NON-INVASIVE FETAL ELECTROCARDIOGRAPHY FOR THE DETECTION OF FETAL HEART RHYTHM DISTURBANCES

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Abstract. To assess whether non-invasive fetal electrocardiography (NI-FECG) enables the diagnosis of fetal arrhythmias, a total of 24 pregnant women were included in this study, among whom, two had a twin pregnancy. Thus totaling 26 fetal cases. Extraction of the NI-FECG from the abdominal electrocardiographic mixture was performed. Abnormal rhythms events were automatically detected similar to a traditional Holter. The NI-FECG based diagnosis was compared to the reference fetal echocardiography diagnosis. NI-FECG and fetal echocardiography agreed on all cases on the presence of arrhythmia or not. It is possible to diagnose fetal arrhythmias using the NI-FECG technique. The elaboration of a fetal Holter ECG device will offer new opportunities for fetal diagnosis and remote monitoring of problematic pregnancies because of its low-cost, non-invasiveness, portability and minimal set-up requirements.

Introduction.

One of the most common fetal heart rhythm disturbances during pregnancy is fetal arrhythmias. Fetal cardiac arrhythmias are defined as any irregular fetal cardiac rhythm or regular rhythm at a rate outside the reference range of 110 to 190 beat per minute (bpm). Arrhythmias are discovered in about 1% of fetuses with about 10% of these being considered potential sources of morbidity [1]. Thus, there is a clear motivation for elaborating a portable system which enables the diagnosis and continuous remote monitoring of the fetal heart.
The principal method of fetal heart rhythm assessment is fetal echocardiography. It allows a correct detection of both atrial and ventricular activity. However, continuous echocardiographic recordings are usually short (typically limited to a few seconds), require the physician to manipulate the probe manually and can only be performed within a clinical environment. Conventional cardiotocography is more accessible, but it is unable to extract the beat-to-beat variability of the fetal heart rate [2]. Magnetocardiography provides perinatal cardiologists with PQRST tracing but this hardware is not available in low- and middle-income countries due to its high cost [3]. Another recording modality, the STAN (STAN, Neoventa Medical, Molndal, Sweden) invasive fetal ECG monitor has shown some improved fetal outcome over cardiotocography at delivery [4]. However, this technique is invasive and can only be used at delivery. Non-invasive fetal electrocardiography (NI-FECG) is a promising non-invasive fetal diagnosis and monitoring alternative which presents a number of advantages: low-cost, possibility of local analysis (no need of long-distance referral for pregnant women), and possibility of continuous long-term remote monitoring. This work investigates the feasibility and interest for a fetal Holter ECG device in the context of fetal arrhythmia detection.

Materials and Methods:
Population. A total of 24 pregnant women were included in this study, among whom, two had a twin pregnancy. Therefore, the number of fetuses that were monitored with NI-FECG was 26. The population was divided in two groups: a group of 12 fetuses diagnosed with arrhythmias (ARR) after fetal echocardiography and a control group of 14 fetuses with normal cardiac rhythm (NR) at the time of the fetal echocardiography. This dataset was selected from a larger database of 500 recordings. The prevalence of fetuses having an arrhythmia was 2.3% in our population. All arrhythmic cases from this database were selected (i.e. 12) and another 14 normal sinus rhythm cases were selected to serve as the control group.

Echocardiography and NI-FECG were collected during a routine medical visit i.e. in a clinical setting. All pregnant women were included after a conventional examination at the Kharkiv municipal perinatal center or at the Ukrainian Children’s Cardiac Center in Kyiv. The study was approved by the Bioethics Committee of the Kharkiv Medical Academy of Postgraduate Education and Ukrainian Children’s Cardiac Center and registered under the ID 0105U002865.

Echocardiographic recording. Echocardiographic examinations were conducted in M-mode, B-mode, color-flow mapping and pulsed Doppler techniques in every case. The Philips iU22 Ultrasounds was used (Philips Healthcare, Bothell, WA). Protocols of investigation were based on segmental approach. For heart rhythm evaluation simultaneous assessment of atrial and ventricular contraction had been conducted using simultaneous Doppler sonography of the mitral inflow–aortic outflow and M-mode sonography of the atrium and ventricle. Figure 1 shows an example of supraventricular extrasystole episode, detected using echocardiography technology.
Non-invasive fetal electrocardiography recording. NI-FECG was recorded following the echocardiography during the same routine medical visit using the Cardiolab Babycard equipment ("XAI Medica"). The equipment consisted of six abdominal electrodes placed on the maternal abdomen and two chest electrodes. The electrodes were connected to the Cardiolab portable ECG monitoring device for the recording of the following signals: 1 chest lead and 5 abdominal leads. Data were acquired at a sampling frequency of 500 Hz or 1000 Hz and with a 16-bit resolution and a range of ±8 mV. Data were recorded continuously for variable durations with a minimum of 7 min and up to 32 min.

Source separation. The method for separating between sources are presented in [5,6]. Briefly, using the detected maternal R-peaks, periodic component analysis (πCA) [7] is first used to estimate the sources of the abdominal mixture. In a second step, the averaged maternal ECG cycle is subtracted to each individual beats in order to remove the maternal ECG contribution to each of the channels in the source domain. In a last step, the residual signals (i.e. after maternal cancellation) in the source space are back-projected to the original subspace using the inverse πCA. The result of a fetal ECG extraction (with supraventricular extrasystoles) is shown (fig. 2).

Automated abnormal rhythm events detection. An event detector algorithm was run to automatically detect abnormal rhythm events. Such events were defined as: a rapid change in the periodicity of the heart beats, or a rhythm below 110 bpm (bradycardia), or a rhythm exceeding 190 bpm (tachycardia).
When an abnormal rhythm event was detected, a 4.5 seconds NI-FECG strip of the NI-FECG trace was automatically generated.

![Fetal ECG with supraventricular extrasystoles](image)

**Fig. 2. Fetal ECG with supraventricular extrasystoles**

**Results.** The recording of NI-FECG was successful for all the pregnant women who were included. The numbers of detected events were in the range of 7-118 for the ARR fetuses in comparison to 1-10 for the NR fetuses. Based on the review of these events, the perinatal cardiologists accurately recognized the following rhythm disorders in our dataset: 6 extrasystoles, 2 tachyarrhythmia, 1 bradycardia, 1 irregular atrial rhythm and 1 case with blocked normal P-waves. NI-FECG and fetal echocardiography agreed in all cases (26/26) on whether the fetus was NR or ARR. In 19/26 cases the diagnoses were identical. In seven cases, the diagnoses differed: in three cases one type of extrasystoles was identified by the short echocardiography whereas two types of extrasystoles were identified on the longer NI-FECG strips; in one case the NI-FECG and echocardiography both identified extrasystoles but disagreed on their origin.

**Discussion.** Our first main conclusion is that NI-FECG can be used for the diagnosis of fetal arrhythmias. NI-FECG was able to accurately flag all the cases with rhythm disturbances.

Our second main conclusion is that NI-FECG provides, in a majority of cases, more detailed information compared to fetal echocardiography. This is because the NI-FECG allows to appreciate over a longer time period the rhythm abnormalities and thus can provide more details on the abnormal rhythm events that are present.

Our third main conclusion is that the NI-FECG provides additional fetal monitoring opportunities; (1) abnormal rhythm events can be automatically detected on the NI-FECG using an event detection algorithm. These events can
be presented to a perinatal cardiologist, similar to a usual Holter review. Such event detector can be run on long-term NI-FECG recordings during home monitoring and thus may provide a better appreciation on whether or not the fetus presents a rhythm disorder. It can also detect intermittent arrhythmias which could be easily missed during the short standard fetal echocardiography examination. (2) NI-FECG can allow for the characterization of some bundle branch blocks conduction events as shown for ARR 1. Such events cannot be diagnosed by conventional fetal echocardiography; (3) The NI-FECG can provide a very precise RR interval time series and therefore open for the possibility of fetal heart rate variability studies.

Our fourth main conclusion is that in the current state of the NI-FECG technology, the technique does not allow to systematically resolve the mechanisms of the arrhythmias. This stems from the difficulty in appreciating the atrial activity (i.e. the P-wave) on the NI-FECG traces. In the current state of the art, we identify the limited P-wave resolution from the extracted NI-FECG to be the main limitation of this monitoring technique for arrhythmia diagnosis.

**Limitations.** The recordings were performed in the clinic and not within the patient home or during the mother’s daily activity as would a standard Holter ECG. In order to be a viable option, fetal Holter must be evaluated on longer recordings and outside a clinical setting. Our rhythm detection algorithm is very sensitive to noise and thus will label any noisy NI-FECG segment as being an event. This can easily lead to an overload of the number of segments for the perinatal cardiologist to review. To overcome this problem, signal quality indices can be used to exclude NI-FECG segments of poor quality from the study and thus reduce the number of false positive detections.

**Conclusion.** This is the first study looking at the detection and diagnosis of a range of arrhythmias using the NI-FECG technique, and comparing the diagnosis against the reference fetal echocardiography. There are two main findings from this research: (1) it is possible to identify fetal arrhythmias using the NI-FECG technique; (2) improvement in algorithms for reconstructing the P-wave is critical to systematically resolve the mechanisms underlying the arrhythmias. This second findings offers a clear perspective for future research to the NI-FECG signal processing community. This paper is a proof of concept and a first step toward the creation of a fetal Holter ECG device for diagnosing and monitoring fetal arrhythmias. Such a device will offer new opportunities for remote fetal monitoring because it is low-cost, non-invasive, and portable.

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STUDY OF THE INFLUENCE OF CONTROLLED ELECTRODE METAL TRANSFER DURING ELECTRIC ARC SURFACING ON THE CONTACT FATIGUE OF THE DEPOSITED LAYER

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The deposited working layer of the rolling rolls of hot and cold rolling mills, crane wheels, guides and other equipment units should have high values of not only wear resistance, but also contact fatigue resistance. The main ways to increase the resistance of weld-up equipment nodes in this case are the development of new compositions of surfacing materials, as well as the improvement of restoration technology. Despite a large number of studies in these areas, the operational stability of the deposited working layer requires a search for ways to further improve.

The use of controlled transfer of electrode metal during electric arc surfacing allows one to increase the melting coefficient of the electrode, reduce the participation of the base metal in the deposited, and also stabilize the depth of the penetration zone for both wire [1] and strip electrodes [2, 3]. However, according to the literature, studies on the effect of controlled transfer parameters on the resistance of the deposited layer to contact fatigue have not been previously conducted.

The need to reduce the cost of manufacturing products requires the development of technology to use the methods of testing the properties of the deposited layer on the samples when simulating the operating conditions of the deposited products. A known method of testing materials for contact fatigue according to the scheme of a three-contact roller machine [4] with the location of the contact rollers at an angle of 120° relative to each other. Tests are conducted on cylindrical specimens with a diameter of up to 200 mm in an oil bath. This test...