Automated Measurement of Fetal Isovolumic Contraction Time from Doppler Ultrasound Signals without using Fetal Electrocardiography

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Abstract

Isovolumic Contraction Time (ICT) is the interval from mitral closing to aorta opening. Fetal ICT can be noninvasively measured from Doppler Ultrasound (DUS) signal. Automated identification of opening and closing of mitral and aortic valves from DUS signal was proposed in recent studies. Fetal electrocardiogram (fECG) has a crucial role as a reference in automated methods by identifying the onset of each cardiac cycle. However simultaneous recording of abdominal ECG and DUS and separation of fECG from the noisy mixture of ECG complicate this technique. In this study the automated identification of valve motion events without using fECG was investigated. The DUS signal was decomposed by Empirical Mode Decomposition (EMD) to high and low frequency components linked to valve and wall motion, respectively. The peaks of the latter were used for segmentation of the high frequency component as a substitute for fECG. The mitral and aortic valve motion was then automatically identified by hybrid Support Vector Machine (SVM)-Hidden Markov Model (HMM). Results show a significant positive linear correlation between average ICT obtained with and without using fECG ($r=0.90$, $p<0.0001$) with the mean absolute difference of 1.4 msec.

1. Introduction

Isovolumic Contraction Time (ICT) is the interval from mitral valve closure (Mc) to aortic valve opening (Ao). Fetal ICT is a reliable index of fetal cardiac contractility and can sensitively detect impaired cardiac function [1-2]. A study by Koga et al., found the prolonged ICT significantly correlated with abnormalities in perinatal course and it was suggested as a prediction of adverse outcome for the fetus [2].

Fetal ICT can be noninvasively measured from Doppler Ultrasound (DUS) signal. However, it is not widely performed in clinical practice according to the difficulty in identification of Mitral closing and aorta opening. Previous studies proposed to use band-pass filtering [1-3], Short-time Fourier transform (STFT) [4], wavelet analysis [5] or Empirical Mode Decomposition (EMD) [6-7] to decompose the DUS signal into a high frequency component linked to the valve motion events. The peaks of this component represent the movement of each valve.

Differentiation of mitral and aorta opening and closing events from the peaks of the high frequency component, was performed manually in earlier [1-5] and automatically in recent studies [6-7]. Simultaneously recorded fetal electrocardiogram (fECG) has a crucial role, particularly in automated methods; by specifying the beginning of cardiac cycle for segmentation. However simultaneous recording of abdominal ECG with DUS signal and separation of fECG from a noisy mixture of maternal ECG and other interfering signals and artifacts complicate this technique.

In this study automated identification of valve motion from DUS signal without using fECG was investigated. To this aim the DUS signal was decomposed by EMD to Intrinsic Mode Functions (IMF). The first IMF (high frequency) was linked to valve motion and the fourth IMF (low frequency) was related to the cardiac wall motion [7]. The peaks of the latter were used for segmentation as a substitute for fECG R-waves. The mitral and aortic valve motion events were automatically identified by hybrid Support Vector Machine (SVM)-Hidden Markov Model (HMM) as described in [7].

2. Methods

2.1. Data

DUS signal was recorded from 21 pregnant women at the gestational age of 16 to 41 weeks with normal single pregnancies at Tohoku University Hospital in Japan. The continuous DUS data were obtained using ultrasonic

transducer 5700 (fetal monitor 116, Corometrics Medical Systems, Inc.) with 1.15 MHz signals. Each recording was 1 minute in length and sampled at 1 kHz with 16-bit resolution. For comparison purposes, abdominal ECG signals were also recorded simultaneous with DUS. Then fECG was extracted using Blind Source Separation with Reference (BSSR) described in our previous paper [8], where more details about the experiment setup can be found.

The study protocol was approved by Tohoku University Institutional Review Board and written informed consent was obtained from all subjects.

2.2. DUS signal decomposition

Similar to our previous studies [6-7] DUS was decomposed by EMD [9] which is a single channel method for decomposing a complicated signal into a set of different oscillatory modes (IMFs). These IMFs naturally have different frequency bands. The first IMF i.e. the highest frequency content was used to identify the valve motion events. The peaks of the absolute value of this IMF can be linked to the opening and closing of the mitral and aortic valves.

On the other hand the fourth IMF, i.e. the low frequency component, includes peaks associated with fetal cardiac wall motion. The atrial wall contractions (Atc) were represented by the prominent peaks of the fourth component occurring once per each cardiac cycle. They were used as a reference for segmentation of the first IMF, as explained in the next section.

The envelope of the first and fourth IMFs were obtained using low-pass filter. Their peaks were then detected based on the sign of the first and second derivatives.

2.3. Segmentation and normalization

The sequence of Atc-to-Atc intervals was calculated from the detected Atc peaks of the fourth IMF. This sequence was processed to fix misidentified Atc peaks as follows. For each window of five consecutive Atc-Atc intervals, the middle interval which was deviated from the mean of the four other intervals by more than 10%, was replaced by that mean value.

The first envelope of the first IMF was the divided into segments of Atc-Atc intervals. Then each segment was normalized by subtracting the mean and dividing by the standard deviation of the segment.

2.4. Identification of valve motion events

The hybrid SVM-HMM method was first introduced in [10] for speech processing and proposed for identification of valve motion in our previous paper [7]. This method has training and testing processes. The hybrid model is trained once and then the trained model can be used for identification of valve motion events from the new data.

The aim is to identify the hidden states which are mitral (M) and aortic (A) valve opening (o) and closure (c) as well as the transitional states (Tr) between them; i.e. Mc, Tr1, Ao, Tr2, Ac, Tr3, Mo, Tr4. In this study we were particularly interested in Mc and Ao versus the other states.

The observation sequence is the amplitude of the peaks of the first IMF envelope, as well as the time interval between each peak and its proceeding Atc peak (the beginning of the segment).

Details of the hybrid SVM-HMM process can be found in [7] and summarized as follows. In the HMM training process the transition probability matrix was estimated from the sequence of the states in train set. SVM was also trained based on the observation and states in train set. The classes were assumed the same as the hidden states. One-against all approach was performed for multi-class SVM and the Radial Basis Function (RBF) with the width of $\sigma = 1$ was used. For the testing process, the observed peaks were classified as one of the events using SVM. The probabilistic output was obtained using Platt's method and the emission matrix was estimated from the output using Bayes' rule. This emission matrix and the transition matrix from HMM training, were used for decoding the observation sequence, using the Viterbi algorithm.

After performing hybrid SVM-HMM, ICT was calculated from the interval between mitral closing and aorta opening. Then beat to beat ICT values were averaged over all cardiac cycles in one minute for each fetus.

2.5. Comparison

For comparison of the new method with the previous technique, fECG for all 21 fetuses were used as a reference to find ICT with the previous method [7]. The Bland–Altman method [11-12] was used to investigate the agreement between previous and new method and to calculate the variability of the estimates. Pearson's coefficient of correlation was calculated to measure the association between the ICT intervals obtained using two methods.

3. Results

Regular wall motion peaks were detected from the fourth IMF and used as a reference for segmentation. Figure 1 shows an example of the segments found using peaks of the envelope of IMF4 (Figure 1.b), which can be compared with the reference from R-peak of fECG (Figure 1.c).

ICT was measured for 21 fetuses using the new method (without using fECG) and previous method (using fECG) [7]. Mean and standard error of the averaged ICT over 1 minute for each fetus are summarized in table 1.

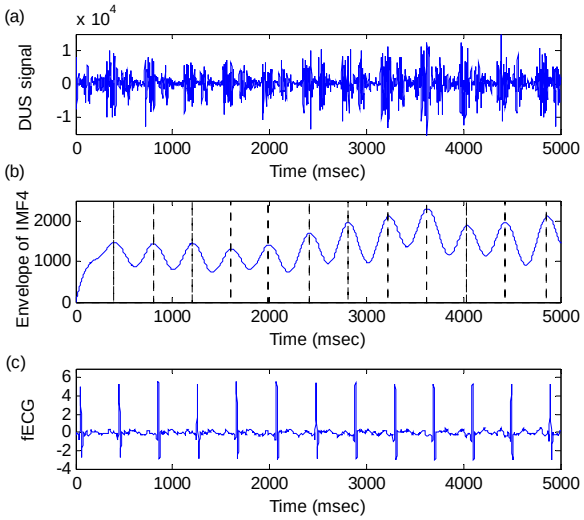

Figure 1. a) 5 second recording of DUS signal. b) Reference from the envelope of IMF 4, which is a low frequency component of the DUS signal. Dashed lines show the segmentation reference points found from peaks. c) Simultaneous fECG.

Table 1. Mean and standard error (SE) of ICT averaged over all cardiac cycles (in 1 minute) for 21 fetuses using the new method (without using fECG) and previous method (using fECG) [7].

Method	Mean (ms)	SE (ms)
New method	37.3	3.6
Previous method	36.8	2.8

The relationship between ICT measured with two methods was almost linear (r^2 = 0.81) (Figure. 2). The agreement between these measurements is shown in Figure 2 and Figure 3, which show the average differences of changes between ICT measured by different algorithms, the variability of the estimates, limits of agreement (±1.96*SD), and the strength of the associations between the two measurements.

The agreement between methods was high, difference was not significant and had a low variability of the estimate. The correlation coefficient r= 0.90 shows a strong association between methods. Although for the new method fECG was not used, the mean of absolute difference of 1.4 msec was obtained which is small compared to the large range of variability of ICT.

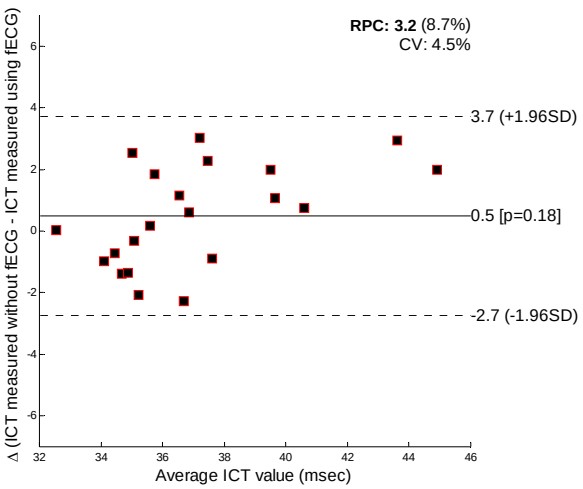

Figure 2. Bland-Altman plot (bias and 95% limits of agreement: ±1.96SD) for the average ICT from 21 fetuses measured by the new method (without using fECG) versus the previous method (using fECG). RPC(%): reproducibility coefficient and % of mean values, CV: coefficient of variation (SD of mean values in %).

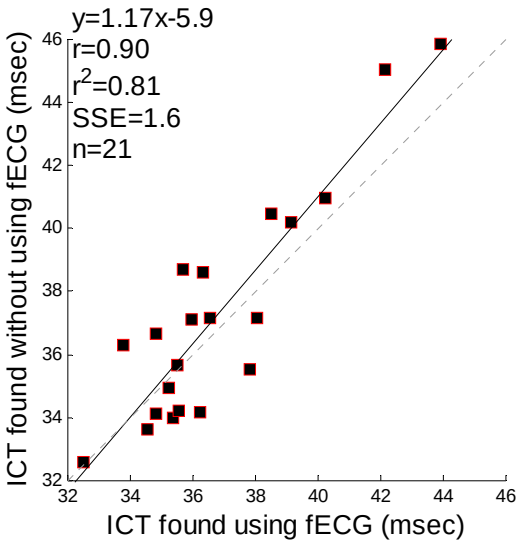

Figure 3. Bland-Altman analysis for comparing the average ICT from 21 fetuses measured by the new method (without using fECG) versus the previous method (using fECG). r: Pearson correlation r-value, r^2 : Pearson r-value squared, SSE: sum of squared error, n: number of fetuses

4. Discussion

ICT is a significant index which can be estimated from

the timing of mitral closure and aorta opening. Although fECG was not involved in manual measurement of ICT proposed in previous studies [1-2], it was required as a reference for automated methods [6-7]. R-peaks of the extracted fECG from the abdominal ECG provide a stable and accurate reference for segmentation of DUS signal component into cardiac cycles. However, to this aim, abdominal ECG should be recorded simultaneous with DUS signal and fECG should be extracted from the mixtures; which require extra cost, equipment and processing. The new automated method without fECG provided ICT measurement in acceptable agreement (limit of agreement (-2.7-3.7 ms)) with the average ICT obtained from the previous method.

However larger differences were found for beat to beat ICA measured with and without using fECG (6.1 ± 3.8 ms). Further studies are required for more accurate segmentation. A combination of DUS components (IMFs) may provide a more stable reference for segmentation. Other processing methods for correction of the false segmentation points may also improve this task.

5. Conclusion

Fetal ICT can be estimated non-invasively from DUS signal. Different from the previous automated methods for identifying ICT, fECG was not used as reference for the technique proposed in this paper. Instead the low frequency component of DUS signal was used for segmentation. Results showed that the measured average ICT with this new method was in agreement with the average ICT measured by the previous method which required fECG as reference (correlation coefficient: r = 0.9, bias = 0.5 ms, 95% limits of agreement: -2.7–3.7 ms).

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