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An Algorithm for Extracting Non-invasive Fetal ECG from the Maternal ECG

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Abstract-This project presents a system for recovering the Fetal Electrocardiogram (FECG) using Multidimensional Independent Component Analysis (MICA). MICA requires multiple observations as sources. To increase the number of observations, MICA is rapidly applied to data sets like measurements taken from the mother's thoracic region. However, methods suggest that the propagation from the maternal heart to the mother's abdomen there is a huge delay, and that approach may sometimes fail. The proposed method first estimates the maternal ECG directly from the mother's abdomen, and inputs this estimated ECG to pre-processing followed by MICA, and then post-processing the noisy FECG signal. The MICA separates the FECG from the MECG and from the other unwanted background interferences, since the FECG contains minimal amount of noise that can be eliminated using post-processing. Finally the FECG signal is extracted and the method is tested with simulation results using MATLAB.

Index terms- **Abdominal ECG, Blind Source Separation (BSS), Fetal ECG (FECG) recovery, Maternal ECG (MECG), Multidimensional Independent Component Analysis (MICA).**

I. INTRODUCTION

The Fetal Electrocardiogram (FECG) is used for the calculation of the fetal cardiac frequency and in the prediction of the fetal acidosis. A major problem in modern obstetrics with respect to fetal monitoring is the lack of possibilities to extract information from the fetus to assess its condition. During pregnancy, the fetal heart rate is monitored using Doppler ultrasound [1]. Unfortunately, this technique is inaccurate and provides a relatively low positive predictive value, it is reliable only when the condition of the fetus is clearly good or clearly bad. In different situations, additional tests, such as micro blood examinations, are required. The extensive use of Doppler ultrasound for fetal heart rate monitoring might be harmful to the fetus. It cannot be used for long-term monitoring due to its high sensitivity. Fetal Heart Rate (FHR) monitoring is a routine for obtaining significant information about the fetal condition during pregnancy and labour [3]. Therefore, FHR carries a significant importance of clinical perspectives. The FECG can be measured by placing electrodes on the mother's abdomen, but it is largely distorted by different types of noise, among which the Maternal Electrocardiogram (MECG) is the most important interference [19]. The technique of Independent ComponentAnalysis (ICA) [2] can be used to separate out the FECG, whichis extremely low voltage, from the MECG,and from other unwanted background interferences, such asthe electrical activity produced by the uterus muscles. It hasbeen suggested that ICA outperforms most of the other signalprocessing techniques [3]. However, ICA is computationallydemanding due to its use of higher-order statistics, and hence, itis not well suited for implementation in real-time applicationsnor in lightweight and portable monitors, as would be desirableto provide mothers freedom of movement [12]. To cope with thisproblem, traditional approaches have been based on Multidimensional Independent Component Analysis (MICA) is an advanced signal processing technique that is used for separating out the FECG from the MECG and the rest of the interferences [2]–[4]. MICA is an extension of Independent Component Analysis (ICA).

MICA is more appropriate than ICA in the fetal ECG extraction problem [18]. Though MICA is generally reliable, thus we propose augmenting the number of inputs to MICA with MECG signals, which are recorded from the maternal abdomen. We point out that these MECG signals have been first cleaned so that they are free from fetal contributions. Experiments on real data show that MICA performs much better when the proposed technique is used.

II. FETAL ECG EXTRACTION

Fetal Electrocardiogram (FECG) is a tool for monitoring the fetal cardiac electrophysiology, which can provide important information about the health condition of the fetus, normally FECG can be extracted between 20th to

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40th weeks of gestation period [2]. It can be proven useful in determining if the fetus is developing or being delivered properly and include heart rate that indicates cardiac disorders such as fetal stress, fetal acidosis, cardiac arrhythmias, it can be used for long-term monitoring of fetal heart rate, and protects the safety of pregnant women and fetuses [3]. The fetal scalp electrode is said to be an invasive method, which acquires FECG during pregnant women's child was born, the recording electrodes have direct contact with the fetal skin [11], and extracts the FECG more accurate, but this method is inconvenient to patient, cannot be used in pregnancy testing, and may have risks for fetal and mother's health, it is limited to recordings. The second method is a non-invasive method of acquiring FECG, electrodes will be placed on the abdomen of pregnant women close to the fetal position to measure signal, and it is a passive receiving fetal heart beat [4]. The signals recorded from the mother's abdomen can be done at any state of pregnancies. Maternal abdominal skin electrode method is often used by pregnant women for its convenience, non-invasive has no effect on fetal growth and development, and it can be repeatedly used in prenatal care.

The FECG signals are often disturbed by electrical noise from other sources [7]. Common ECG noise sources, such as power-line interference, muscle contractions, baseline wander, respiration, skin resistance interference, and instrumental noise, motion artifact, ambient noise, in addition to electromyogram (EMG) and electrohysterogram due to uterine contractions, can corrupt FECG signals significantly. These noises make problem of FECG and fetal heart rate extraction from the MECG and becomes a very complex task [14]. To extract the FECG parameters from the noisy ECG signal, very first need is analysis of ECG signal to get which type of noise mesh up with the signal.

The signal-processing algorithm needs to remove the MECG complexes, reduce the effects of motion artifact and muscle noise, and then enhance the FECG to analyze the FECG for the monitoring of FHR. There are several techniques used for extracting FECG in that the most commonlyusedare Blind Source Separation (BSS), Principal Component Analysis (PCA), Singular Value Decomposition (SVD), and Independent Component Analysis (ICA). By using these techniques there are several disadvantages such as increased execution time, increased cost, not suited in real-time applications, FECG was affected by unwanted interferences. When compared to different methods, multidimensional independent component analysis is easy to implement in both real-time and synthetic data where there is no complexity in developing this algorithm. Hence, in proposed system MICA is implemented for the FECG extraction. The objective of this paper is firstly to review different FECG techniques mentioned above are analyzed in depth and to extract the FECG using MICA without noise, less execution time, to implement in real-time applications.

III. MULTIDIMENSIONAL INDEPENDENT COMPONENT ANALYSIS

The detection of the FECG is yet a difficult task even when the maternal component of the signal has been reduced. In order to observe the FECG, some technique should be applied for improving the Signal-to-Noise Ratio (SNR) and eliminating the maternal contribution to the signal. To extract the FECG with less amount of noise there are different techniques used, in that we are using Multidimensional Independent Component Analysis (MICA) [10]. In the implementation side we are using pre-processing and post-processing connected to MICA in order to reduce the noises and to produce the FECG signal efficiently.

MICA is often applied to data sets that include MECG signals taken at the mother’s thoracic region, which are almost free from fetal contributions [2]-[3]. They can be thought of as references to estimate the maternal sources and, then to eliminate these maternal sources from the signals recorded at the mother’s abdomen the more mixtures of thesources are used, the MICA will be able to identify them [6].
This paper proposes to recover the MECG directly from the pregnant woman’s abdomen. It is more realistic to assume that the maternal heartbeat signal propagates from the chest cavity to the abdomen. Consequently, the source signals that explain the abdominal MECG may not be the same as the source signals that explain the thoracic MECG, for example, there may be slight propagation delays among them. Hence, to estimate the maternal sources directly from the abdominal recordings seems to be a more suitable approach.

Multidimensional Independent Component Analysis (MICA) is the simplest method. In this we use Joint Approximate Diagonalization of Eigen Matrices (JADE) to separate the FECG signal from the MECG and from the other unwanted background interferences, so the cost of implementation is less and hence easy to implement [3]. The time complexity of this algorithm is very less and SNR improvement is high. It is well-suited for the implementation in real-time applications [5]. When this happens the algorithm has efficient fetal ECGsignal and

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the doctor can predict the fetus health condition whether it has normal heart rate or affected by any cardiac disorders.

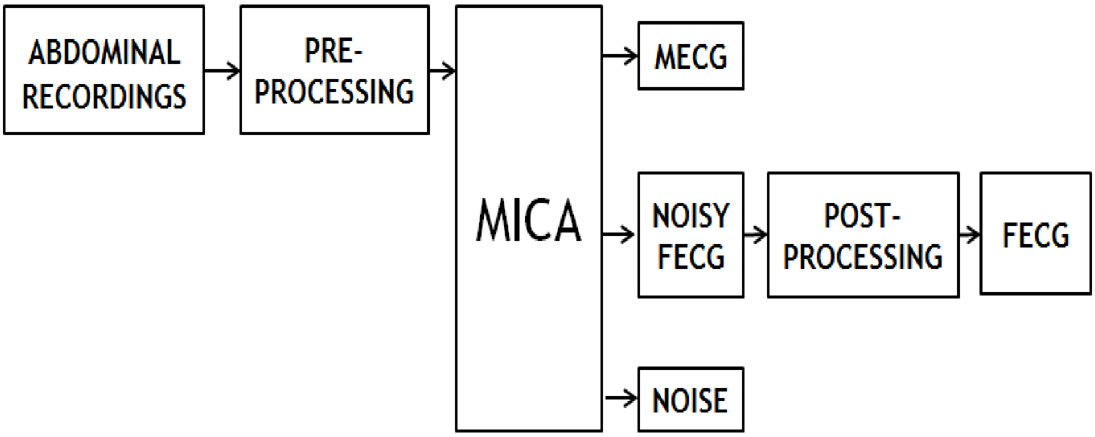

Fig. 1 Block diagram of Multidimensional Independent Component Analysis

A. Abdominal Recordings

The abdominal recording is the input signal taken from the mother's abdomen using the electrodes. The signal contains severalnoises that can be reduced by using pre-processing the abdominal signal.

B. Pre-Processing

The pre-processing is used to process the FECG signal before extracting the information, Finite Impulse Response (FIR) filter are designed to remove the baseline wander, EMG noise, uterine muscle noise with cut-off frequencies at 1Hz and 90Hz [12].Infinite Impulse Response (IIR) filter removes the power-line interference from each signal with cut-off frequencies at 60Hz. FIR filters are filters having a transfer function of a polynomial in z^{-} and is an all-zero filter in the sense that the zeroes in the *z*-plane determine the frequency response magnitude characteristic. The *z* transform of an *N*-point FIR filter is given by

$$H(z) = \sum_{n=0}^{N-1} h(n) z^{-n} \quad (1)$$

Where H(z) is the output response, and h(n) is the input response of the filter. FIR filters are particularly useful for applications where exact linear phase response is required. The FIR filter is generally implemented in a non-recursive way which guarantees a stable filter. FIR filter design essentially consists of two parts, approximation problem, and realization problem. An IIR filter is a property of signal processing systems [18]. IIR systems have an impulse response function that is non-zero over an infinite length of time.

$$H(z) = \frac{\sum_{i=0}^{P} b_i z^{-i}}{1 + \sum_{j=1}^{Q} a_j z^{-j}} \quad (2)$$

Where b_i and a represents the poles and zeroes in the response. IIR notch filter is the well-known or simplest filter to remove the power-line interference [18], it removes the artifact or set its value to zero.

C. MICA Separation

Multidimensional Independent Component Analysis (MICA) is used for separating the FECG from MECG and from the unwanted background interferences. One approach to perform MICA is to estimate the basic MICA model and then group the components according to their dependencies [12]. The inputs to MICA are the pre-processed abdominal maternal signals as they were recorded from electrodes. MICA is based on a geometric parameterization which is free of the indeterminacies of matrix-based modelling. MICA relies on the idea of vector-valued component rather than on scalar source signals [13]. A canonical MICA decomposition is proposed as an invariant decomposition which can be empirically computed by post-processing the results of MICA decomposition. The method has been tested using real-time data from the non-invasive fetal ECG database [9]. The database contains abdominal non-invasive recordings using 8 electrodes, taken from a single subject of 25[th] weeks of pregnancy. The calculation of MICA was carried out using the Joint Approximate Diagonalization of Eigen matrices (JADE) algorithm. In MICA, we use a data set points sampled at 500 Hz with 8 electrodes located on the abdomen of a pregnant woman. First we run the JADE algorithm, yielding (in about 500 K flops) this estimate of mixing matrix. Applying A inverse to the observations yields an estimate of 3 source signals which are displayed in the second column. Mixing matrix is estimated:

$$A = \begin{vmatrix} 3.4672 & -4.5059 & 7.5136 \\ 1.2643 & -9.4990 & -15.4075 \\ 1.4886 & 11.2593 & -2.4293 \end{vmatrix}$$

Second the cardiac rhythms in the second column reveal that the algorithm has extracted one source signal coming from the fetus heart and two source signals coming from the mother heart [5]. Therefore, this data set seems well modelled by MICA decomposition into one mono-dimensional (1-D) fetus component and one bi-dimensional (2-D) mother component. The orthogonal projection matrix on the 2-D mother's subspace is estimated:

$$Pm = \begin{vmatrix} 0.7702 & 0.1694 & 0.3851 \\ 0.1694 & 0.8752 & -0.2838 \\ 0.3851 & -0.2838 & 0.3546 \end{vmatrix}$$

Since the fetus signal clearly appears first in the second column, the orthogonal projection matrix on the 1-D fetus subspace is estimated:

$$Pb = \begin{vmatrix} 0.6158 & 0.2246 & -0.4315 \\ 0.2246 & 0.0819 & -0.1573 \\ -0.4315 & -0.1573 & 0.3023 \end{vmatrix}$$

The Oblique projection matrix onto 2-D mother subspace orthogonally to 1-D baby subspace is estimated:

$$PTm = \begin{vmatrix} 0.4752 & 0.3868 & 0.8795 \\ -0.1914 & 1.1410 & 0.3207 \\ 0.3677 & -0.2710 & 0.3838 \end{vmatrix}$$

The Oblique projection matrix onto 1-D baby subspace orthogonally to 2-D mother subspace is estimated:

$$PTb = \begin{vmatrix} 0.5248 & -0.3868 & -0.8795 \\ 0.1914 & -0.1410 & -0.3207 \\ -0.3677 & 0.2710 & 0.6162 \end{vmatrix}$$

The same scale is used for each row since vectors all live in the same space, the scale in the second column which represents vector is arbitrary, and it is conventionally determined by the JADE algorithm in such a way that the three entries have unit variance [5]. JADE was applied to the set formed by the three abdominal recordings. Here the fetal heartbeat signal is apparent and it was separated from the unwanted signals, since the FECG contains minimal amount of noise that can be eliminated using post-processing.

D. Post-Processing

In post-processing the FECG signal is filtered again with the median filter to improve the SNR. Median filtering is a non-linear operation and it is more effective than convolution when the goal is to simultaneously reduce noise and preserve edges.

$$B = \text{medfilt2}(A) \tag{3}$$

Where A is the input signal, B is the 2-dimensional median filtered output signal. It performs median filtering of the matrix in two dimensions, performs median filtering of the matrix A using the default 3-by-3 neighbourhood. medfilt2 pads the image with 0s on the edges, so the median values for the points within [m n]/2

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of the edges might appear distorted. Finally, it removes the maternal ECG interferences, other noises and produces the FECG signal as clearly visible.

IV. SIMULATION RESULTS AND DISCUSSION

The method is tested with simulation results using MATLAB. MATLAB stands for matrix laboratory. It is an interactive system whose basic data element is an array that does not require dimensioning. This allows solving many technical computing problems, especially those with matrix and vector formulations, in a fraction of the time it would take to write a program in a scalar non-interactive language such as C or FORTRAN. Toolboxes are comprehensive collections of MATLAB functions that extend the MATLAB environments to solve particular classes of problems. Areas in toolboxes are available include signal processing, control systems, neural networks, fuzzy logic, wavelets, simulation and many others. The toolbox used to visualize signals in time and frequency domains, compute FFTs for spectral analysis, design FIR, IIR and adaptive filters and implement convolution, modulation, resampling, and other signal processing techniques. The MATLAB version used is 7.12.0. Signal processing toolbox is mainly used.

A. Abdominal Signal

The abdominal recording is an input signal taken from the mother's abdomen using the electrodes.

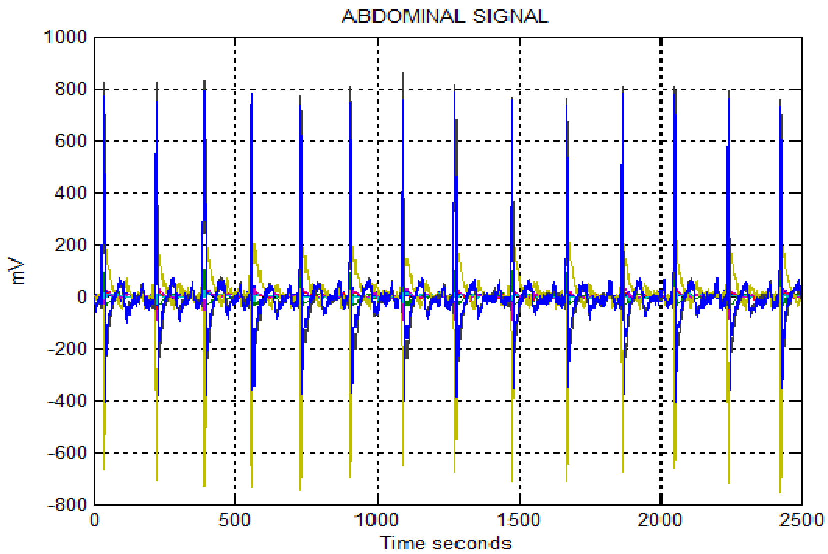

Fig. 2 Abdominal Signal from Mother's Abdomen

Fig. 2 shows the abdominal signal from maternal abdominal region. It is a combination of different biological signals such as Maternal Electrocardiogram (MECG), Fetal Electrocardiogram (FECG), various interferences such as baseline wanders, power-line interference, Electromyography (EMG) noise, uterine muscle noise, and these signals overlaps with FECG makes it invisible. To reduce the unwanted noisy signals we are using pre-processing.

B. Pre-Processed Signal

The abdominal signal is further processed and combined using Finite Impulse Response (FIR) band-stop filter and Infinite Impulse Response (IIR) notch filter and said to be the pre-processed signal. Pre-processing is used to extract the FECG signal with fewer noises. The FIR band-stop filter is used to process the abdominal signal, and to produce filtered output. It is a stable filter which requires no feedback whose response is of finite duration, because it settles to zero in finite time. This is the first step to improve the signal and to reduce the noise, here the abdominal signal is filtered using finite duration impulse response filter to produce stable results, EMG noise, and baseline wandering is reduced. The IIR notch filter results in infinite duration, it is unstable because it has a feedback. It is to improve the performance of the signal, here the power-line interference is reduced. The Fig. 3 shows the pre-processed signal, after pre-processing the FECG signal overlaps with MECG

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and the unwanted noises that can be eliminated by first separating the pre-processed signal using MICA, then by using post-processing.

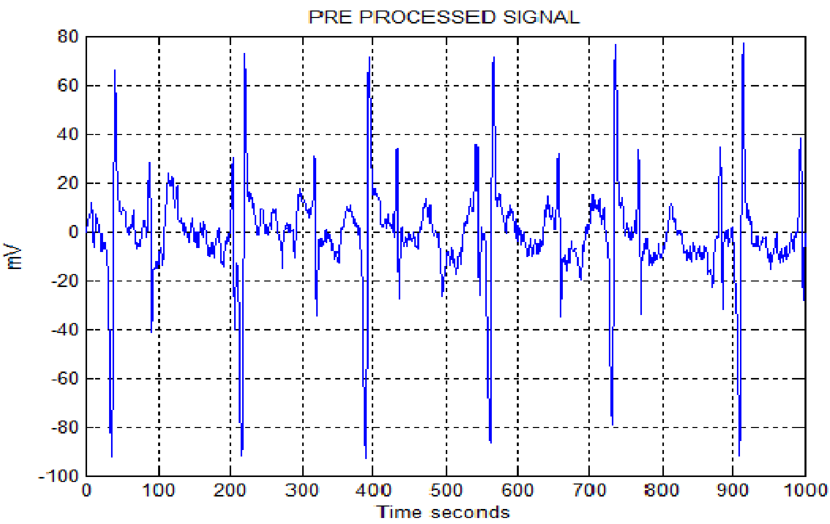

Fig. 3 Pre-processed Signal

C. *Separation using MICA*

MICA is used for signal separation. It was carried out using JADE algorithm, first it separates the maternal electrocardiogram signal, noisy fetal electrocardiogram signal, and the unwanted noises.The MECG signal is the mother's ECG signal. It contains the maternal cardiac frequency, normal ECG or abnormal ECG, and to predict whether the mother having any cardiac disorders these can be identified in MECG signal.

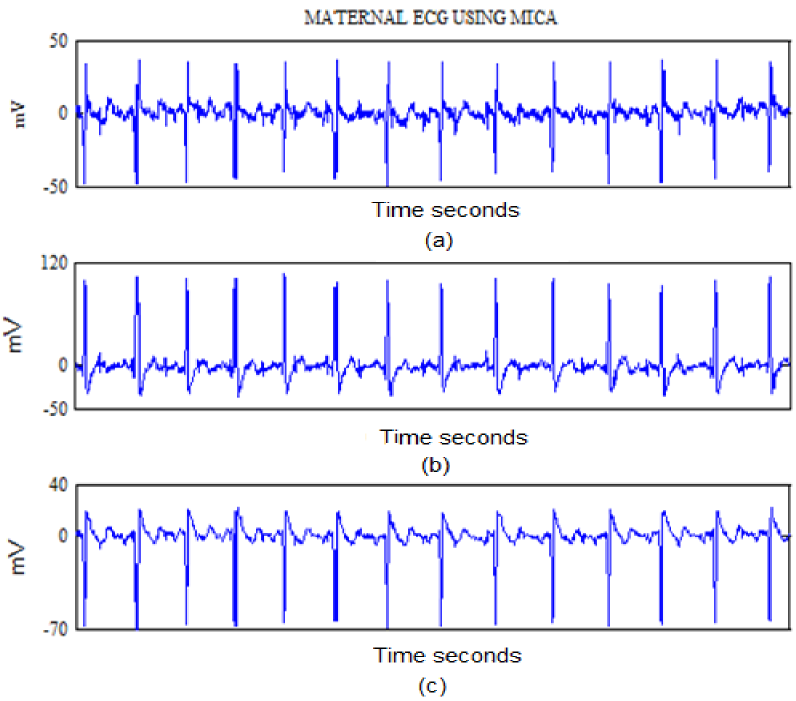

Fig. 4 Separation of MECG Signal using MICA, (a), (b), (c) shows MECG signal with Different Dimensions.

The fig. 4 (a), (b), (c) shows the separation of MECG signal with multiple dimensions using MICA. The MICA uses the Joint Approximate Diagonalization of Eigen matrix (JADE) algorithm to separate the signal. It contains

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the MECG signal with mother's heartbeat, breathing, movements and some unwanted interferences. The separation of noisy FECG signal with multiple dimensions using MICA is shown in fig. 5 (a), (b), (c). Here the FECG signal is invisible, and it contains the MECG interference which is most important noise that can be removed by post-processing the FECG signal by using filtering technique.

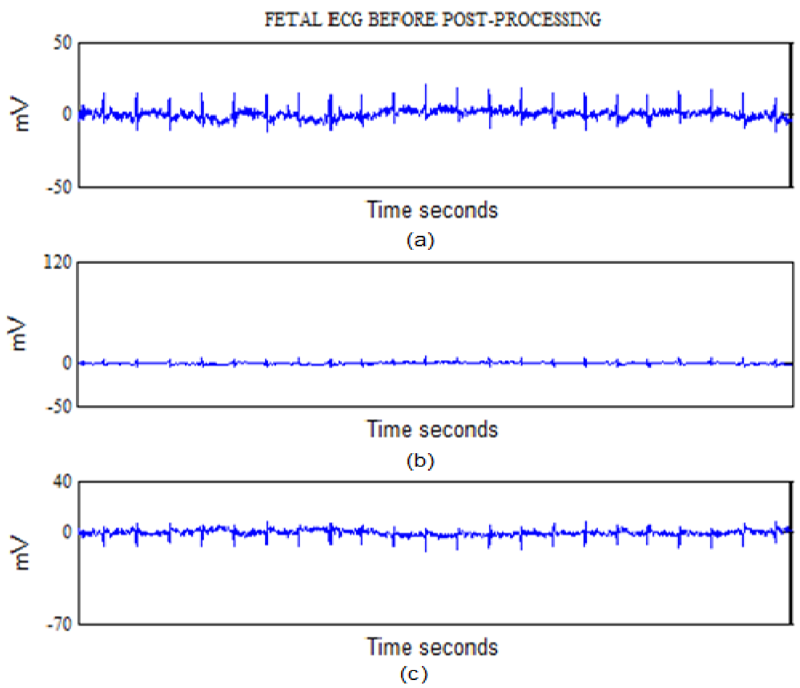

Fig. 5 Separation of FECG Signal before Post-processing, (a), (b), (c) shows Noisy FECG Signal with Different Dimensions.

D. Post-Processed Signal

The separation of noisy FECG signal can be post-processed using median filter, post-processing extracts the fetal ECG signal without any noises.

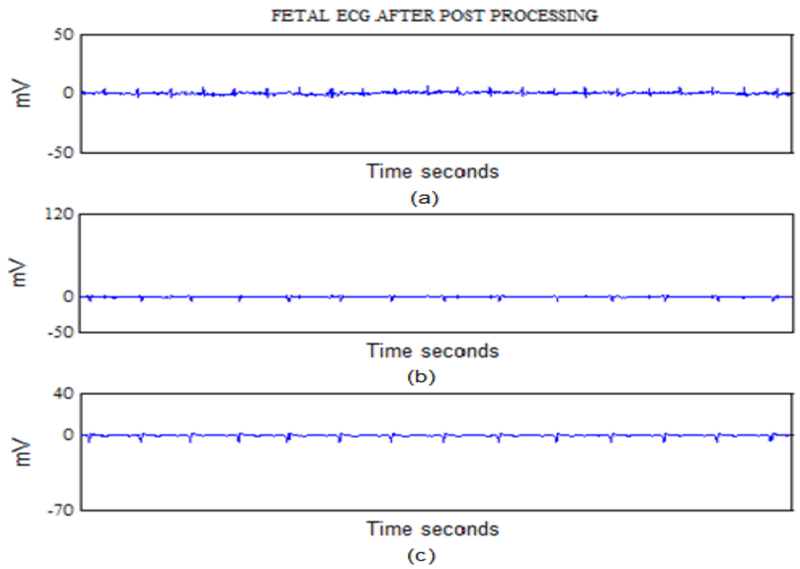

Fig. 6 Post-processed FECG Signal, (a), (b), (c) shows Estimated FECG Signal with Different Dimensions.

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Median filter is used to post-process the FECG signal. The median filter eliminates the MECG interference and preserves the edges in the signal. Finally the FECG signal is clearly visible. The FECG signal contains the fetal heart rate, using this doctor can predict or identify the fetus having normal cardiac frequency, any cardiac disorders such as fetal stress, fetalbradycardia, and fetal tachycardia. The fig. 6 (a), (b), (c) shows the post-processed FECG signal with multiple dimensions, here the fetal R peaks are visible, and used to calculate the FHR. The result shows that FHR is normal, with 120-180 beats/minute, and has no cardiac disorders.

Table I. Comparative Study

FEATURES	BSS	PCA	ICA	MICA
Multi-dimensional View	Not possible	Not possible	Not possible	Yes
Real-time	Yes	No	No	Yes
SNR Improvement	Low	Low	Medium	High
Efficiency	Low	Low	Medium	High
Implementation Complexity	Medium	Complex	Medium	Medium
Computational Cost	High	Medium	Medium	Medium

The table I shows the detailed comparison between the existing methods BSS, PCA, and ICA based on the thorough literature survey [12]-[13]. Compared to these techniques the proposed method MICA produce better results and efficient in all aspects.

V. CONCLUSION

The Fetal Electrocardiogram (FECG) extraction using MICA technique is a simple, fast method and implemented using real-time data. The simulation result for FECG extraction can be observed in MATLAB environment along with literature survey. It is clear that the real-time abdominal signal recorded from the mother's abdomen using the electrodes contains several noises like baseline wanders, MECG, FECG, power-line interference, and uterine muscle noise, these can be eliminated by pre-processing and post-processing the FECG signal using filters followed by MICA technique, MICA separates the FECG signal from MECG and from the unwanted noises. After post-processing the FECG signal, it is clearly visible which is suitable for hospitalized applications. In future, the MICA technique can be compared with other extraction techniques such as neural network method and genetic algorithm may be considered, and outputcan be obtained for more number of input samples.

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