35th Annual International Conference of the IEEE EMBS
Osaka, Japan, 3 - 7 July, 2013

Automated Identification of fetal cardiac valve timings

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***Abstract*— In this paper a new noninvasive method is proposed for automated estimation of opening and closure timings of fetal cardiac valves. These timings are obtained from Doppler Ultrasound (DUS) signal and fetal electrocardiogram (fECG) as a reference. Empirical Mode Decomposition (EMD) is first applied to the DUS signal to decompose it into different components called Intrinsic Mode Functions (IMFs). The envelope of the first IMF is then taken and its peaks are identified. The opening and closure of the valves are then automatically assigned to the IMF peaks by using Hidden Markov Model (HMM).**

It is shown that this new method can continuously evaluate fetal cardiac valves' (aortic and mitral) motion timings for 82.5~99.7% of cardiac cycles. The estimated timings are verified using the Pulsed Doppler images. These findings can be used as sensitive markers for evaluating the fetal cardiac performance.

I. Introduction

Antenatal fetal assessment techniques are advocated to identify antepartum fetal risks. The evaluation of fetal heart activity is one of the main concerns in fetal assessment which provides valuable information about the fetal status [1]. Cardiac timing events are sensitive markers for evaluating electromechanical coupling of the heart which is a fundamental and clinically significant part of the heart physiology [2, 3]. The opening and closure timings of the cardiac valves are the main bases for estimating these electromechanical indices [4]. Among these markers the Systolic Time Intervals (STI) have received considerable attention as the indicators of the myocardial function [4-6].

Fetal echocardiography is a technique for identification of the timing events, which can visualize different parts of the heart structure as well as the blood flow through the valves. However it is an expensive and highly specialized method and only particular maternal and fetal conditions indicate the need for it [7]. Due to these problems simpler and more accurate alternative methods have been investigated. Starting in 1980s, a body of research has been devoted to the noninvasive evaluation of fetal cardiac timing events, based on the Doppler Ultrasound (DUS) signal and noninvasive recorded fetal electrocardiogram (fECG) [8-11]. Band pass filter is used in these methods for filtering the DUS signal, after which the cardiac events are identified manually. The major problem with these methods is the highly variability of the DUS signal over time as well as the poor quality of the abdominal ECG. With the improved signal processing techniques and more powerful processors over the last decade, the information content of the DUS signal has been acquired more easily. In 2001, Koga et al. used the digital narrow band-pass filter to divide the DUS signal into different frequency shift ranges. The mitral and aortic valve motions are then identified from the peaks in one of the filtered signals [11]. In another study, Shakespeare et al. proposed to analyze the DUS signal with Short Time Fourier Transform (STFT) [12]. They have shown that the high frequency component of the DUS signal is linked to the valve movements, while the low frequency one is associated with the cardiac wall motion. A common issue which is noticed in all of these studies is the transient nature of the DUS signal as well as the wide changes in temporal and spectral characteristics. The DUS signal also highly depends on the position of the fetus and the transducer. Therefore another method is recently reported which applies the multi-resolution wavelet analysis to the DUS signal to decompose it into different scales with resolution levels [13]. Valve movements are visualized as peaks in the detailed signal at level 2 wavelet decomposition.

All methods up to now recognize the valve movements manually by assigning them to the peaks of the high frequency component of the DUS signal. However, DUS is usually corrupted by noise and interferences and it is also sensitive to the position of the transducer. The peaks in the DUS signal component which correspond to different events are usually similar and cannot be distinguished easily. Moreover the peaks may not be observable or manually detectable in some cardiac cycles. Therefore current methods which are based on manual recognition may not be

*Resrach supported by Australian Research Council grant (LP100200184).

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accurate. They are also time consuming and subject to inter- and intra-observer errors.

Thus an automated approach is proposed in this paper; in order to identify the occurrence of the cardiac events based on timings of the peaks of the DUS signal component and the sequence of events.

In this paper, instead of STFT or the wavelet analysis, it is proposed to use Empirical Mode Decomposition (EMD) because of its valuable properties. EMD is a data-driven algorithm and it is used for decomposing nonlinear and nonstationary time series [14]. It has been used extensively in many different applications, such as: speech processing, image processing and biomedical signal processing. EMD has been also used for better estimation of the fetal heart rate, using Ultrasound Doppler or CTG [15- 16].

fECG is used as a reference for the segmentation of the DUS signal into cardiac cycles. The DUS signal is decomposed by EMD into the components with different frequency content, called Intrinsic Mode Functions (IMFs). Then Hidden Markov Model (HMM) is used to automatically identify the fetal cardiac events from the first IMF which has the highest frequency content. The valve motion events are taken as hidden states and the peaks of the IMF are used as observations. Events are then recognized by HMM decoding procedure based on the emission and transition probabilities. This procedure is described in the methods section.

The estimated timings which are verified by the Pulsed Doppler images are shown in the results section.

II. Methods

A. Data

Simultaneous recordings of the abdominal ECG and DUS signals from 45 pregnant women at the gestational age of 16 to 41 weeks with normal single pregnancies were collected from Tohoku University hospital. A total of 45 recordings (each of 60 minute's length) were sampled at 1 kHz with 16-bit resolution. The study protocol was approved by Tohoku University Institutional review board and written informed consent was obtained from all subjects. fECG was extracted from the abdominal ECG using blind source separation with reference (BSSR) as described in an earlier study [17].

B. Decomposing the DUS signal by EMD

EMD first introduced by Huang et al. [14] is a single channel method for decomposing a complicated signal into a set of different oscillatory modes. These components are called Intrinsic-Mode functions (IMF) and are zero mean, orthogonal and spectrally independent. EMD is an empirical procedure which is defined only by an algorithm and basically does not focus on any analytical formulation for theoretical analysis.

In brief, the EMD adaptively decomposes a signal into the IMFs through a specific algorithm which is called "sifting procedure". For each mode, the highest frequency component is locally extracted out of the input signal.

In this paper it is proposed to apply EMD to the DUS signal to decompose it to the IMFs which naturally have different frequency bands. The first IMF which has the highest frequency content is used to identify valve motions.

C. Automated identification of valve motions by HMM

After decomposing the DUS signal to the IMFs, the valve motions are automatically identified from the first IMF. The absolute value of the first IMF has a sequence of peaks which is associated with opening and closure of the atrioventricular and semilunar valves. For a better assessment, the envelope of that IMF is obtained using low-pass filter. Then the filtered IMF is normalized over each cardiac cycle and its peaks are detected. The cardiac cycles are previously found using R-R intervals of the fECG. Each peak of the IMF represents one of the cardiac events or none of them.

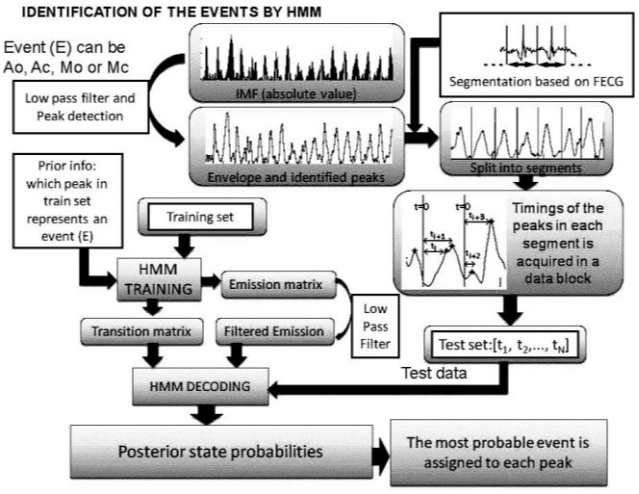

Figure 1 HMM approach block diagram

In order to assign valve motion events to the peaks, HMM is used. It can find the most probable event linked to each peak based on the timings of the peak and the probabilistic model of the occurrence sequence of the events. These events are Mitral opening (Mo), Mitral closure (Mc), aortic valve opening (Ao) and closure (Ac), which occur periodically.

HMM was developed in the 1960s [18] and has been widely used in many signal processing applications. In contrast to the Markov model, in HMM the observed symbols are emitted from some hidden states. In our application the hidden states are the opening and closure of the valves and

the observations are the timings of the IMF peaks. Some peaks however may not represent valve motions. Therefore the cases of "no event" are also considered among hidden states and can occur between different cardiac events. HMM uses transmission and emission matrices. In this paper the supervised approach is used to obtain these matrices because for a limited training set for which we have prior information, both input and output of the process are available. Usually because of the limitations in the training set, the estimated matrices have some zero values. Therefore a smoothing process is used to improve the performance of decoding the new data using the estimated model. The decoding process aims to find the most probable hidden states given a new observation sequence. HMM Matlab toolbox is used for both training and decoding processes.

After decoding, a matrix is obtained which contains the probability of the occurrence of each cardiac event (or none of them), for each peak. Then the event with the highest estimated probability of occurrence among all events is assigned to each peak. The sample procedure for detecting a cardiac event is shown in figure 1.

III. RESULTS

For evaluating the results, the timings are verified by the Pulsed-wave Doppler images which visualize the direction and the characteristics of the blood flow through the valves.
In this paper the total number of 45 different data sets of

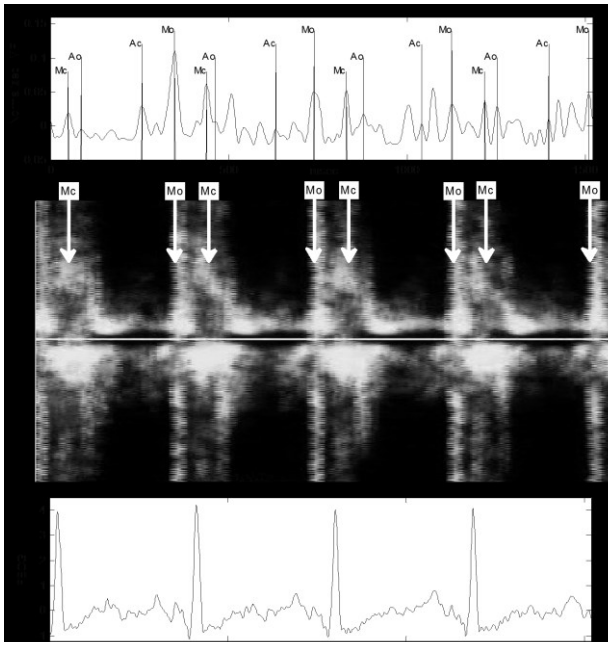

Figure 2 Identification of openning and closure of the mitral valve

DUS and corresponding fECG are used for testing the algorithm and obtaining the timings. In order to train HMM, cardiac timings of 30 cardiac cycles from three different patients were determined manually based on expertise. The algorithm is then applied to the data sets from 45 different patients to find the timings during 40 cardiac cycles.
Figure 2 shows an example of the normalized envelope of the high frequency IMF and the identified events, the fECG and the Pulsed Doppler image of the mitral valve movement for three cardiac cycles from one of the test sets.
Figure 3 shows the result of using another data set with the fECG and the Pulsed Doppler image of the aortic valve movement.
Table 1 shows the percentage of the estimated events using all data sets from 45 patients. For each patient the mean of the timings is first calculated over all cardiac cycles; then the mean and standard deviation of these average timings over all 45 patients is obtained and shown in table 1.

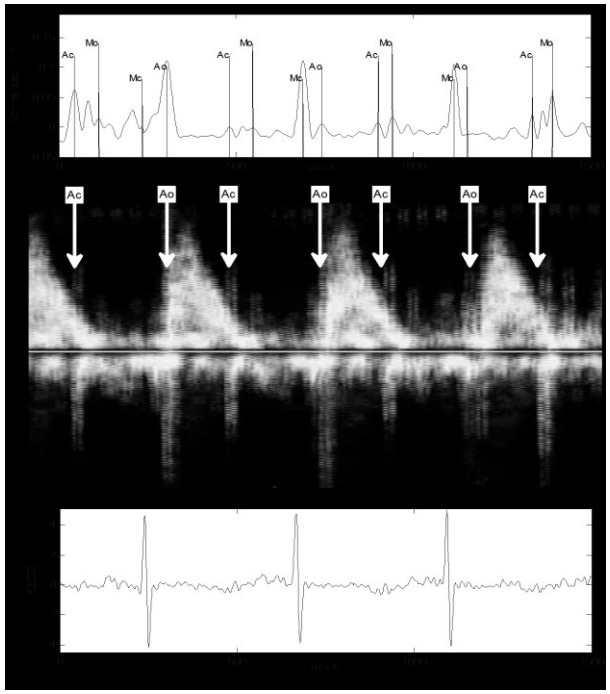

Figure 3 Identification of openning and closure of the aorta

TABLE I. MEAN ± STANDARD DEVIATION OF THE AVERAGE TIME INTERVALS (MSEC) OF OPENING AND CLOSURE OF THE AORTIC AND MITRAL VALVES OVER 45 PATIENTS AND THE RATE OF IDENTIFIED EVENTS.

Intervals	*Mean±SD*	*rate*
R-R	413.07 ± 26.07	100.0 %
R-Mc	30.99 ± 3.98	82.5 %
R-Ao	69.46 ± 4.27	89.1 %
R-Ac	219.92 ± 5.19	94.7 %
R-Mo	305.74 ± 3.90	99.7 %
Ao-Ac	150.45 ± 6.86	87 %

IV. DISCUSSION

In previous studies, the cardiac events have been identified from DUS signal by using digital filtering, STFT or wavelet [8-13], while in this paper EMD is employed which is simple and practical. It has been extensively used for

decomposing nonlinear and non-stationary signals but it has not been used for this application before. The results show that by applying EMD the component which is linked to valve movements is practically separated and its peaks which correspond to the events can be discriminated.

All previous studies have been based on manual identification of the cardiac event timings. However it is sometimes difficult to recognize the peaks manually, especially for nonexperts. Moreover the appearance of particular types of events in DUS signal strongly depends on the location of the ultrasound transducer and the fetus. Some peaks which are linked to the cardiac events may not be visible in some situations or extra peaks may appear which may be confusing for manual recognition. It also takes more time to carefully investigate the signal to recognize the events. There are visual errors as well as inter- and intra-observer errors when events are recognized based on human observation. Therefore in this paper for the first time, an automatic method is proposed to recognize the events in each cardiac cycle. HMM is used for this aim, which assigns the cardiac event to the peaks of the first IMF, based on the timings of the peaks and the sequence of the events. As shown in table 1, by using this method, a high percentage of the valve movement events is identified. The timings are also compared with the Pulsed Doppler images which verify the successful identification of the events.

The estimation of the timing of cardiac events would have been very difficult without using FECG as a reference for segmentation. In this study the position of the R-waves helps us for segmentation of the signal into cardiac cycles.

V. Conclusion

A new framework for noninvasive automated identification of fetal cardiac event timings from DUS signal is proposed in this paper. EMD is used for decomposing the DUS signal into different components (IMFs). In comparison with STFT and Wavelet which have been used in previous studies, EMD is a data driven and practical algorithm which is better for decomposing nonlinear and non-stationary signals. In this study EMD is combined with HMM which provides the automatic identification of the events, while all previous methods have been manual. Results show that by this automated process, a high percentage of events can be detected. The manual methods were time consuming and needed expertise. Moreover, some peaks may not be easily and accurately visualized and identified. This automated method on the other hand, provides automated continuous beat to beat identification of the cardiac event timings which will be an asset to the clinical applications.

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