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A novel approach for phonocardiographic signals processing to make possible fetal heart rate evaluations

Vijay S. Chourasia [a,*], Anil Kumar Tiwari [b], Ranjan Gangopadhyay [c]

[a] *Manoharbhai Patel Institute of Engineering & Technology, Kudwa, Gondia (Maharashtra), 441614, India*
[b] *Indian Institute of Technology, Rajasthan, MBM College Campus, Jodhpur, India*
[c] *The LNM Institute of Information Technology, Post Sumel, Jamdoli, Jaipur (Rajasthan), 302031, India*

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ABSTRACT

In this paper, a non-invasive, portable and inexpensive antenatal care system is developed using fetal phonocardiography. The fPCG technique has the potential to provide low-cost and long-term diagnostics to the under-served population. The fPCG signal contains valuable diagnostic information regarding fetal health during antenatal period. The fPCG signals are acquired from the maternal abdominal surface using a wireless data acquisition and recording system. The diagnostic parameters e.g., baseline, variability, acceleration and deceleration of the fetal heart rate are derived from the fPCG signal. A model based on adaptive neuro-fuzzy inference system is developed for the evaluation of fetal health status. To study the performance of the developed system, experiments were carried out with real fPCG signals under the supervision of medical experts. Its performance is found to be in close proximity with the widely accepted Doppler ultrasound based fetal monitor results. The overall performance shows that the developed system has a long-term monitoring capability with very high performance to cost ratio. The system can be used as first screening tool by the medical practitioners.

1. Introduction

Antepartum antenatal care has become an essential component of pregnancies for early screening of prenatal anomalies [1]. The previous studies suggest that intrapartum hypoxia has an antepartum origin [2]. Monitoring of FHR patterns is an established way of fetal surveillance and offers important information about health of the unborn [3]. The detailed study of FHR pattern shows that there are certain idiopathic factors which can convert a low risk pregnancy into high risk one, during any time after 32 weeks of gestation. The instantaneous value of FHR is usually normal even for pregnant women with high risk for premature labor and miscarriage. Thus, all pregnancies need to be monitored continuously for longer duration to identify any abnormality in FHR pattern for fetal well-being [4].

The existing technique for antenatal care and prenatal diagnosis, in clinical practice, is based on Doppler ultrasound methodology [5]. This technique is very reliable and widely accepted by gynecologists and obstetricians. The major limitation of Doppler ultrasound is that, during the measurements, the ultrasound transducer pulses (2 MHz frequency at 10 mW/cm^2 intensity) are penetrated into the mother's womb. Exposure of these ultrasound waves for longer duration to the fetus as well as to the mother is not recommended. Thus, this technique is not suitable for long-term monitoring of the FHR [6]. Fetal heart activity can also be monitored by fetal electrocardiography (fECG) technique by capturing the ECG from the maternal abdominal surface [7]. But the task of extracting the fetal signal from the received one requires complex signal processing. Another problem of this technique is that the signal quality highly depends on the proper placement of electrodes. Therefore, a long-term recording can be inconvenient for the mother and may require frequent electrode adjustment due to fetal movements. Furthermore, during the critical period of 24 to 36 weeks of gestation, the reliability of this method is only 60% [8,9]. During this time, the amniotic fluid fails to provide adequate electrical coupling between the fetus and the mother's abdomen.

Auscultation is widely used by gynecologists and obstetricians to evaluate fetal well-being and detect the presence of abnormalities [10]. However, using the conventional stethoscope to screen the prenatal anomalies requires clinical practice and the experience of the clinician. The modern form of auscultation is phonocardiography [11]. In fetal phonocardiography (fPCG), natural vibroacoustic signals (fPCG signals) from the maternal abdominal surface are detected using a microphone installed in a stethoscope

* Corresponding author. Fax: +91 7182251587.
E-mail addresses: chourasiav@gmail.com (V.S. Chourasia), anil.k.tiwari@gmail.com (A.K. Tiwari), ranjan_iitkgp@yahoo.com (R. Gangopadhyay).

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and analyzed with the support of a computer to diagnose the fetal related problems [12]. The key features of fPCG technique are its non-invasiveness, cost-effectiveness and simplicity in operation [13]. The acquired signals can also be visualized on a monitor screen for online surveillance and simultaneously recorded for further analysis. These signals carry some additional features of fetal heart activity such as: fetal breathing movements, split effect and cardiac murmur. Owing to these advantages, this technique can be used for good quality home care of the unborn. Many pathological conditions that cause irreversible neurological damage or even fetal death manifest much earlier in fPCG technique. Thus fetal heart sound signal analysis may provide a simple non-invasive method of detecting and monitoring fetuses at risk in the antenatal period [14,15].

Despite these advantages, the fetal phonocardiography technique has been long overlooked by medical fraternities mainly because the fPCG signals are highly susceptible to various noises, sensor position and fetal/mother presentation [13].

Numerous efforts for improvement and re-establishment of this technique have been reported in the literature. Miguel et al. (1995) presented a system for the assessment of the reliability of the processed fetal phonocardiographic signal to detect beat to beat variations when it is compared with abdominal ECG. They concluded that the instantaneous fetal heart rate (FHR) estimation by phonocardiography assures an accurate measurement of beat to beat intervals [16]. Kovács et al. (2005) presented a real-time method for FHR monitoring based on signal processing of the fetal heart sounds. The processing algorithm was implemented in a low-power portable electronic instrument to enable long-term fetal surveillance [17]. Tan et al. (2000) developed a simple, low cost and non-invasive PC-based system that is capable of processing real time fetal phonocardiographic signal. A new electronic stethoscope with enhanced performance was also developed. The audio output unit enables the system to provide simultaneous listening and visual representation of the heart sound [18]. P. Várady et al. (2001) presented a novel two-channel phonocardiographic device and an advanced signal processing method, which provided a performance comparable to that of an ultrasound cardiography. The developed system provided 83% accuracy compared to the simultaneous reference ultrasound records [19]. M. Godinez et al. (2003) developed an on-line fetal heart rate monitor with a LabView-Matlab program. The monitor acquires and simultaneously processes PCGs during twenty minutes in order to detect fetal cardiac sounds. It also offers the possibility to see the CTG almost on-line, save and manually correct the CTGs once the time acquisition has finished [20]. Chen et al. (2008) developed a portable phonocardiographic fetal heart rate monitor which provides instantaneous fetal heart rate [21]. Kósa et al. (2008) presented a heuristics-based successive approximation method for heart beat detection in the fetal phonocardiographic signals, which was advantageous on some a-priori biological knowledge. The algorithm reached above 90% in terms of accuracy of the heart rate identification [22]. Miitra el al. (2008) attempted to develop an artificial womb that replicates acoustical state of a pregnant woman's abdomen [23]. Ruffo et al. (2010) presented a new algorithm for fetal heart rate estimation from fetal phonocardiographic recordings. Phonocardiographic signals have been recorded simultaneously to ultrasonic cardiotocographic signals in order to compare the two fetal heart rate series. Their results show that the proposed algorithm provides reliable fetal heart rate signals, very close to the reference cardiotocographic recordings [24]. Kósa et al. (2008) discussed the application of PCG in a tele-monitoring system enhancing its diagnostic capabilities, allowing long-term measurements even at home. This paper summarized the intensive fetal monitoring campaign carried out in Hungary during the last three years that yielded useful experience regarding recent and future possibilities of fetal monitoring [25]. Kovács et al. (2009) demonstrated the capability of fetal phonocardiographic measurements to indicate some congenital heart defects. During the investigations fetal cardiac murmurs presenting typical waveforms and incidences of acoustic signals were recorded [26]. Kovács et al. (2011) presented a complex heuristic method for the evaluation of fetal heart sounds, applying simultaneously several algorithms, where the autocorrelation technique has been completed with the wavelet transform and the Matching Pursuit methods [27]. Ruffo (2011) in his PhD thesis also analyzed fetal heart rate recordings and compared different methodologies for fetal health monitoring [28]. Cesarelli et al. (2012) presented simulator software of fetal phonocardiographic signals relative to different fetal states and recording conditions. Before developing the software, they conducted a data collection pilot study with the purpose of specifically identifying the characteristics of the waveforms of the fetal and maternal heart sounds [29].

All the earlier researchers have contributed significantly to improve the performance of fPCG technique for fetal monitoring. These studies were primarily focused on removing the existing limitations related to different parameters. However, it has not resulted in the development of a comprehensive system which is wearable, portable and suitable for long-term home monitoring of the fetus.

The objective of the present work is to provide a design framework and to implement a non-invasive and economical antenatal care system. The system will be simple enough to be used by the mothers themselves even in their home environment. The developed system consists of a simple data acquisition and recording module along with an online monitoring station. The monitoring station collects the fPCG signals detected from the abdominal surface of pregnant women through the wireless data acquisition module. The diagnostic parameters, which could be used for monitoring the fetal well-being, are derived from these signals. These parameters are fed to a model based on adaptive neuro-fuzzy expert system for classification of fetal health status. The results are obtained in an easily understandable manner for expectant mothers to monitor themselves at their homes. Besides these features, the system can be easily integrated with mobile for online distant monitoring and guidance.

The rest of the paper has been organized into the following sections. Section 2 covers a brief discussion on fetal heart sound and its characteristics. Section 3 describes the acquisition and preprocessing method for fetal heart sound signal. Section 4 consists of computationally efficient algorithms for denoising of the signal, envelope detection, segmentation, FHR calculation and features extraction from the fetal heart sound. Section 5 deals with the development of an ANFIS based expert model for antenatal care. Section 6 discusses the integration of all the developed algorithms through graphical user interface. The results are discussed in Section 7 and finally the concluding remarks are made in Section 8.

2. Fetal heart sound and its characteristics

Auscultation is the process of listening the vibroacoustic signals generated by mechanical action of the human organs [30]. Fetal heart sounds are produced by muscular action, valvular actions, motion of the heart and blood as it passes through the heart. A normal cardiac cycle of fetal heart contains two major sounds; S1 followed by systolic period and S2 followed by diastolic period in this sequence in time [31]. While pathological conditions such as hypoxia, acidemia, drug induction, intrauterine growth restriction (IUGR), maternal hypertension, gestational diabetes, congenital heart disease (CHD) etc., produce noticeable variations in the pattern of S1 and S2, they also cause additional sounds or murmurs, and/or split of S2 into two distinct components. These variations

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