Identifying Fetal Heart Anomalies using Fetal ECG and Doppler Cardiogram Signals

Ahsan H Khandoker[1], Yoshitaka Kimura[2], Marimuthu Palaniswami[1], Slaven Marusic[1]

[1]The University of Melbourne, Parkville, Australia
[2]Tohoku University, Sendai, Japan

Abstract

This study presents an automated and non-invasive technology using an integrated fetal transabdominal electrocardiogram system and Doppler cardiogram (DCG) to identify fetal heart anomalies. Multiresolution wavelet analysis and Jensen-Shannon divergence (JSD) methods were used to identify the frequency contents of the Doppler signals to be linked to the opening and closing of the heart's valves (Aortic and mitral). For the normal fetuses, PEP (Pre-ejection period), VET (Ventricular ejection time), ICT(Isovolumic contraction time) and IVRT (Isovolumic relaxation time) were found to be 75.0±11.9 (msec), 153.2±18.9 (msec), 50.0±15.9 (msec) and 69.6±9.7 (msec) respectively. On the other hand, for fetuses with heart anomalies, these timing intervals were found to be 89.0±10.3 (msec), 168.6±25.0 (msec), 52.2±17.2 (msec) and 51.6±13.7 (msec) respectively. PEP, VET and IVRT values are significantly ($p<0.01$) different between the two groups.

1. Introduction

Fetal health is critical to peri- and post-natal normality with consequences for general health status of later life. However, even when pregnancies show no identifiable risks, 100% healthy births do not happen. The principal aim of antenatal fetal welfare testing is to identify fetuses at risk of intrauterine compromise or death, so that these adverse outcomes can be prevented. In recent decades, many techniques for assessment of fetal well-being have been introduced into clinical practice. Despite widespread use of these techniques, there is limited evidence to guide their optimal use or to demonstrate their effectiveness at improving perinatal outcomes. In developed nations, current perinatal mortality rates are approximately 10/1000 births and fetal deaths account for approximately 50% of deaths between 20 weeks of pregnancy and 1 year of age [1], with congenital malformations and perinatal hypoxia being the principal causes. Even though fetal surveillance (performed more frequently on "high-risk" pregnant groups) may significantly reduce the incidence of fetal deaths, perinatal morbidity and maternal distress in such groups, the majority of stillbirths and malformations now occur in "low-risk" pregnancies (i.e., those with no identified risk factor) [1]. This apparent anomaly emphasizes the urgent need to develop more effective ways of identifying "at-risk" fetuses in "low-risk" groups. In "high-risk" pregnancies, ultrasound-based technologies are the most common diagnostic procedure for identifying fetal compromise, while in "low-risk" groups reduced fetal activity is the only assessment shown to identify fetuses at risk, albeit with poor positive predictive value.

Cardiotocography (CTG), which is a record of the fetal heart rate (FHR) and uterine contraction activity measured via transducer on the abdomen, is commonly used for fetal welfare evaluation. Sometimes abnormal variability in fetal heart rate may not necessarily represent the compromised fetus. As reported in several recent studies, the indices adopted in CTG do not appear to have brought about a reduction in fetal mortalities [2]. Fetal movement, particularly in early stage fetuses, often results in signal loss and consequently mis-diagnosis. Actually, no unified health assessment method for the fetus currently exists. The interval between the onset of the QRS complex of fetal ECG and the start of ventricular ejection (i.e., the opening of aortic valve) and the interval from opening to closure of aortic valve, are known to be very sensitive indicators of fetal myocardial performance [3-5]. However, the challenge of reliably estimating fetal cardiac valves' timings under fetal movements still exists. Therefore, the present study aims to address the challenge by analysing the Doppler signals to detect cardiac valve (aortic and mitral) opening and closing timings with reference to fetal ECG in normal as well as fetuses with heart anomalies.

2. Methods

2.1. Subjects

Simultaneous recording of the abdominal ECG signals and Doppler ultrasound signals from 5 pregnant women at the gestational age of 28~36 weeks with normal single pregnancies and five pregnant women who were diagnosed to have fetal heart anomalies were collected from Tohoku University Hospital. A total of 10 recordings (each of 1 minute's length) were sampled at 1000 Hz 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 traces were extracted using a method that combines cancellation of the mother's ECG signal and the blind source separation with reference (BSSR) as described in our earlier study [6].

2.2. Wavelet analysis and feature extraction

Fig. 1 shows the relative opening and closing timings of the heart's aortic and mitral valves in relation to the FECG. Doppler frequency shifts associated with cardiac activity can be visualized. Interpretation of DUS signals in relation to cardiac valve movements has been performed using time frequency wavelet analysis[4,5]. One example of DUS signals together with and their reconstructed signals from detailed coefficients after wavelet decomposition are shown in Fig. 2. A sliding window (50 samples) given by the position of its center was moved along the set of reconstructed Doppler sound signal and Jensen-Shannon Divergence (JSD) values between successive windows were calculated. The general Jensen-Shannon Divergence (JSD) is an information theoretical function that quantifies the difference between two (or more) probability distributions [10]. JSD can be better estimated by quantifying the difference between two probability distributions when it reaches its maximum value exactly at the point that the time series leads to different probability distributions. Here in our case we compared the probability distributions of the left and right side as shown in Fig. 2.

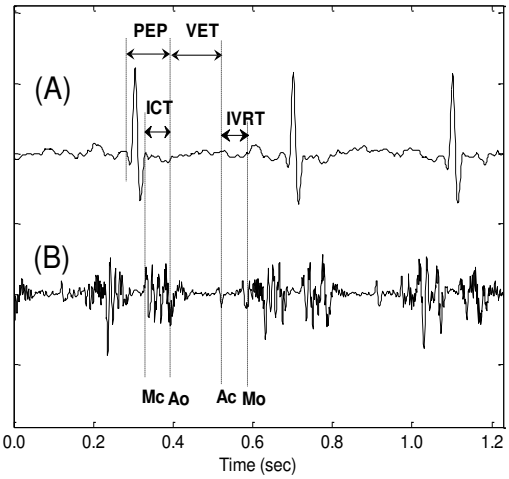

Figure 1. Example of simultaneously recorded fetal ECG and Doppler ultrasound data. (A) fetal ECG signal extracted from maternal abdominal signals using blind source separation with the reference signal [6]. (B) Data from the non-directional channel of the ultrasound from the fetal heart. Aortic opening/closing (Ao, Ac), Mitral opening/closing (Mo, Mc), pre-ejection period (PEP), left ventricular ejection time (VET) in relation to the ECG[3]. Isovolumic contraction time (ICT), isovolumic relaxation time (IVRT).

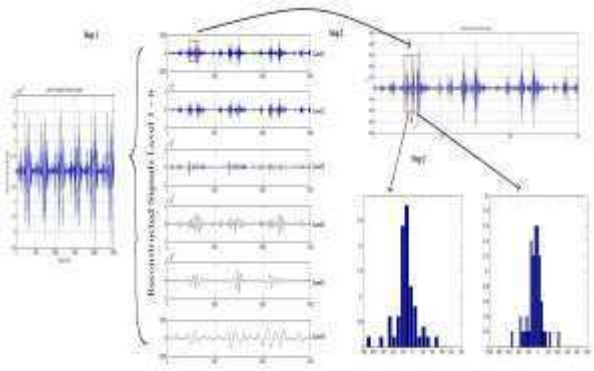

Figure 2. Wavelet decomposition of DUS signals and estimation of JSD.

3. Results

Two examples of the FECG for several cardiac cycles together with DUS signals and their details signals at level 2 wavelet decomposition are shown in Fig. 3&4 . The timings of aortic valve motions (in Fig. 3) and mitral valve motions (in Fig. 4) with respect to the ECG, the origin of the events highlighted within the DUS were

elucidated and verified by pulsed Doppler ultrasound in the bottom panel. In order to detect the peak timings of aortic valve's motion events, the time durations from R wave within each RR interval chosen for each event were 0.05~0.10 sec for Ao and 0.14~0.26 sec for Ac. On the other hand, for mitral valve's relative timings, 0.00~0.05 sec for Mc and 0.26~0.33 sec for Mo were used in calculation.

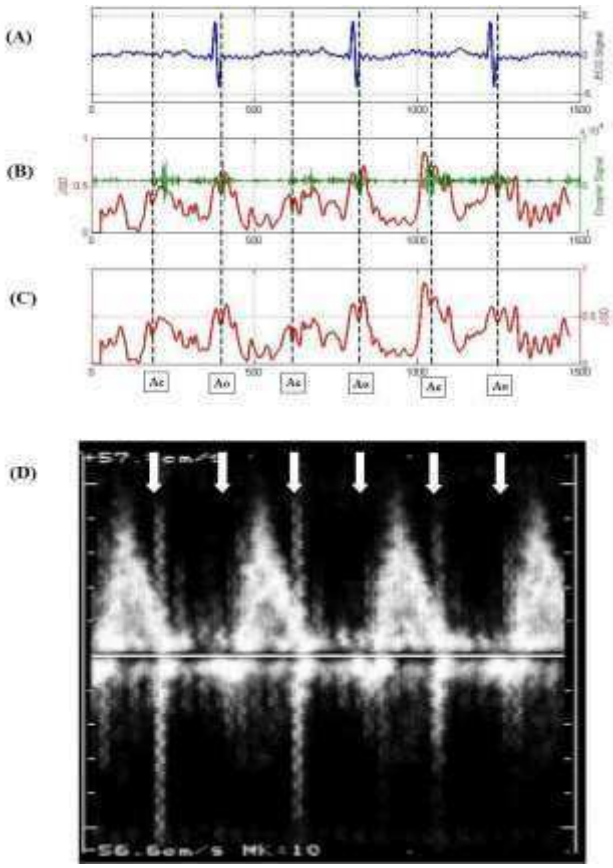

Figure 3. Panel (A) shows an example of fetal electrocardiogram signals extracted from abdominal ECG signals using BSSR [6]. Panel (B) shows the detailed signal after wavelet decomposition of DUS signal at level 2. Panel (C) shows the JSD values of the detailed signal in panel (B). Panel (D) shows the example of Pulsed-wave Doppler signals of fetal aortic valve movements annotated to show how the specific signals are linked with opening and closing events. Ao and Ac represent the opening and closing of aortic valve.

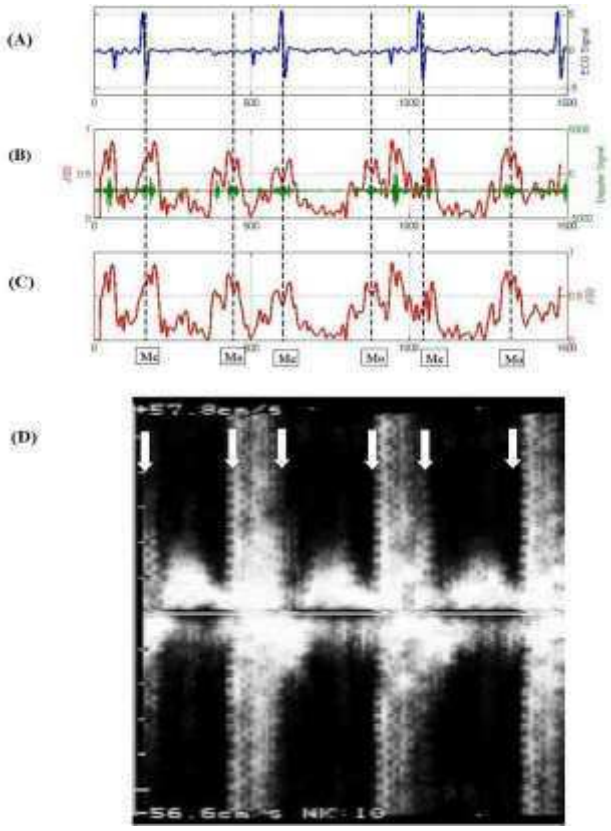

Figure 4. Panel (A) shows an example of fetal electrocardiogram signals extracted from abdominal ECG signals using BSSR [6]. Panel (B) shows the detailed signal after wavelet decomposition of DUS signal at level 2. Panel (C) shows the JSD values of the detailed signal in panel (B). Panel (D) shows the example of Pulsed-wave Doppler signals of fetal mitral valve movements annotated to show how the specific signals are linked with opening and closing events. Mo and Mc represent the opening and closing of mitral valve.

Table 1. Mean and SD values of PEP (Pre-ejection period), VET (Ventricular ejection time), ICT(Isovolumic contraction time) and IVRT (Isovolumic relaxation time) of normal fetuses and fetuses with heart anomalies. Total cardiac cycles analysed were 840. * indicates $p<0.05$.

		Mean	SD
Normal fetuses (5)	PEP	75.0	11.9
	VET	153.2	18.9
	ICT	50.0	15.9
	IVRT	69.6	9.7
Heart anomalies (5)	PEP	89.0*	10.3
	VET	168.6*	25.0
	ICT	52.2*	17.2
	IVRT	51.6*	13.7

4. Discussion

In developing new techniques for fetal welfare assessment, it is logical to examine parameters of fetal cardiac activity and function, given the pivotal role the fetal heart plays in fetal welfare and the capacity of fetal cardiac parameters to reflect compromising situations.

Cardiac valves' opening and closing time intervals have long shown potential for assessment of fetal cardiac function. The pre-ejection period (PEP–QRS onset until aortic valve opening) and isovolumic contraction time (ICT–mitral valve closure until aortic valve opening) are known to correlate with gold-standard invasive indices of cardiac contractile function [3]. They are known to be sensitive indicators of fetal myocardial performance[3], and thereby allow differentiation of fetuses with fetal growth restriction (FGR) and other perinatal problems [7,8]. Isovolumic relaxation time (IVRT – aortic valve closure until mitral valve opening) measures ventricular relaxation. In the fetus, prolongation of the IVRT accurately identified fetuses with FGR secondary to abnormal placental function up to 8 weeks prior to abnormalities of conventional Doppler haemodynamic indices[9].

Until recently these time intervals have been predominantly assessed by ultrasound with manual measurement of valve motion events. As a consequence, they have remained largely research tools. Development of integrated fetal ECG and cardiac Doppler signals from heart valve and wall motion events provides the potential for automated non-invasive assessment without obstetric ultrasonography expertise. Widespread application of this technology may therefore be possible, enabling assessment of its value in antenatal screening of both fetal well being and cardiac function.

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Address for correspondence.

Dr Ahsan Khandoker
Dept. of Electrical & Electronic Engg.
The University of Melbourne, Parkville, VIC -3010, Australia.
E-mail:ahsank@unimelb.edu.au