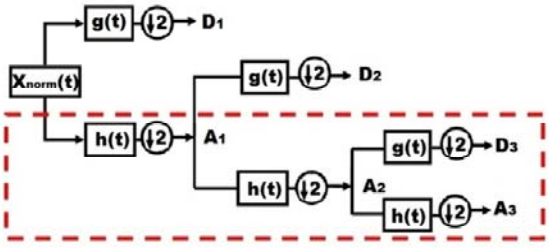
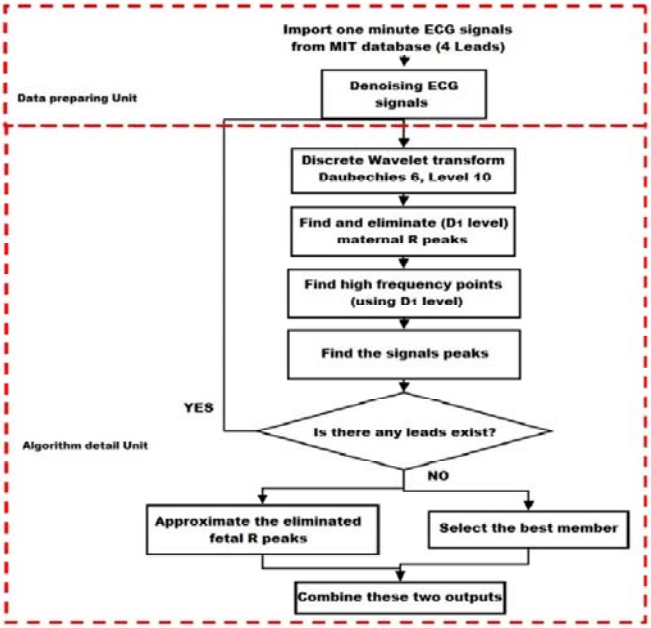


Figure 1.Structure of DWT in low and high frequency

2.2. Algorithm flowchart



The flowchart of the algorithm is shown in Figure. 2.

Figure 2. Flowchart schematic of the processing stages.

2.2.1. Preprocessing and denoising

The first step of preprocessing is estimate the non-value data. The missing data was then regenerated based on the

statistical distribution of the data. In order to remove the power line noises a band stop finite impulse response filter was implemented in four different harmonics. Using the discrete wavelet transform, the low frequency noises were removed by eliminating the reconstructed signals in approximations of level 10 and also details of levels 7, 8, 9 and 10. The final preprocessing stage was using a wavelet-denoising technique based on the estimation of the wavelet coefficients.

2.2.2. Detection of maternal R peaks of denoised signal

There is a big difference between maternal and fetal ECG signals in structure and properties. The cause of this difference is related to the composition of Fetal Heart Rate (FHR) and Maternal Heart Rate (MHR) in ECG mixture. Maternal R points should be detected in another way because of this structural difference. Two important points that should be noted in detection of maternal R peaks are as follow:

1- The application of wavelet transform is not sufficient for detection of maternal R points.

2- Depending on fetus age, the amplitude of fetal R peaks can largely very, so it may confuse the algorithm of maternal R peaks detection.

2.2.3. Elimination of maternal QRS complex

As mentioned above, fetal QRS complex has higher frequency than maternal one. Fetal and maternal QRS complexes are observed together in D_1 level. After detection of maternal R points, the range of maternal QRS complex should be eliminated from D_1 level, so other high frequency points should probably be related to fetal QRS complex.

2.2.4. Finding high frequency points and refining them

Because of the random noises, some of the high frequency points should be removed, since they might be noise. These points are found thanks to wavelet transform. In order to do so, the feature of a specific distance should be used between two fetal heart rates. The components which are placed in a suitable distance are put in a new vector.

2.2.5. Repeating the last steps for all 4 leads

The fetal QRS complex is observed clearly in some leads. As a result, all the four leads should be used to achieve the best accuracy. At the end of this step, the below vectors are produced:

Temp1-lead 1; Temp1-lead 2; Temp1-lead 3;
Temp1-lead 4

2.2.6. Selection of the appropriate members of the last stage output arrays

In this step, four vectors of the previous step outputs are combined with a priority so that each lead that has a higher quality is used first. Each lead has a lower noise distribution and has larger length vector that extracted from 2.2.5 is in priority.

The standard deviation of signal D1 is required for finding the lead that has lower noise distribution. The standard deviation is:

$$s = \left(\frac{1}{n-1} \sum_{i=1}^{n} (x_i - \bar{x})^2 \right)^{0.5} \qquad (4)$$

The score1 is given for this parameter, so that each lead that has minimum s gets maximum of score1 (3) and each lead that has maximum s gets minimum of score1 (zero).

$$n = \text{length}(\text{Temp1} - \text{lead}\,i) \qquad (5)$$

The score2 is given to the length of the vectors of the stage 2.2.5 (n), so that each lead that has the maximum of n gets maximum of score2 (3) and each lead that has minimum n gets minimum of score1 (zero). Finally, we sum up the scores and each lead that got more score is used as first.

$$\text{score} = \text{score1} + \text{score2} \qquad (6)$$

2.2.7 Prediction (approximation) of the eliminated fetal R peaks

The output vector of 2.2.6 does not contain all fetal QRS complexes. In addition, some of the complexes are not considered because of following reasons:

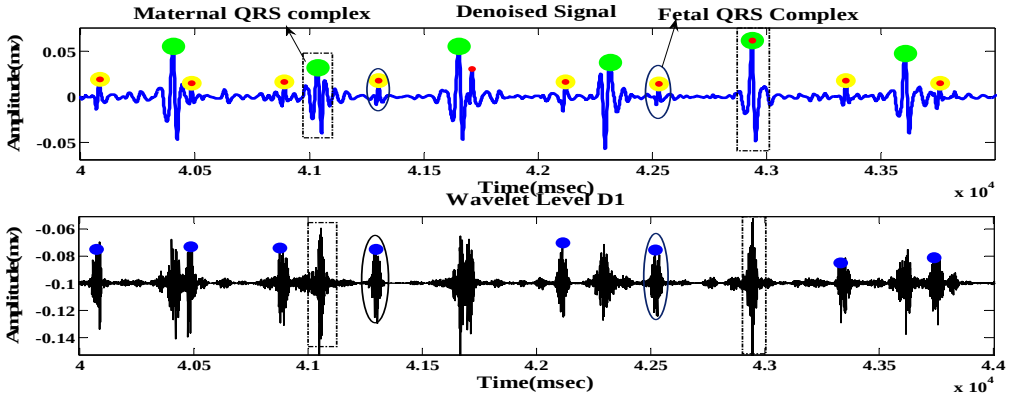


Figure 3.Denoised signal and its wavelet level D1

1-Some of these FHR that are located on maternal QRS complex are not considered.

2-There is a possibility that none of the vectors in 2.2.6 have members between the two sequential maternal R-points. Thus, the beats locations which not consider because of two above reason should be approximated. The methodology of this approximation is as follow:

The high frequency points, which have a specific order, are placed in a new vector. The distance between sequential arrays is determined, and then median of them is obtained. The median is the average of fetal R-R intervals (named FRR-ave). Then location of the missing fetal heart rate with FRR-ave is approximated and the exacted FHR location is found using denoised signal.

2.2.8. Combination of the output arrays of 2.2.7 and 2.2.6

The component sets which are obtained from 2.2.7 and 2.2.8 are fetal heart rates. By sorting the components of this vector in ascending order, the fetal heart rate vector is achieved (Fetal-R). The extracted fetal QRS complexes are showed in Figure 3.

3. Discussion and conclusions

In this paper, we have presented a method that is robust to noise and can obtain acceptable accuracy in different kind of ECG mixtures, because we have used the ranges that can support variable structure of ECG mixtures. Although these ranges may reduce accuracy in some special cases, they will provide good mean score on set a and set b. We obtained score 108.766 and 15.480 on phase 1, but when the structure of maternal QRS complex detection completely changed and some filters were also used in the algorithm, the score reduced to 63.750 and 11.198 on phase2.

References

[1] Congenital Heart Defects. March of Dimes. 2005 [Online]Available:http://www.marchofdimes.com/professionals/14332_1212.asp

[2] Minino AM, Heron MP, Murphy SL, Kochanek KD. Deaths: Final data for 2004. National Vital Statistics Reports.August. 2007

[3] Congenital Heart Defects in Children Fact Sheet. American Heart Association; 2008. [Online]. Available: http://www.americanheart.org/children

[4] Pajkrt E, Weisz B, Firth HV, Chitty LS. Fetal cardiac anomalies and genetic syndromes; Prenat Diagn Dec. 2004: 1104-1115. [Online]. Available: http://dx.doi.org/10.1002/pd.1067

[5]]Houghton AR, Gray D. Making sense of the ECG, Arnold, 1997

[6] Sameni R, Clifford GD. A review of fetal ECG signal processing; issues and promising directions. Open Pacing Electrophysiol Ther J 2010; 3:4–20.

[7] Zuckerwar A, Pretlow R, Stoughton J, Baker D. Development of a piezopolymer pressure sensor fora portable fetal heart rate monitor. IEEE Trans Biomed Eng 1993; 40:963–969. [PubMed:8288288]

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