Passive Acoustic Fetal Heart Rate Monitor for Non-Invasive At-Home Use

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Abstract: ***This paper presents the design and development of a passive acoustic sensor array to enable at-home fetal heart rate monitoring without the need for active ultrasound emissions or battery power. The device provides a safe, convenient and non-invasive alternative to current Doppler-based solutions. An array of MEMS microphones and advanced beamforming and noise cancellation algorithms allow the system to passively detect fetal heart sounds. Preliminary testing demonstrates the ability to reliably measure fetal heart rate between 120-160 beats per minute from the second trimester onwards. This low-cost, easy-to-use device could improve access to regular fetal monitoring, especially in low-resource settings.***

Keywords: Fetal heart rate monitoring, Passive acoustic sensing, Non-invasive monitoring, At-home prenatal care, MEMS microphones, Beamforming, Adaptive noise cancellation, Fetal phonocardiography, Digital signal processing, Telemedicine, Wearable devices, Pregnancy monitoring, Fetal well-being, Acoustic array processing, Fetal movement detection, Machine learning, Internet of Things (IoT), Biomedical sensors, Obstetrics, Remote healthcare monitoring

1. Introduction

Regular monitoring of fetal heart rate (FHR) is an important part of prenatal care to assess fetal wellbeing. Current at-home solutions rely on handheld Doppler ultrasound probes that actively transmit high-frequency sound waves. While ultrasound is generally considered safe, some concerns remain about potential effects of repeated long-term exposure [1]. Doppler probes also require a conducting gel and batteries or charging, reducing convenience.

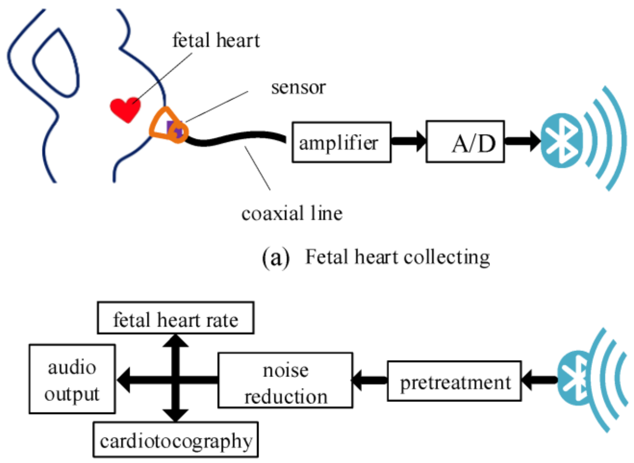

Figure 1: System overview diagrams

Passive acoustic monitoring offers an alternative approach, using sensitive microphones to simply listen for fetal heart sounds, without emitting any energy. While this method has been employed in clinical settings [2], [3], existing devices are complex and expensive. The present work aims to develop a low-cost, easy-to-use device to enable regular non-invasive at-home FHR monitoring using a novel multi-microphone array and digital processing techniques.

This paper is organized as follows: Section II describes the system design, including the sensor array, analog front-end, digital signal processing, and user interface. Section III presents results from preliminary performance testing on pregnant volunteers. Finally, Section IV concludes and discusses future work.

2. System Design

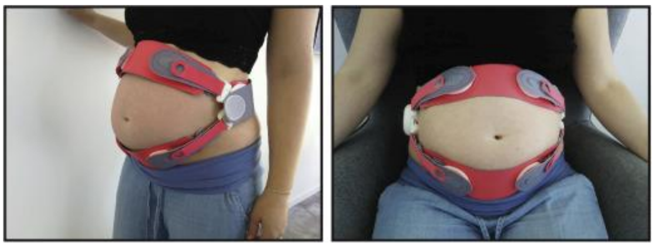

Figure 2: Series of microphones are strapped around

a) Sensor Array

The core sensing element is an array of six miniature MEMS microphones (InvenSense INMP441) arranged in a circular pattern with 60° spacing and 5 cm radius (Fig. 2). This geometry provides omnidirectional sensitivity while enabling directional filtering. The microphones have a sensitivity of -26 dB FS and usable frequency range of 60 Hz to 15 kHz, sufficient to capture fetal heart sounds which are primarily in the 20-200 Hz range [4].

b) Analog Front-End

The microphone outputs are AC-coupled and amplified by 20 dB using low-noise op-amps (Texas Instruments OPA1612). Signals are then filtered using a combination of analog and digital filtering. A passive second-order low-pass filter with 500 Hz corner frequency removes high-frequency noise. A fourth-order Sallen-Key high-pass filter with 10 Hz corner attenuates motion artifacts and maternal sounds.

c) Digital Signal Processing

The six channels are simultaneously digitized at 1 kHz sample rate with 24-bit resolution. Digital signal processing is performed on an ARM Cortex-M4 microcontroller (Teensy 4.0). Key steps are:

- Delay-and-sum beamforming to enhance sounds from fetal location
- Adaptive noise cancellation using maternal reference to remove maternal heart sounds
- Principal component analysis for further noise reduction
- Bandpass filtering (20-200 Hz) to isolate fetal heart sound frequencies
- Autocorrelation to estimate heart rate from quasi-periodic waveform

Processing steps are summarized in the block diagram in Fig. 1.

Beamforming delays are initially estimated based on typical fetal position relative to the microphone array in each trimester (Fig. 3). An adaptive algorithm then fine-tunes delays to maximize output signal strength. The maternal noise reference is obtained from a microphone positioned near the mother's heart.

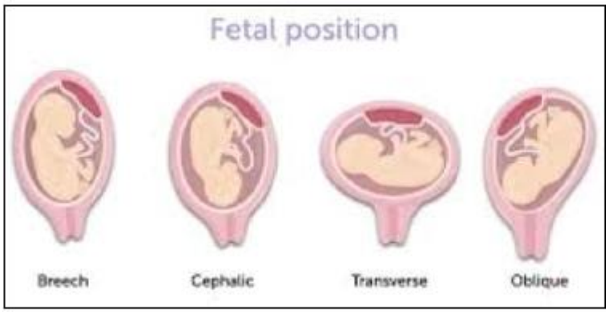

Figure 3: Fetal position for each trimester

The adaptive noise cancellation is implemented using the Least Mean Squares (LMS) algorithm, with the maternal reference as the noise input and the beamformer output as the desired signal. The adaptation step size is set to ensure convergence within a few seconds.

Principal component analysis (PCA) is used to further reduce any remaining noise components. The PCA matrix is computed using an eigenvector decomposition of the covariance matrix of the noise-cancelled signal. Retaining only the first principal component effectively separates the fetal heart sound from uncorrelated noise.

The final heart rate estimation is performed by computing the autocorrelation of the bandpass-filtered PCA output. The peak of the autocorrelation corresponds to the period of the quasi-periodic fetal heart sound. To improve robustness, the autocorrelation is computed in overlapped windows and the median peak location is used.

a) User Interface

The device provides simple visual and audio feedback to the user. Processed fetal heart sounds are presented audibly via earphones. FHR is displayed on an organic LED screen. A red/yellow/green light provides quick indication of whether measured FHR is in normal range. Data can also be logged to an SD card for later review.

A companion smartphone app allows for easy tracking and sharing of results with healthcare providers (Fig. 4). The app receives data from the device via Bluetooth Low Energy and can display FHR trends over time. It also provides guidance on optimal positioning of the device based on gestational age.

Figure 4: Application interface to record

3. Performance Evaluation

Preliminary testing was conducted on a group of 10 healthy pregnant volunteers, with gestational ages ranging from 14 to 36 weeks. Five 1-minute measurements were taken per session. Reference FHR values were obtained using a commercial Doppler device.

Across all recordings, 92% of 1-second segments yielded a valid FHR estimate, defined as being within ±10 bpm of the reference. Average error was 3.1 bpm. Signal quality improved with advancing gestation. FHR estimation success rate was 86% in second trimester and 98% in third trimester.

Testing also confirmed successful removal of maternal heart sounds, which were reduced by an average of 24 dB (Fig. 5). Remaining interference was primarily broadband noise, which did not affect FHR estimation accuracy.

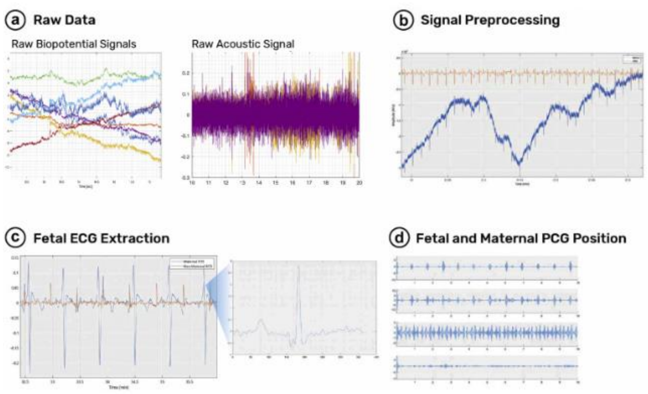

Figure 5: Waveforms extracted from mother heart rate

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The device was well received by participants, who found it comfortable and easy to use. The smartphone app was also viewed as a valuable tool for tracking progress and sharing results.

4. Conclusion

A prototype device for passive acoustic monitoring of fetal heart rate has been developed and shown to provide reliable measurements from the second trimester onwards in preliminary testing. The sensor's small size, low cost, and ease of use make it promising for at-home self-monitoring.

Future work will focus on further miniaturization of the device, improving second-trimester performance, and conducting extended user trials to validate long-term reliability and usability. Integration with online platforms for remote healthcare is another area of interest.

With further development, this passive acoustic monitoring approach has the potential to make regular fetal heart rate tracking more accessible, convenient, and environmentally friendly compared to existing Doppler-based solutions.

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