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Trends in fetal monitoring through phonocardiography: Challenges and future directions

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ABSTRACT

Monitoring the well-being of a fetus through Fetal Phonocardiography (FPCG) has been occurring for more than a century. Throughout history, there have been continuous advances in sensor development, data acquisition systems, and signal processing techniques. Despite these advancements, FPCG based point of care technologies are facing serious challenges in translating from basic research to clinical trials and commercialization. This is partly due to the noisy characteristic associated with FPCG, to the lesser clinical knowledge about fetal and maternal physiological profiles, to the unavailability of gold standard databases, and to the limited application of reliable signal processing techniques. In order to understand why FPCG continues to be underutilized, it is necessary to know about the existing standards of fetal monitoring, data collection trends, and the signal processing aspects. To serve this purpose, this paper will first provide an overview of the existing standards of fetal monitoring and then provide a comprehensive survey on Fetal Phonocardiography with focus on trends in data collection, signal processing techniques and synthesis models that have been developed to date. Finally, a set of guidelines will be proposed for future research and use in signal analysis, processing and modeling based on the outlined challenges.
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1. Introduction

Center for Disease Control and Prevention (CDC) estimates that more than one million fetal deaths occur in the United States per year [1]. Complications such as preterm delivery, hypoxia, intrauterine growth retardation or others not only lead to fetal distress and neonatal death but also can cause risks to maternal health. There is a lesser knowledge about the incidence, etiology and prevention strategies for these complications; therefore it is critical to monitor the status of both fetal and maternal health throughout pregnancy. Consequently, Electronic Fetal Monitoring (EFM) was introduced in 1960s as a valuable tool for diagnosing Fetal Heart Rate (FHR) during antepartum and intrapartum periods of pregnancy [2]. Today, EFM is used in 90% of the labor diagnosis procedures in the United States [3] and includes Electrocardiography (ECG), Phonocardiography (PCG), Pulse Oximetry, Magnetocardiogram (MCG) and Tocodynamometer. Organizations such as the International Federation of Gynecology and Obstetrics (FIGO), the American College of Obstetricians and Gynecologists (ACOG), the National Institute of Child Health and Human Development (NICHHD), the Royal College of Obstetricians and Gynecologists (RCOG), and the National Institute of Clinical Excellence (NICE) have standardized the use of EFM in conjunction with Maternal Uterine Contractions (MUC) known as Cardiotocography (CTG) to optimize the outcomes for the mother and the new born infant [4,5].

Fetal Phonocardiography (FPCG) was discovered by the interventions of Marsac, Kergardec and Kennedy during the 17th century [6,7]. Although FPCG was discovered many years ago, interest in this research has only occurred over the last few years. Fig. 1 displays the number of peer reviewed articles published in the Institute of Electrical and Electronics Engineers (IEEE), the Science Direct, and the National Institute of Health (PubMed) databases. Currently, the application of FPCG is limited to FHR analysis and is seen as a noninvasive means for data acquisition; it is only used as a secondary diagnosis tool in the antepartum, and has never been utilized for complete clinical diagnosis. There are few reasons as to why FPCG is not clinically accepted for a complete diagnosis: First, the FPCG is very noisy, owing to the fact that the acquired signal is a mixture of acoustic and pressure components from the fetus, the mother and other noise sources; Second, the characteristics of the aforementioned components are highly dependent on the location of data acquisition, gestational age, fetal and maternal positions which result in the non-stationarity; finally, the non-linear transmission medium dynamically morphs all the components to result in a narrow band signal.

Today's standard of care in fetal monitoring suspects that the fetal heart rate is predictive of pregnancy complications [8]. As a consequence, EFM relies predominantly on FHR and does not incorporate the characteristics of the FPCG waveform in the assessment of fetal and maternal outcomes. The primary reason for the exclusion of this information from clinical practice is that the technology to measure the Fetal Heart Sounds (FHS) reliably is not yet available. Secondly, the existing signal processing techniques are unable to deliver a FHS signal from the acquired FPCG signal without considerable distortion.

The rest of this paper is organized as follows: Section 2, a description of existing standards of fetal monitoring; Section 3 an overview about morphology of FPCG; Section 4, a comprehensive description about all the fundamental acoustic and pressure components of a FPCG signal; Section 5, information about trends in data collection and databases; Section 6, a survey of the FPCG based signal processing techniques; Section 7, mathematical models of the FPCG signal; Section 8 summarizes the existing challenges and provides potential directions for future research.

2. Standards of fetal monitoring

Optimizing and improving the fetal and maternal outcomes during pregnancy, labor and delivery is the main objective of fetal monitoring. Existing standards of fetal monitoring assess the well-being of the fetus and the mother by performing various tests at different stages of pregnancy and labor. Table 1 provides a summary of all the essential parameters acquired using electronic instrumentation, the current gold standard and the history of FPCG use within the literature throughout pregnancy. Monitoring during first and second trimesters, weeks 5–28, of pregnancy is accomplished to ensure sustained growth of the fetus. Among existing technology, ultrasound is considered as a gold standard during this stage of pregnancy. In antepartum, weeks 29–40, fetal movement, fetal respiration, FHR, MUC and blood flow in the umbilical cord are being monitored; in particular, both ultrasound and tocodynamometer are considered the gold standards at this stage. Maternal Heart Rate (MHR), FHR and MUC are monitored during intrapartum, labor stage 1 and 2; the gold standard for this period could be either ultrasound or electrocardiogram. For a comprehensive overview of

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