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Comparison of envelope detection and signal normalization methods for foetal heart rate extraction from foetal heart sound

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***Abstract*— Foetal heart rate is an important indicator of foetal well-being which indicates fetal distress during antepartum and intrapartum period. This paper provides systematic comparison of four different methods envelope detection and four different methods of signal normalization to determine the fetal heart rate from fetal heart sound. To obtain the ground truth, each heart beat was manually identified by visualizing the sound recording on a computer screen. Four different measure of error are used compare various combinations of envelop detection and normalization methods. It is found that the homomorphic filtering gave highest accuracy. Choice of normalization methods did not affect accuracy measurement in most cases.**

Keywords—fetal heart sound;envelope;

I. Introduction

Though the first observation of foetal heart sound was reported during the 17th, it was Lejumeau Kergaradec who reported the usefulness of the auscultation in diagnosis of twins, foetal lie and presentation during the pregnancy [1]. Foetal heart rate is an important parameter in the assessment of foetal wellbeing both intrapartum and antepartum, Kilian was the first to propose that changes in heart rate can be used to diagnose foetal distress and to indicate the time for clinical intervention [1]. The normal range of foetal heart rate(FHR) is 120-160bpm.The foetal heart rate helps in assessing various conditions: hypoxia, asphyxia, foetal bradycardia(<110bpm) and foetal tachycardia (>160 bpm). Apart from directly listening to the foetal heart sounds using stethoscope or pinard cone, various devices are currently in use for monitoring foetal heart rate: foetal Doppler, foetal electrocardiography(fECG), foetal magnetocardiography(fMC) and foetal phonocardiography(fPCG)[2].The foetal cardiotocography(CTG) which is used in Non-Stress Test includes two transducers: one for measuring the foetal heart rate and the other one for uterine activity. In CTG machine, the foetal heart rate is measured using Doppler ultrasound. It is the most widely used method to monitor the foetal heart rate. Foetal Doppler probe exposes foetus to Ultrasound waves and shift in frequency of the reflected signal is used to detect the heart motion. The fECG obtained due to electrical activity of the heart is of two types namely :Direct and Indirect. The direct method uses fetal scalp electrode to obtain the signal whereas indirect methods uses electrode placed on maternal abdomen to obtain the signal and can be done from the 16th week of pregnancy but the signal may contain various artefacts along with maternal electrocardiogram, therefore various advanced signal processing techniques must be applied to obtain fECG [3]. The amplitude of the fECG also decreases in 28-32 week of pregnancy due to vernix caseosa surrounding the foetus [4]. Foetal Magenetocardiogram is the recording of the magnetic field produced by the electrical activity of the heart. It is recorded by squid array placed over maternal abdomen and measuring foetal and maternal magentocadiographic signals [5]. The fMCG is extracted and the heart rate is calculated. The major disadvantage of this method includes: cost, trained staff required, no long term monitoring. In fPCG, natural acoustic signals from the maternal abdomen are acquired using electronic stethoscope to assess the foetal wellbeing. Though this approach is non-invasive and requires simpler instrumentation, the foetal heart rate measurement in this approach has two problems: firstly, the intensity of the foetal heart sound is low compared to the interference signals such as digestive sounds or the signals from the environment. Secondly, the intensity and the frequency varies depending on the position of the foetus (occiput anterior position/occiput posterior position) [6].

A preliminary evaluation foetal heart sounds is reported in [7] to determine the foetal heart sound characteristics between intrauterine growth retarded foetus and normal foetus and gave a pathway to use the heart sound to determine the foetal wellbeing. Various signal processing techniques reported in the literature for extraction of fetal heart rate include: autocorrelation method, S1 heart sound positions, repetition frequency determination and blind source separation. In autocorrelation based method, the signal is passed through a bandpass filter followed by envelope detection and autocorrelation of the signal [6]. Matched filtering or other de-noising techniques can be used before the envelope detection and autocorrelation step to improve the accuracy of FHR measurement. Methods using S1 heart sound positions determines the FHR by locating the S1 heart sound in the signal [9,10,11,12]. The heart sounds are repetitive in nature, therefore a method which describes tracking these frequency repetition to determine the heart rate and tested in the noisy environment using the simulated data from the physionet is proposed by

Tang. *et.al* [13] Single channel blind source separation uses empirical mode decomposition and Nonnegative matrix factorization to extract the fPCG and the FHR is determined [14]. Though more advanced techniques are being proposed requiring additional computational resources, there is no comparison available in literature on adequacy of these approaches using real clinical data.

Though various signal processing techniques are proposed in literatures, there is no insight whether the techniques can be used in resource limited settings. This paper systematically compares various methods suitable for implementation on low cost electronics formed by combination of various envelope detection approaches named: Shannon Energy envelope, Hilbert Envelope, Full wave rectification and low pass filter (FWR-LPF) and Homomorphic envelope along with four common normalization techniques to determine the best performing foetal heart rate extraction method for resource limited settings.

II. METHODOLOGY

The heart sound contains two major heart sounds S1 (due to atrioventricular valve closure) and S2 (due to closure of semilunar valve) occurring at different time intervals. The time interval between first heart sound and second heart sound is shorter compared to adults. Therefore, during auscultation typically only one dominant sound is heard in the case of foetal [14]. The various methods to extract heart rate is tested on randomly selected 15 datasets from 26 datasets made available by Ruffo *et al.* on physionet [10, 15]. To determine the accuracy of various methods, a benchmark is needed against which the heart rate readings can be compared. The benchmark used in this case is the reference HR measurements determined by manually annotated heart sound positions similar to method used by Springer *et al.* [16].

A. Reference Heart Rate Measurement

The reference HR measurements were computed by manually detecting heart sound positions in every 4s window of one-minute-long data resulting in 15 HR measurements for a subject. In each of the 4s window, the median time interval between detected peaks is calculated to determine the HR[16]. The process is repeated for remaining datasets to obtain the reference HR resulting in total of 210 measurements. An example of the manually detected S1 positions is shown in Fig 1.

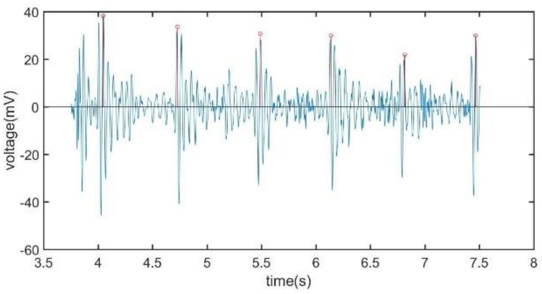

Fig.1 Manually Annotated S1 positions

III. ANALYSIS OF FOETAL HEART SOUND

The automated heart rate estimation is done using a total of 16 methods (combination of 4 envelope detection methods and 4 normalization methods).

A. Pre-processing

Prior to envelop detection, filtering of foetal heart sound is done using band pass butterworth filter with the passband of 30-150 Hz and filter order of 3.

B. Envelope Detection

(i) FWR-LPF

The FWR-LPF is type of envelope detection method where the signal is full wave rectified followed by low pass butterworth filter of order 3 at 50 Hz to remove unwanted frequencies.

(ii) Hilbert Envelope:

The Hilbert envelope is obtained by determining the absolute value of the analytic signal, the analytic signal is nothing but the addition of the original signal with the hilbert transform of the original signal to form a complex signal given by:

$$z(n) = x(n) + j\acute{x}(\mathrm{n}) \qquad (2)$$

Where,
Z(n) is the analytic signal
x(n) is the original signal
$\acute{x}$(n) is the Hilbert transform of x(n)

The Hilbert transform of the signal is determined by:

$$\acute{x}(\mathrm{n}) = \frac{1}{\pi}\int_{-\infty}^{\infty}\frac{x(u)}{\pi-u}du \qquad (3)$$

(iii) Homomorphic Filter:
Homomorphic filtering is mostly used in image processing for image enhancement. It transforms the original signal into another domain, where the linear filter is applied to remove unwanted components, then transformed to the original signal. The homomorphic filtering process is explained below:
A signal can be considered to have a slow varying component and a fast varying component [18] shown in the equation below:

$$x(t) = m(t) * f(t) \qquad (4)$$

where,
m(t) - slow varying part in the signal.
f(t) - fast varying part in the signal.

Applying logarithm to the above equation, we get

$$\ln(x(t)) = \ln(m(t) * f(t)) \qquad (5)$$

The envelope of the signal is extracted by low pass filtering (LPF)the signal at 50 Hz after log transformations to remove high frequency f(t)

$$LPF(ln(x(t))) = LPF(ln(m(t)) + ln(f(t))) \qquad (6)$$

$$(ln(x(t))) = (ln(m(t)) \quad (7)$$

Finally, the envelope is obtained by taking exponential of the above term.

(iv) Shannon Envelope:
The Shannon envelope is based on the Shannon energy given by the formula:

$$Z_{Es} = \frac{1}{N}\sum_{n=1}^{N} x(n)^2 * \log(x(n))^2 \quad (8)$$

where,
x(n) is the original signal.

The envelope is determined by taking a window of length of 0.02s and overlapping segment of 0.01s [18,19]. The Shannon envelope has the property of accentuating medium intensity signals, while attenuating the low and high intensity signals.

C. Normalization Methods

After the envelope detection, normalization of the signal is done to limit variation between the signal obtained from various subjects, four normalization methods were investigated: Maximum amplitude in the signal, Subtracting the mean and dividing by the percentile value in the signal [18], dividing by root mean square of the signal and lastly subtracting the mean and dividing by the standard deviation. All the four normalization methods were applied to above explained envelope detection methods.

D. Autocorrelation

The autocorrelation of the signal is taken after normalizing the Envelope signal. It is defined as:

$$R_x(m) = \frac{1}{N-|m|}\sum_{m=1}^{N-1-m} z(n) * z(n+m) \quad (9)$$

Where,
z(n) is the signal after envelope.
z(n+m) is the shifted version of the signal s(n)

As seen from the equation above, autocorrelation measures the similarity between the original signal and its shifted version for a series of time interval. It gives lag versus correlation graph. The autocorrelation graph is Fig. 2

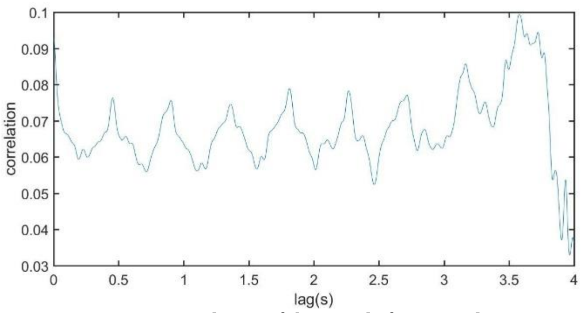

Fig. 2: Autocorrelation of the signal after normalization

E. Heart Rate Estimation Method

The Peaks are detected in the auto correlation waveform using the equation:

$$R_x(m)-R_x(m-1)>0 \quad (10)$$
$$R_x(m)-R_x(m+1) <0 \quad (11)$$

This method computes the maximum peak in the permissible range 0.3s -0.75s [12] in the auto-correlation waveform which corresponds to 80 to 200 bpm. The heart rate is calculated as:

$$HR=60/lag \text{ (maximum peak) bpm} \quad (12)$$

IV. RESULT

The difference between the reference HR measurements and the measurements obtained after the pre-processing is computed to know the accuracy of HR measurements using various envelope and normalization techniques. The various accuracy measurements include: (i) Fraction of results within 5% of reference measurement (5% tolerance), (ii) 10% tolerance, (iii) Mean Absolute Error (MAE) (iv) Root Mean Squared Error (RMSE)

A. 5% and 10% tolerance:

Accuracy of HR measurements is computed by calculating the difference between the reference and automated HR.. Then the percentage of measurements that are not within the 5 or 10% of reference HR measurements are calculated and shown in in Fig.3 &4 respectively.

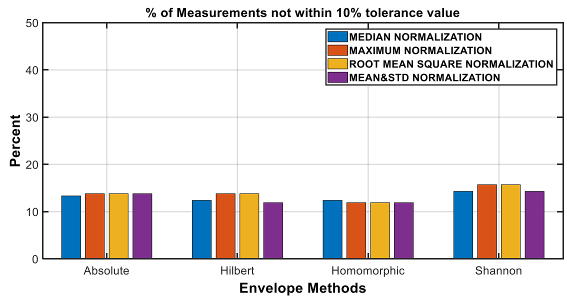

Fig.3. Percentage of Measurements not within 10% of HR reference measurements

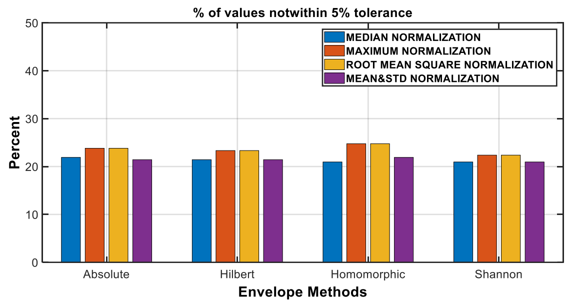

Fig.4. Percentage of Measurements not within 5% of HR reference measurements

B.Mean absolute and Root mean square error

Mean absolute error and root mean square error measures how far the estimated value is from the actual value. The estimated value here is the automated HR and the actual value is the manual measurement. The RMSE and MAE is calculated by using the formula below:

$$MAE = \frac{1}{n}\sum(absolute(Xa - Xe)) \quad (13)$$

$$RMSE = \sqrt{\frac{1}{n}\sum(Xa - Xe)^2} \quad (14)$$

Where,

n→ total number of values

Xa → Actual Value

Xe→Estimated Value

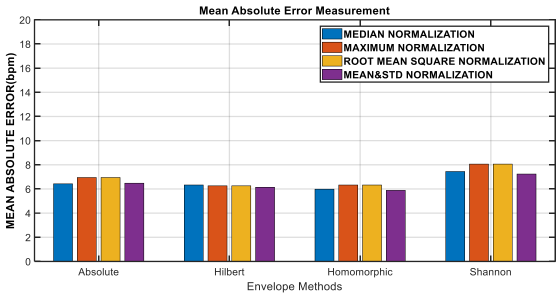

Fig.5: Mean Absolute Error

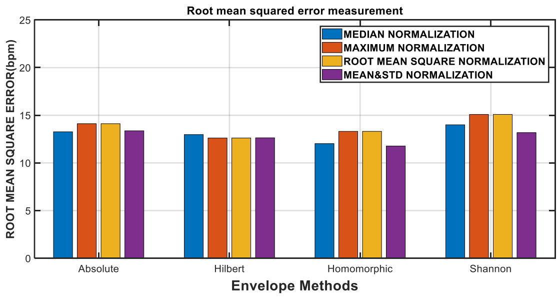

Fig.6: Root mean squared error

DISCUSSION

An accuracy of 85% and 79% is obtained for 10% and 5% tolerance respectively when automated heart rate measurements are compared to manual measurements. The comparison of various envelope techniques and normalization method is done to determine which envelope method along with the normalization techniques give better heart rate measurement when used with auto-correlation technique. It is seen from the above graph that the heart rate determination accuracy at 10% shows homomorphic envelope gives better results and at 5% hilbert envelope gives better results even though the variation of accuracy among the envelope methods is only 1-2%. The MAE and RMSE also shows only 1-3bpm difference among the envelope methods. Therefore, it is seen that all the envelope methods give more or less the same accuracy in the heart rate determination and no difference is seen among the various methods. In order to see how well the automated methods, agree with the manual measurements a bland-altman difference plot is done and is shown in Fig.7

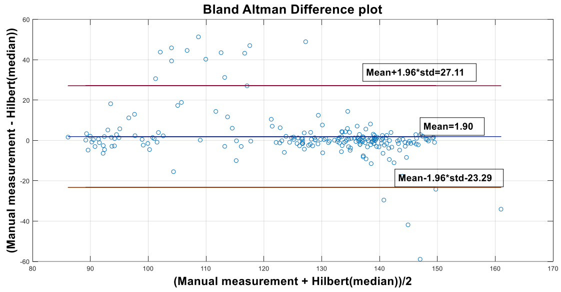

Fig.7: Difference Plot of hilbert(Median) and difference between hilbert(Median) and Gold standard

The plot shows a good agreement between the manual measurement and hilbert(median) except in the mean range of 110-120bpm, this trend is seen in all the bland-altman plot of envelope technique and manual measurement graph. This may be due to one of the two tins: 1. the peak detection identifies the peak wrongly or 2. the manual measurement in that area is wrong. The wrong peak detection can be avoided by either validating the detected peaks or by using advanced signal processing techniques such as Wavelet denoising, cyclostationary[13] or single cannel blind source separation[14] to effectively remove the noise so that they don't interfere in peak detection.

CONCLUSION AND FUTURE WORK

In this paper, comparison of various envelope methods along with different normalization technique is done to extract fetal heart rate measurements. These techniques are tested on the clinical data from the Physionet for a total of 210 measurements and accuracy measurements is done to evaluate the performance of the envelope technique to correctly detect the fetal heart rate. It is noted that the accuracy of heart rate detection is about 79% for 5% tolerance and 85% for 10% tolerance respectively; Further improvement to the algorithm can be done by applying advanced signal processing techniques namely: wavelet analysis, single cannel blind source separation, and cyclostationary signal processing, therefore the future work includes implementing the above processing techniques and comparing them with the envelope detection methods to see if it shows any improvement in the accuracy of the heart rate determination.

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