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Non-Invasive Feto-Maternal Well-Being Monitoring: A Review of Methods

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Abstract

Monitoring of fetal and maternal well-being is extremely critical during pregnancy and during labor to reduce the occurrence of fetal and maternal distress in high risk pregnancies. There are many approaches to identify and quantify the real-time feto-maternal well-being by measuring physiological parameters viz. fetal movement, fetal temperature, fetal respiration rate, fetal kick count, fetal heart rate, maternal ECG acquired from both chest and abdomen region, uterine contraction, blood SpO2 concentration, amniotic fluid pH etc. In this paper, different techniques to acquire and measure these physiological parameters non-invasively are evaluated and compared for the purpose of monitoring feto-maternal well-being.

Keywords: Fetal monitoring, non-invasive, physiological parameters, feto-maternal monitoring, distress, well-being

1. Introduction

Early information about fetus well-being is among the fundamental goals of fetal monitoring both during pregnancy and labor. The quantification of fetal distress patterns helps the obstetricians to decide for a chronic or acute fetal state. Chronic state means abnormalities in fetal nutrition uptake leading to improper neural development and restricted fetal growth also referred as Intrauterine Growth Restriction (IUGR). Acute state such as Asphyxia of fetus can further lead to severe hypoxic ischemic organ damage in fetus followed by severe life-long pathologies [1]. IUGR occurs when fetus is deficient of necessary nutrition's or because of infections. IUGR can also occur due to reduction of feto-maternal respiratory exchange. Abnormalities in fetal heart rate, fetal movement and fetal kick count patterns also indicate fetal well-being [2].

Since fetal well-being is a common indication for the necessity of Caesarian delivery, it is important to obtain highly accurate status of fetal well-being, which assist the physician in early diagnosis of dangerous situations and also prevent false fetal distress detection, which might result in unnecessary operative actions [3].

2. Methods

A variety of invasive and non-invasive techniques exists, which measures physiological signals from fetus and mother to evaluate the level of stress in real time. Some of the widely studied physiological signals and their technique to evaluate fetal and maternal well-being have been discussed in this paper.

2.1Fetal Heart Rate (FHR)

FHR is the number of heartbeats in the fetus (under non-stressed condition) that occur in a given unit of time. In early stage of gestation, the FHR is primarily controlled by the sympathetic nervous system [4], but as the fetus develops its FHR decreases in response to parasympathetic nervous system and FHR variability becomes more noticeable [5]. The FHR is also affected by many factors, including maternal fever, uterine contractions, maternal-fetal hypotension, fetal hypoxia, fetal metabolic acidosis and due to certain medications [6]. The normal FHR is between 110 beats/min and 160 beats/min. The small up and down fluctuations in the FHR are called variability and a long term deviation in the FHR that lasts more than 15 minutes is considered a change in baseline [7,8]. FHR pattern analysis as shown in Figure 1 and 2 are highly accepted means of fetal distress monitoring which includes:

i. Baseline FHR
ii. FHR Variability (Variation from the baseline)
iii. Fetal Tachycardia (Baseline FHR > 160 bpm)
iv. Fetal Bradycardia (Baseline FHR < 110 bpm)
v. Periodic FHR Changes such as accelerations, early, late, variable and prolonged decelerations

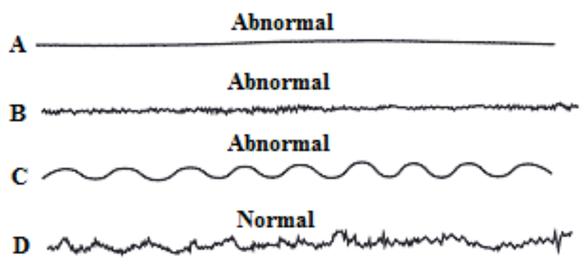

Fig. 1. FHR Variability. **A**: Short-term variability absent, Long-term variability Absent-Abnormal. **B**: Short-term variability present, Long-term variability Absent-Abnormal. **C**: Short-term variability absent, Long-term variability Present-Abnormal. **D**: Short-term variability present, Long-term variability Present-Normal.

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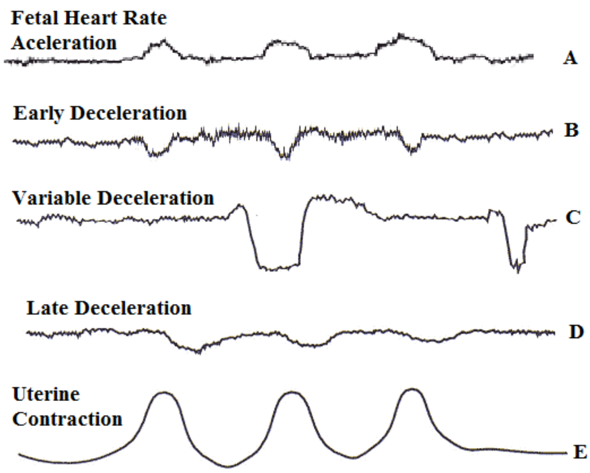

Fig. 2. Periodic FHR Changes. **A**: Fetal heart rate accelerations, **B**: Early decelerations, **C**: Variable decelerations, **D**: Late decelerations, **E**: Uterine contractions

Fetal heart produces electrical patterns from 18 weeks itself. But this signal level is nearly 1000 times less than normal cardiac signals and camouflaged by other electrical signals like maternal cardiac signal, muscle potentials and other electrical disturbances. These factors make it difficult to pick up and analyze them. The magnitude of the signal is found to be in the range of micro-volts and the frequency spectrum is within 15 to 40 Hz [9].

Some of the most widely used methods to acquire FHR are discussed below: -

1) Intermittent Auscultation (IA) or Phonocardiography

It involves listening to fetal heart sounds at periodic intervals to access the FHR. IA of the fetal heart can be performed with a Pinard fetoscope. It provides a safe alternative to more expensive and risky technology, such as a Doppler device. An example of fetal phonocardiography signal is shown in Figure 3.

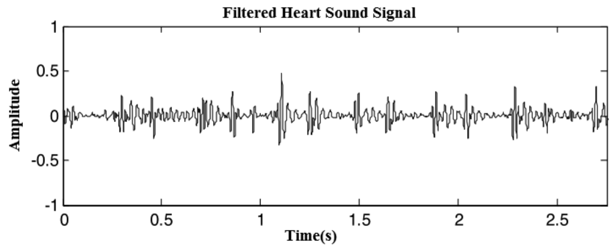

Fig. 3. Fetal Phonocardiogram

K. Yang *et al.* proposed an adaptive pattern matching method for fetal heart rate extraction from fetal sound envelopes with high accuracy. Its real-time performance has been verified preliminarily on a low-power DSP [10].

P. Várady *et al.* presented a novel two-channel phonocardiographic device and an advanced signal processing method for determination of the FHR. The developed system provided 83% accuracy compared to the simultaneously recorded reference ultrasound measurements [11].

M. Moghavvemi *et al.* builds a low cost and non-invasive PC-based electronic stethoscope that is capable to process real time fetal phonocardiographic signal [12].

2) Doppler Ultrasound

Doppler ultrasound and ultrasound stethoscope transmit ultra-high frequency sound waves in the range of around 1-2.3MHz. It is used for measuring activity like opening and closing movement of heart valves during each cardiac cycle, reflecting the overall movement of the fetal heart and convert these reflected sound signals into an electronic signal that can be counted. The reflected sound signals can also be demodulated and filtered to produce an audio signal of frequency around 200-1500Hz representing the Doppler frequency shifts imposed upon the original ultrasound frequency by fetal heart movements. These movements include both heart wall and valve motion giving rise to a complex pattern of Doppler shifts during the heart cycle as shown in Figure 4 [13, 14].

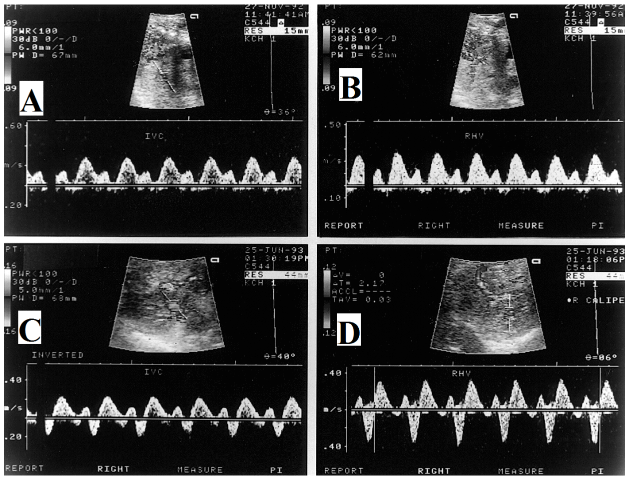

Fig. 4. Upper panels, **A**: Normal waveforms of inferior vena cava and **B**: Right hepatic vein. **C and D**: Corresponding waveforms in a compromised fetus [13].

3) Fetal Electrocardiography (FECG)

An ECG measures the electrical activity of the heart and the pattern of the heartbeat. The FECG is a well-known non-invasive fetal monitoring technique. It is carried out by suitably placing the electrodes on the mother’s abdomen to pick up the potential differences on the maternal body surface resulting from the currents flowing within the fetal heart, and there by recording the combined maternal and fetal ECG [15]. Figure 5 shows an example of abdominal ECG and fetal ECG. With this composite signal, fetal ECG signals are extracted by the rejection of maternal ECG signal, and required FHR is calculated [16]. The major benefits of FECG are that it can provide unobtrusive, long-term and risk-free ambulatory monitoring via small recording units that are simple enough to be used for domiciliary monitoring by the mothers themselves [17]. In FECG recordings are obtained from electrodes attached to the maternal surface, and because of interference from the larger maternal ECG, it has low signal-to-noise ratio (SNR) [18]. Although there are numerous methods proposed for the rejection of the maternal signal; the automated evaluation of FECG is less accurate than other methods [19]. Another limitation is the signal quality, which directly gets affected by electrode placement. The FECG require electrode adjustment due to fetal movement and therefore long-term recording can be inconvenient for the mother.

a) FECG Extraction using Adaptive Filter

D. P. Morales *et al.* proposed a system based on two different reconfigurable devices, for FECG estimation from mother’s abdominal ECG (AECG) signals. Adaptive Filter is used for FECG extraction as shown in Figure 6. Least mean square (LMS) algorithm structure is used for updating filter coefficients for FECG extraction using adaptive noise cancellation. This algorithm calculates the output error signal ε(n) at instant n as $\varepsilon(n) = d(n) - y(n)$. This error signal is used for updating the finite impulse response (FIR) filter coefficients following the equation: $w(n+1) = w(n) + \mu\varepsilon(n)x(n)$, where, w(n) is the coefficient vector for the filter at instant n, μis the step size of the adaptive filter and x(n) is the filter input vector. The step size (μ) value affects the convergence speed, steady state error, and stability of the adaptive filter [20].

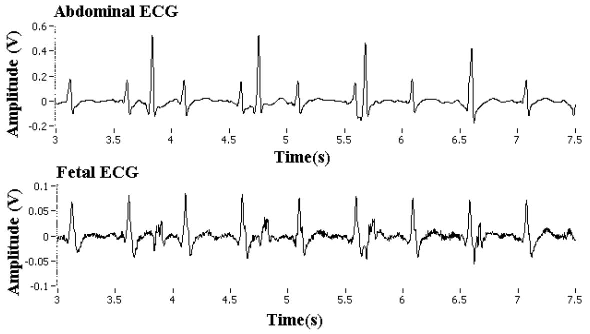

Fig. 5. Abdominal and fetal ECG

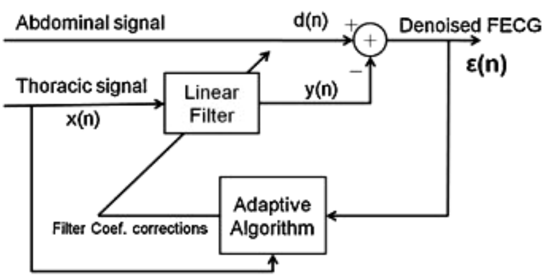

Fig. 6. Adaptive Filter for FECG extraction

M. B. I. Reaz *et al.* proposed an adaptive method to separate fetal ECG from composite ECG that consists of both maternal and fetal ECGs by using ADALINE (Adaptive Linear Network). Adaptive linear neural network filter was used to reduce the noise by functioning similar as moving average windows [21]. The filter architecture is similar to Figure 6.

b) FECG Extraction using Wavelet Filter

S. Wu *et al.* proposed a method for fetal ECG extraction based on wavelet analysis, the least mean square (LMS) adaptive filtering algorithm, and the spatially selective noise filtration (SSNF) algorithm were used to obtain fetal ECG [22].

c) FECG Extraction using Neural Network

G. Camps *et al.* shows that a finite impulse response (FIR) neural network can be included in the familiar adaptive noise cancellation scheme in order to provide highly nonlinear dynamic capabilities to the recovery model and their outcome indicates that the FIR network is a reliable method for the FECG recovery [23].

4) Fetal Magnetocardiography (FMCG)

The FMCG is a non-invasive method to learn about the fetal heart, without even touching the mother. The magnetic fields produced by the currents flowing within the fetal heart are recorded which are called as fetal magnetocardiograms. The magnetic field component which is perpendicular to maternal abdomen is measured as shown in Figure 7. These magnetic fields are extremely weak (10^{-13} tesla). In contrast, the earth's magnetic field is a million times stronger (5×10^{-5} tesla) [24]. To monitor such weak magnetic fields a highly sensitive sensor like SQUID (Superconductive Quantum Interference Device) is required. Presently these SQUID sensors have to be cooled by liquid helium (-269°C) [25]. Due to high SNR (signal-to-noise ratio) of FMCG it is extraordinarily free of maternal interference as compared to the FECG. In this technique, fetal heart rate variability (FHRV) has been found to be more accurate than Doppler ultrasound measurements [26]. Size, cost and complexity of the instrumentation is the only disadvantage of FMCG.

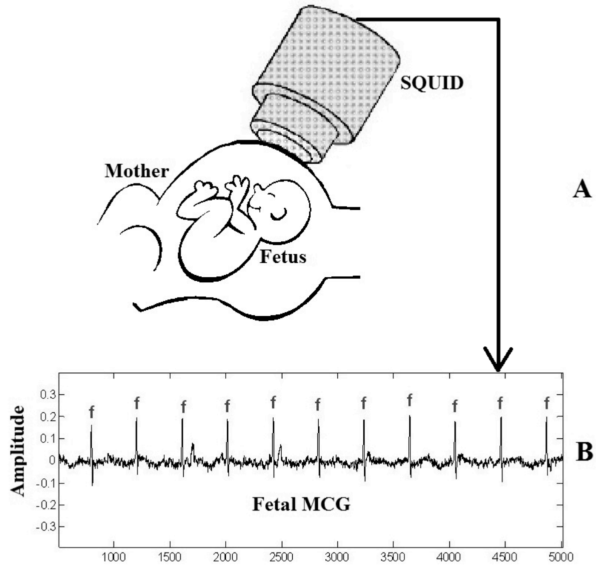

Fig. 7. The measuring position and waveform of the FMCG

The FMCG has the potential to provide complete beat-to-beat fetal heart rate analysis both in normal rhythm as well as in fetal arrhythmias. Fetal movement can also be assessed by amplitude changes in the FMCG, via a technique known as actocardiography (ACG). ACG might be helpful in monitoring fetal movements and for the overall diagnosis of fetal behavioral states [27]. Unlike FECG it is unaffected by noise and remains proportional to age throughout pregnancy as shown in Figure 8, and therefore FMCG provides a valuable alternative for monitoring fetal cardiac health and overall development.

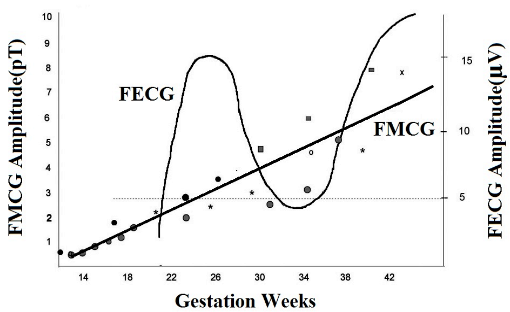

Fig. 8. Unlike FECG, the FMCG signal amplitude remains proportional to fetal age throughout pregnancy

5) Fetal Cardiotocography (FCTG)

FCTG is the most standard and extensively used method FHR detection. A cardiotocograph (CTG) is a graphical recording of the response of fetal heart to maternal uterine activity as well as information about its rate and rhythm

[28]. Ultrasound is sonic energy at frequency above the audible range. When a beam of ultrasound energy passes from one medium to another, a portion of that energy is reflected and the rest is refracted. If the reflected ultrasonic wave comes after striking off a moving object, a change in the reflected frequency is observed. This change directly indicates the presence a moving object. The reflected ultrasound waves can easily be used to calculate the FHR, since it is correspondingly modulated by the fetal heart movements [29]. The FCTG signals are accessible from the 12th week of pregnancy with usually good SNR. Previous studies show that ultrasonic power level generally used in fetal monitoring yields no chromosomal damage or any other kind of damage to the fetus, even after long exposures. At least 90% of patients who are calm and normal can be monitored throughout the labor by Doppler FHR system [30,31]. However, this method characteristically produces an average heart rate and hence cannot give beat-to-beat variability. Also the FCTG technique cannot be used for long term monitoring because of its invasive nature [32].

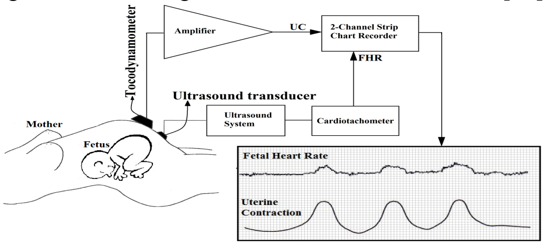

Fig. 9. Electronic Fetal Monitoring System for measurement of Fetal Heart Rate and Uterine Contraction

6) Photopleythysmography (PPG)

PPG is a simple and low-cost optical technique that is used to identify blood volume changes in the microvascular bed of the tissue. These changes are caused by the pressure pulse within the circulatory system. It is detected by illuminating the skin with a light source like light-emitting diode (LED) and then measuring the amount of light either transmitted or reflected to a photodiode. Each cardiac cycle appears as a peak, as shown in the Figure 10. PPG is often used non-invasively to make measurements at the skin surface. PPG uses near infra-red (NIR) non-ionizing light of low power levels that are harmless and hence suitable for continuous real time signal acquisition due to its fast response [33]. However, PPG signals often get corrupted by artifacts like; motion artifacts, poor blood perfusion or error in ambient light falling on photodetector [34]. A lot of study has been done to reduce the effect of artifacts however, still it is a major challenge and a topic of rigorous research.

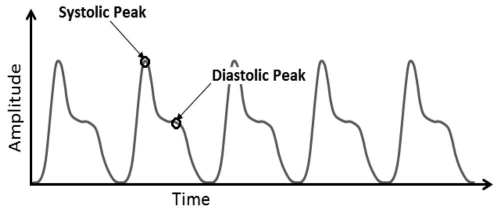

Fig. 10. Morphology of typical PPG waveform

Table 1. Various Studies related to Fetal ECG Extraction

Authors	Proposed FECG Extraction Method	Algorithm/Technique Used	Software Used	Results
K. Prasanth *et al.* [35]	Adaptive filters for noise cancellation and digital filters for FECG extraction. FECG extraction algorithm (LMS) is implemented in MATLAB using Simulink models	Adaptive filter and Least Mean Square (LMS) algorithm	MATLAB™	FHR is extracted by counting the peaks of R-R interval from the extracted FECG noise free signal
J. Khalaf *et al.* [36]	FECG extraction directly from the composite signals without the need of recording the maternal ECG reference signal but taking into account the propagation delays of the different electrical activities recorded by multiple electrodes placed at different abdominal locations	Independent Component Analysis (ICA) and Adaptive filtering	------	Combination of a BSS technique with adaptive filtering constitutes a very powerful and efficient technique for FECG extraction
O. Perlman *et al.* [37]	FECG source signal enhancement using a modified linear combiner which includes 3 phases - synthetic signal creation, obtaining an emphasized FQRS signal, and FQRS complexes detection	A modified linear combiner	------	Significant improvement in FHR and peak detection
L. O. S. Alvarez *et al.* [38]	Method for locating QRS complex in non-invasive FECG, using techniques based on MECG cancellation, and Principal Component Analysis (PCA).	Principal Component Analysis	------	The proposed method locates the fetal QRS complexes with efficiency above 80%
Z. Wei *et al.* [39]	2-D phase space based adaptive filter is used, consisting AECG signal as the primary input and	2-D phase space based Adaptive filter	------	Improved robustness and fidelity in restoration of the FECG, compared

	TECG signal as the reference signal			with the classical adaptive filter
C. H. L. Peters *et al.* [40]	An algorithm was developed that enhances fetal QRS complexes and thereby detecting the beat-to-beat fetal heart rate in recordings with poor signal-to-noise ratios.	Cross correlation and Mathematical approach	------	The method is excellent for signals with higher signal-to-noise ratios
J. J. R. Immanuel *et al.* [41]	ICA is applied on the AECG signal to separate into FECG and MECG signals and are reconstructed using wavelet reconstruction.	Wavelet transform and Fast ICA	MATLAB™	Lifting Wavelet Transformation and FASTICA algorithm produces the best SNR value of 11.39 for maternal and 10.10 for fetal ECG signals.
M. Nasiri *et al.* [42]	Proposed an algorithm to decomposed AECG signal to its Intrinsic Mode Functions (IMFs) through Empirical Mode Decomposition to boost FECG extraction process	Empirical Mode Decomposition algorithm, Adaptive Neuro Fuzzy Inference System (ANFIS) and Particle Swarm Optimization	------	Able to distinguish and remove MECG signal components from the recorded signal and hence obtained a good approximation of FECG signal
M. Kotas *et al.* [43]	Spatial and temporal properties of the extracted four-channel FECG was exploit to construct a new channel with higher signal-to-noise ratio	Spatio-temporal filtering (STF)	------	STF allowed to decrease the number of the detection errors also noisy fetal QRS complexes can be visualized by the help of STF
M. Hasan A. *et al.* [44]	A new method using combination of Artificial Neural Network (ANN) and Correlation approach	Supervised multilayer perception (MLP) network	------	Better and efficient result in terms of accuracy for FECG extraction and R-peak detection in the AECG signal
M. A. S. Ali *et al.* [45]	Extracted FECG by denoising abdominal ECG (AECG) and cancellation of MECG by adaptive filtering. The thoracic signal (TECG) was used to cancel MECG	Adaptive filter and Genetic algorithm	MATLAB™	The FECG signal extracted is comparable to standard FECG signals
W. Jia *et al.* [46]	Extracting FECG based on adaptive linear neural network	Adaptive Linear Element (ADALINE) with Widrow-Hoff learning rule	GENWAVE signal generator program of UG DigiScope	Clearer FECG can be acquired better than using only Adaptive filter
R. Vullings *et al.* [47]	Linear prediction of each separate wave in the MECG. Its performance in MECG removal and FHR detection is evaluated by comparison with spatial filtering, adaptive filtering, template subtraction and independent component analysis techniques	A new technique (WAMES) is presented	MATLAB™	WAMES outperforms the other techniques in both MECG removal and fHR detection (by more than 3%)
M. Kotas *et al.* [48]	Application of normalized matched filtering (NMF) to fetal QRS complexes enhancement and QRS detection as criterion function minimization (CFM)	A combination of NMF and CFM Algorithm and Decision rules	------	Significant increase of the QRS detection as compared to classical detection methods
G. M. Ungureanu *et al.* [49]	Demonstrates the performance of the event-synchronous interference canceller (ESC) in MECG removal from abdominally recorded signals (ADS)	Adaptive filter	------	ESC proved to be a suitable ADS processor which preserves the FECG morphology. ESC is also considered for the analysis of the fetal

MCG signal

Authors	Proposed FECG Extraction Method	Algorithm/Technique Used	Software Used	Results
C. Peters *et al.* [50]	A low amplitude abdominal ECG is simulated by adding noise to fetal scalp ECG recordings and then FHR is calculated using cross-correlation	Cross correlation algorithm	------	Correlation between FHR calculated by the algorithm and FHR from the original scalp ECG was found to be 0.99 ($p<0.001$)
J. F. Guerrero-Martínez *et al.* [51]	An exponentially averaged pattern of the MECG is obtained and subtracted from AECG then fetal R detector based on a Smoothed Nonlinear Energy Operator (SNEO) is applied to the residual signal	Adaptive filter based on the LMS algorithm	------	The results presented high values of sensitivity and positive prediction with some adjustments of the detector
C. Chareonsak *et al.* [52]	Low-cost FPGA hardware architecture for the realization of a real-time BSS in the application of FECG signal separation. The FPGA design implements the modified Torkkola's BSS algorithm	Independent Component Analysis (ICA) based on Blind Source Separation (BSS) framework	Xilinx™ and MATLAB™	BSS algorithm based FPGA that successfully separates maternal ECG and fetal ECG in real-time
E. C. Karvounis *et al.* [53]	Fetal QRS is detected using multi-channel MECG recordings without the need of any noise filtering	Complex continuous wavelet transform (CCWT) and Modulus maxima theory	------	Computationally fast and excels in performance when compared with other methods
V. Zarzoso *et al.* [54]	Compared BSS method based on higher-order statistics with a significant classical technique for FECG extraction, such as Widrow's multi-reference adaptive noise cancellation (MRANC)	Blind Source Separation (BSS) algorithm and Optimal Wiener-Hopf filtering	------	BSS techniques can be implemented as diagnostic tool in prenatal medicine
K. A. K. Azad *et al.* [55]	Detection of fetal QRS complexes from enhanced FECG signal obtained by using a fuzzy decision algorithm	Fuzzy approach	Borland C++ and FULDEK	Results were successful in most cases except noisy signals
N. M. Gibson *et al.* [56]	Application of Matched filters to the detection of R- waves in fetal electrocardiogram (FECG) data, recorded during labor using a scalp electrode.	Adaptive Neural Network	------	Adaptive matched filter is essential for data containing bursts of noise joined by relatively clean segments
P. P. Kanjilal *et al.* [57]	The MECG and FECG components are identified then elimination of the MECG and determination of FECG are achieved through selective separation of the SV-decomposed components	Singular Value Decomposition (SVD)	------	The method is numerically robust and computationally efficient in any composite signal, where the signals can be configured to be algebraically orthogonal to each other
Y. C. Park *et al.* [58]	The proposed fetal QRS detection method computes the averaged magnitude of the difference between the fetal ECG signal and the reference signal to detect the fetal QRS event	Moving Averaged Magnitude Difference (MAMD) method and Matched Filter approach	------	MAMD approach yields higher performance scores than the Matched Filter approach

B. Fetal Movement (FM)

The motion of a fetus in vivo caused by its own muscle activity is known as fetal movement (FM). Fetal body movements also indicate the development of fetus nervous system. Fetal movement detection is also an assessment of fetal well-being. Mothers can also feel the movement of their fetus as early as 13 weeks' gestation. The first gentle kicks that the fetus does are called as quickening. Second-time mothers can more easily distinguish the fetus kicks than first-time mothers. Usually, the average sensitivity of maternal perception of fetus body movements is only 30% [59]. Initial studies on fetal movements were conducted mostly on exteriorized fetuses. The survival was limited to a few minutes during which the fetus was stimulated with tactile stimuli [60]. In the 1980s, the breakthrough in fetal movement studies arose from the introduction of advanced ultrasound equipment.

The most widely used techniques for fetal movement detection can be classified as follows: -

1) Abdominal Movements

A MEMS based piezoelectric sensor can be used to detect fetal movements for quantification of fetal stress according to the stress imposed by sensor on the fetus [61]. Solid-state accelerometers that uses digital signal processing (DSP) based experimental approach are also employed for the detection of fetal movements [62]. Fetal movement data acquired from accelerometers can be used to predict the fetus health status by applying time-frequency distribution (TDF) approach [63]. Accelerometer-based fetal movement detection system does not require much training and can be used outside a clinic or at home by the mother herself [64]. Strain-gauge transducers are also a simple and safe means of evaluating fetal movement, however they react to all types of abdominal movements and thus the assessing instrument must differentiate between maternal and fetal movements. The differentiation may be accomplished by selecting a suitable size for the transducer and also by using an adaptive filter [65]. **Eiji Ryo** *et al.* designed and developed a capacitive acceleration sensor based recorder that can identify the oscillations of the maternal abdominal wall triggered by fetal movement [66].

2) Electrical Impedance Measurement

Electrical impedance based instruments can be used for non-invasive continuous recording and monitoring of inside electrical field distribution of closed objects in terms of voltage for a given current. Fetal movement inside the mother produces electrical field variation that can be measured non-invasively by placing electrodes on mothers' abdomen. This variation in surface voltage is likely to provide information regarding fetal movement and its overall development. The current and voltage electrodes are interchanged through different combinations so that the transfer impedance is measured for different position of applied currents. Electrical Impedance Tomography (EIT) uses the same principle in which an image of electrical conductivity distribution within a cross-section of the closed object is obtained. EIT exploits the electrical property of the human tissues by computing voltages induced on the electrodes attached to the surface when currents are passed between them. By using appropriate image reconstruction algorithm an image of conductivity distribution of the closed object can be obtained [67].

EIT is a non-invasive medical imaging procedure in which input current is applied to surface of the body through contact electrodes and the output surface voltages so obtained as shown in Figure 11 are used in reconstruction of images. EIT does not uses harmful radiations and it is exclusively based on electrical properties of the material, mainly the conductivity of material which is used to construct the phantom [68,69]. EIT can be applied as an imaging technique for a closed body system with special reference to fetal monitoring in-utero during pregnancy and labor [70].

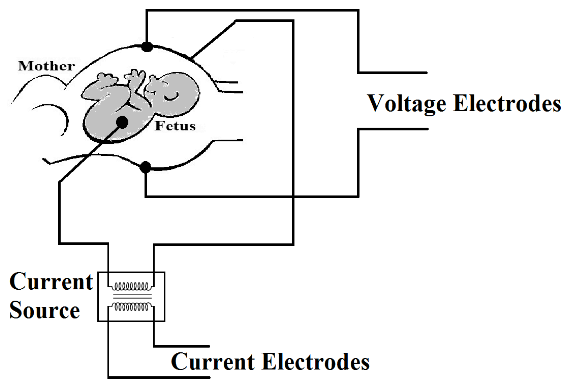

Fig. 11. Layout of Impedance Measuring System

3) Fetal Actocardiography

The real-time record of fetal movement (FM) and fetal heart rate (FHR) by the use of a single ultrasound transducer or by a magnetogram transducer is called an actocardiogram. Actocardiography is an extremely precise and reliable method for monitoring FHR, FHR variability, and fetal activity. The actocardiograph is used concurrently with the ultrasound machine, with proper measures to avoid interference of the two ultrasound signals [71]. Since, actocardiograph shows that FHR acceleration was related to FM, FM can be automatically detected using multichannel fetal magnetocardiogram (FMCG) [72,73,74] signals or by using ultrasonic Doppler monitor [75]. FMCG actocardiography is based on detection of fetal QRS amplitude variability arising from changes in position and direction of the fetal heart due to fetal movement. Changes in magnetic field strengths in FMCG are indicators of fetal body movements. These changes could be due to either the fetal heart activity or by the displacement of the fetal body or the combination of both [76]. Fetal behavioral states like real-time interpretations of fetal eye movements, breathing movements and body movements can be diagnosed by the use of actocardiograph [77]. Active and resting fetal states can also be differentiated by means of fetal actocardiograph [78]. The main advantage of FMCG analysis is the collective analysis of both fetal movement and FHR accelerations by constructing reliable actocardiograms.

4) Ultrasound Imaging

Phased-array ultrasonography can be used to detect fetal movements as early as in the first trimester. As the gestation age increases the complexity in fetal movement patterns also increases [79]. Fetal movements patterns such as isolated body extension, thumb sucking, head rotations, hiccups, hand-face contacts, stretches, yawns, sucking, swallowing, eye movements, smiling, breathing movements or repetitive chest wall excursions etc. can be easily seen in the preterm infants with ultrasound in utero [80,81,82].

5) Doppler Ultrasound

The Doppler transducers used for FHR signal can also be used to detect fetal movements and found to be in good correlation between the unprocessed Doppler signal and the fetal movements [83]. Several other studies have shown that Doppler ultrasound systems designed to detect the FHR can be modified for the extraction of fetal movement data [84,85]. A transducer fusion system which uses two ultrasound scanners can view and record a larger area of fetus that would better define the characteristics of fetal movement [86]. The disadvantage of ultrasound transducers is that when it is used at higher frequency it transmits energy into the body which is potentially dangerous to fetal health.

6) Fetal Phonogram

The tone fetal heart sounds serve as an effective diagnostic tool for a large category of fetal stress conditions, such as fetal hypoxia or oxygen deficiency in the fetal blood. The fetus body adapt to all the above conditions by changing the fetal heart rate accordingly [87]. Audible heart sounds carry a lot of valuable information about the condition of the heart. The typical manner to interpret this information is that the physician listens to the heart sounds and writes down a description of his individual opinion. Recording the sound signal, extract more information from it by using spectral analysis and ultimately visualizing the sound as a picture in both time and frequency domains is a more accurate and reliable procedure. Phonocardiography (PCG) is a graphical recording of heart sounds. The notion of telemetric PCG is beneficial compared to ECG for heart rate monitoring since it requires only a single probe, electrodes are not used and the patient does not need to carry a separate Holter device [88]. Fetal PCG sounds generated by fetal activity are sensed at the maternal abdomen by means of a sensitive transducer. This is a passive technique and can be used for long term monitoring. Other biophysical parameters that can be measured using fetal PCG includes fetal heart sounds, fetal heart rate, fetal breathing, and fetal movement. **M. Moghavvemi** *et al.* developed a non-invasive, low cost and real time PC-based system that is capable of processing fetal PCG signal for heart sound studies [89].

7) Optical Flow Displacement Histograms

Optical flow is the term used to define a range of computer vision algorithms that work under the hypothesis that a pixel's intensity remains constant while its position changes from x and y with dx and dy over time period dt [90], where dx, dy and dt represent small variations of x, y and time t. This condition is known as the brightness constancy assumption (Equation 1).

$$I(x, y, t) = I(x+dx, y+dy, t+dt) \quad (1)$$

In a preliminary study by **Cristina Surlea** *et al.* proposed a method based on optical flow displacement histograms which are trained by means of backpropagation neural network for categorizing fetal movement [91].

8) Abdominal ECG Shape Identification

M. J. Rooijakkers *et al.* proposed a method for fetal motion detection, which is based on variations of the amplitude in the fetal QRS complex. The method is based on the basis that the fetal ECG waveform as observed on the maternal abdomen changes as a result of a displacement of the cardiac vector with respect to the measurement electrodes [92]. The variation in QRS-wave height and shape can, then be used to indicate a thoracic movement and be used to give an indication of the fetal movement [93].

9) Fetal Vectorcardiogram (FVCG)

Vectorcardiography (VCG) is a method of recording the magnitude and direction of the electrical forces that are produced by the heart by means of a continuous sequence of vectors that form curved lines around a central point. Some studies suggest that VCG can be an alternative method for fetal movement quantification. The spatial information of the fetal ECG, obtained by using several electrodes spread over the maternal abdomen, can be combined to produce the fetal VCG as shown in Figure 12. VCG delivers information about rotation of the fetal heart and the fetal thorax. A disadvantage of this method is that only the fetal thorax movement can be identified and movement of the extremities cannot be identified. However, the technique is capable of long-term monitoring [94]. VCG loop alignment can be an effective methodology to suppress motion-induced QRS variability in non-invasive fetal ECG recordings [95], a Bayesian framework can be employed for the loop alignment method [96]. However, multi-channel measurements and complex signal processing techniques necessary for fetal VCG loop alignment escalation the power necessities.

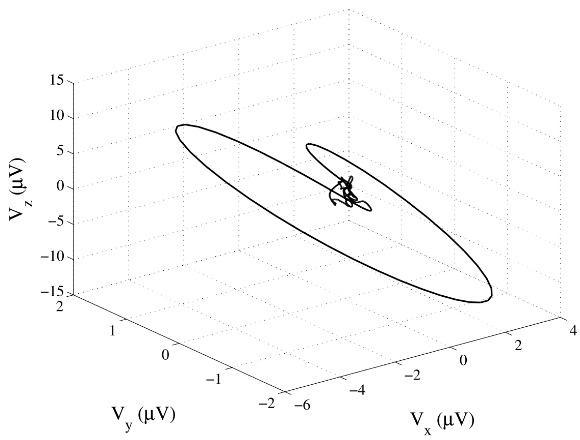

Fig. 12. Example plot of a fetal VCG [94]

10) Fetal Breathing Movements (FBM)

The existence or nonexistence of fetal respiration could be very helpful in fetal health surveillance if a reliable indicator is derived from it. FBM appear between 12 and 13 weeks of gestation [97] and their characteristics change with gestational age [98]. Fetal breathing rate range between 30 and 90 breaths per minute corresponding to the frequency 0.5 - 1.5 Hz. FBM can be extracted from the maternal abdominal wall by placing a Doppler transducer. The directional Doppler signal acquired can be processed with M-mode representation to identify fetal respiration movements. The Doppler signals can also be acquired continuously both during fetal breathing and apnea [99]. FBM can be measured by inductive transducers also as they are comparatively passive device in contrast to commonly applied ultrasound transducers. The compliance of the inductive transducer sensor should match with the compliance of the maternal abdominal wall in order to detect the very weak acoustic signal caused by specific fetal breathing movements. This enables long-term observation of fetal movements and sounds [100]. **J. D. Gough** *et al.* reported the application of the continuous wave (CW) ultrasonic Doppler technique to the detection of movements, they also analyzed the changes of fetal venous flow caused by breathing [101]. **B. J. Trudinger** *et al.* reported on the detection of breathing based on the analysis of a sonogram of the umbilical vein flow [102]. **R. E. Besinger, T. Wheeler, N. Shinozuka** *et al.* presented the recording of fetal movements and breathing by means of pulsed Doppler ultrasound [103,104,105]. **K Kaluzynski** *et al.* had done assessment of fetal activity using a CW Doppler method taking into account several aspects, such as cardiac rhythm, breathing movements, body and limb movements [106].

C. Fetal Respiration and Fetal Pulse Oximetry

In modern clinical practice pulse oximetry is the most commonly used method for measuring pulse rate and oxygen saturation of arterial blood. It is very challenging task to determine the arterial oxygen saturation of the fetus in different phases of pregnancy, during labor and during delivery. An oxygen deficiency might have fatal consequences concerning the overall growth of the fetus. The fetal reflective type of pulse oximetry could be a solution for this problem. The measurements can be performed trans-vaginal or trans-abdominal. Trans-abdominal measurement is non-invasive and decreases the risk for mother and fetus [107].

S. Ley *et al.* describes a sensor circuit for non-invasive fetal pulse oximetry. A physical working model or a phantom is required for the evaluation of the sensor circuit and the separation algorithms, which reproduces the maternal and fetal pulse waves [108].

N. Stuban *et al.* introduces the working principles and construction of the wireless fetal pulse oximeter which eliminates the use of catheter from the monitoring system and gives the possibility of free movement to the mother in labor [109].

D. Uterine Contraction (UC) or Uterine Activity (UA)

Monitoring of fetal abnormalities in pregnant women at high risk is very significant. However, the occurrence of the risk can be reduced by well-timed identification of preterm labor. Fetal heart rate (FHR) and uterine contractions (UC) are confirmed to be the most vital parameters for determining fetal well-being. Electronic monitoring of UC along with FHR is a routinely activity during labor and during delivery, this process is called as Cardiotocography (CTG) or TOCO. The mother's uterus is a biological system comprising of a large number of cooperating smooth muscle cells. The uterine activity is generally quiescent during pregnancy but varies considerably with time and exhibits forceful synchronized contractions at term leading to fetus expulsion [110,111]. Detection of UC and FHR variability gives significant information to distinguish between a normal fetus and a fetus that has developed metabolic acidosis [112].

Philip A Warrick *et al.* proposed a way of modelling the dynamic relationship between UC and FHR using a non-parametric approach which successfully reflects the fetus state and can differentiate between normal and hypoxic fetuses [113,114,115]. **S K Pahuja** *et al.* measured UC along with fetal movement with the help of a MEMS based piezoelectric sensor [116].

Uterine muscle like other muscles produces electrical signals of specific characteristics. Uterine muscle does not come back to the original position during relaxation after contraction. The uterine muscles are found to produce asynchronous (alpha) waves and synchronous (beta) waves. Alpha waves are irregular and low amplitude whereas beta waves are regular and incrementing contraction. These are known as Braxton Hick's contraction [117]. Due to this uterine muscle contraction intra-uterine pressure increases. The magnitude of the signal will be in the range of a few millivolts and frequency spectrum of the alpha and beta waves found to be within 0.03 to 2 Hz. [118,119]. The records of these electrical signals from uterine contraction is known as Electrohysterogram (EHG).

UC are caused by electrical activity in the form of action potentials (AP - the cyclic depolarization and repolarization of the smooth muscle cells) that spread throughout the myometrium cells with a certain velocity. The propagation of APs through an adequate number of cells results in a synchronized mechanical contraction of the myometrium. Thus monitoring of uterine activity can be accomplished using the electrical signals of uterine muscle by electrodes placed directly on the uterus as well as by surface electrodes on the maternal abdominal wall. Contractions identified by this means resemble closely with those identified by traditional clinical methods [120]. This non-invasive method of UA monitoring has the potential to provide the ease of use and applicability of TOCO. Since the signal is recorded with the set of ordinary electrocardiographic surface electrodes placed on the pregnant woman abdomen the method is reasonable and modest in application. Frequency, duration, intensity, resting tone and interval of the uterine contractions are some of the factors used in assessing uterine activity. Uterine activity can be monitored by different methods:

1) Mechanical Activity

a. **Self-palpation**: the efficiency of this maternal method is limited because patients usually identify an average of 15 % of their contractions.
b. **Intra-uterine pressure**: obtained with a catheter introduced by extra or intra amniotic way. This method gives a good idea of the uterine pressure but is limited because of the infection risks. It is presently the only reference signal allowing a quantification of uterine activity. But, obviously it cannot be used during pregnancy.
c. **External measurement**: a transducer is placed on the abdominal wall by means of an elastic strap. This method is used in obstetrical practice for parturition monitoring. But it allows the quantification of only the contraction frequency and is limited because of its high sensitivity to movement artifacts.

2) Electrical Activity

The recording of abdominal EHG should be of wide interest for pregnancy monitoring as it usually offers information about both excitation and propagation of electrical activity of uterus which are the main parameters developing throughout pregnancy.

3) Magnetic Activity

The Uterine MMG is a non-invasive technique that measures the magnetic fields associated with the action potentials generated due to contractions of muscles of uterus. The conduction velocity of the uterine contraction bursts can be calculated by Magnetomyogram (MMG) signals.

Uterine Contractions (UC) can be acquired by following methods:

1. **Uterine Electromyogram (EMG)**

Also referred as Uterine Electrohystogram (EHG) is the uterine activity that can be acquired non-invasively from transabdominal surface measurements that underlines the mechanical contractions of the uterus. The EMG bursts acquired corresponds to uterine contractions [121, 122, 123]. There is a substantial proof that the electrical events of the uterus are linked to uterine contractions [124]. The EHG is a very promising biophysical indicator of preterm labor. But still a solid knowledge of interferences and artifacts that effects the EHG signal is required and therefore, EHG measurements are not yet standardized [125,126].

M Khalil *et al.* considered the uterine EMG signal as a non-stationary signal and applied dynamic cumulative sum (CDS) analysis of the wavelet transform. And, shows that this approach is very efficient for detection of both frequency and energy changes related events of uterine EMG [127].

V Shulgin *et al.* proposed a non-invasive method and algorithm to approximate the uterine activity based on combined analysis of amplitude and time-frequency features of EHG signals. The result shows that EHG signal has the potential to turn into an accurate and effective means of uterine activity monitoring [128].

C Marque *et al.* shows that temporal and spectral analysis of the EHG helps in categorizing them into two physiological states firstly, low frequency and long duration state which corresponds to the local uterine activity and secondly, high frequency and shorter duration which corresponds to propagating and coordinated labor uterine activity. Therefore, EHG is a good complement to TOCO [119].

2. **Uterine Magnetomyogram (MMG)**

The uterine MMG is a non-invasive technique that measures the magnetic fields linked with the electrical action potentials generated due to contractions of uterus wall muscles. The conduction velocity of the uterine contraction bursts can be calculated by MMG signals. The uterine MMG recordings have significant features which makes them a suitable contender for the uterine activity investigation: (i) they are independent of tissue conductivity (ii) the acquisition of the signal outside the skin boundaries is possible without making any electrical contact with the body and (iii) they do not dependent on reference points, which ensures that each sensor mainly records localized activity. **A Furdea** *et al.* has developed a method comprising of several stages to detect uterine contraction bursts in MMG signals [129,130].

3. **Tocodynamometer**

A Tocodynamometer or simply called TOCO is a non-invasive pressure sensitive contraction sensing transducer which measures the tension in the maternal abdominal wall externally from the surface. However, these measurements are easily corrupted by motion artifacts and other interferences.

4. **Intra Uterine Pressure Catheter (IUPC)**

It is very accurate and sensitive invasive device which measures the contraction forces during labor. The pressure signal acquired from the IUPC is directly correlated with the uterus wall contractions forces. But, due to invasive nature of IUPC there is a risk of infection to both mother and fetus. Comparison of amplitude vs time characteristics of signals acquired from EMG, IUP and TOCO has been shown in Figure 13.

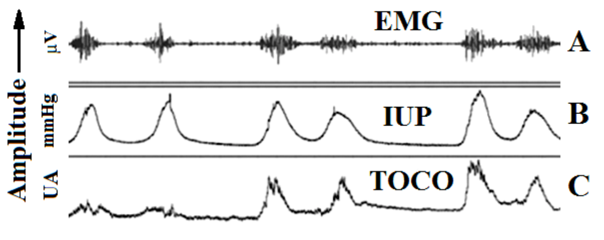

Fig. 13. Comparison of amplitude vs time characteristics of signals acquired from EMG, IUP and TOCO

Zifang Huang *et al.* proposed a knowledge assisted sequential pattern analysis framework to predict the IUP in real time and to estimate the next contraction pattern based on previous patterns [131].

S L Horner e*t al.* modified the already existing intra uterine catheter for FECG measurement into a catheter for measuring both FECG and UC with one sensor [132].

5. **Ultrasound**

Ultrasound signal can also be used for detection of uterine activity. **Chiara Rabotti** *et al.* proposed the use of transabdominal ultrasound measurements also known as Mechanohysterogram (MHG). Analysis of MHG shows that EHG is effected mainly by two phenomena's i.e., changes in uterine wall thickness during contractions and uterine wall movements induced by respiration [133].

Some more recent studies on uterine activity are discussed below: -

S Rihana *et al.* developed a uterine cell model that simulates the complex uterine electrical activity. This model will guide researchers to find the most important physiological parameter related to the evolution of uterine activity along pregnancy [134, 135]. This work is further extended by **J Laforet** *et al.* who proposed an electrophysiological model that aims at describing the multiscale evolution of uterine activity from its genesis at the cell level to its propagation at the myometrium level up to its projection through the volume conductor tissue to the abdominal surface (EHG) [136].

D Alamedine *et al.* developed a feature selection method based on Particle Swarm Optimisation (PSO) and the classifiers used has a strong influence on selected EHG features which can give relevant information [137].

K Horoba *et al.* extracted slow waves from EHG signals as they resemble with mechanical signals and can be regarded as contraction waves. These contraction waves can be used for measurement of uterine contraction. This also confirms a close relationship between electrical and mechanical signals of uterine activity [138].

S Devi *et al.* measured the uterine contraction signals from three different zones of uterine muscles along with FECG signals. Starting from fundus of the uterus up to the pubic region the contractile signals are picked up which helps in determining the degree and the frequency of the contraction at various heights of uterus. These signals along with FHR signal gives information about the well-being of the fetus [139]. The dynamic relationship between FHR variability and UC has been compared and confirmed with previous documented work. The fetal FHR variations like accelerations, decelerations (early, late, and prolonged) are correlated with the uterine contractions [140].

3. Conclusion

Fetal heart rate monitoring is a very essential procedure in high risk pregnancies or pregnancies complicated by certain medical conditions like high blood pressure, diabetes, autoimmune disease, obstruction in umbilical cord, infections like STDs or HIV etc. because these conditions presents risk to both mother and fetus. A vast number of devices (such as the fetal phonogram, fetal scalp electrode, Doppler ultrasound, Magnetocardiogram, TOCO, IUPC etc.) and techniques (such as ultrasound imaging, electrical impedance tomography, abdominal ECG acquisition etc.)

have been proposed since the beginning of the 20th century. Fetal scalp electrode placement method is considered as a gold standard in FHR detection but its invasive nature is a disadvantage. Abdominal fetal ECG is more reliable and accurate method of FHR detection than ultrasound because of its non-invasive and easy to implement nature. Abdominal ECG electrodes placement method for FHR detection has widespread clinical acknowledgment as it is suitable for long-term real-time monitoring with the ability to detection beat-to-beat FHR variability also. The technique of Doppler ultrasound in FHR monitoring is used on a regular basis in clinical environment because it is relatively inexpensive, quick and convenient. However, it is not suitable for prolonged monitoring as it has some heating effect and the resolution of images obtained is often limited. M-mode ultrasound analysis technique is also used by the clinician but has the drawback of imaging inaccuracies and errors in separating the electrical properties from these images. Later on CTG monitors were also introduced by companies like HP and BPL which were capable of continuously monitoring FHR tracings and maternal uterine contractions simultaneously but has the drawbacks of having low accuracy and being difficult to interpret. Only a well-trained and qualified medical personnel can clearly interpret the FHR and UC tracings obtained from CTG monitors. The fetal MCG has solved the accuracy problem seen in the devices discussed above but is relatively expensive, has large size, complex design requirements and mothers are not allowed to move during measurements, these measurements are taken for short durations. More recently, non-invasive optical method like PPG has been suggested for FHR detection. PPG uses near infra-red (NIR) non-ionizing light of low power levels that are harmless and hence suitable for continuous real time signal acquisition due to its fast response. PPG system can be designed to be portable, robust and at low cost. All of these advantages have made the PPG a very remarkable technique for future biomedical research. Still, there is a need of a standalone, portable and affordable feto-maternal device to quantify fetal well-being that can contribute towards better fetal outcome. Home-based telemonitoring of high risk pregnant women by employing a multi-parameter portable feto-maternal device will ensure effective and timely medical care.

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