

Review Article: Non-Invasive Fetal Heart Rate Monitoring Techniques

Enas W. Abdulhay, Rami J. Oweis*, Asal M. Alhaddad, Fadi N. Sublaban, Mahmoud A. Radwan, Hiyam M. Almasaeed

Biomedical Engineering Department, Faculty of Engineering, Jordan University of Science and Technology, Irbid, Jordan

*Corresponding author: oweis@just.edu.jo

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Abstract Fetal heart rate monitoring is a process carried out during pregnancy and/or labor to keep track of the fetal heart rate and in some devices the uterine contractions. A variety of techniques has been studied and is used on a daily basis in many hospitals. This review discusses and compares the operating principle, the key signal processing techniques, advantages and drawbacks of five of those techniques: fetal electrocardiography (FECG) using abdominal surface electrodes, photoplethysmography (PPG) using near infrared (NIR) light, Doppler ultrasound, ultrasound based cardiotocography (CTG) known as electronic fetal monitoring and fetal magnetocardiography (FMCG). The review leads to the conclusion that the PPG overcomes almost all of the drawbacks of the other methods and thus deserves the most attention in future biomedical research.

Keywords: fetal heart rate, FECG, PPG, CTG, FMCG, fetal pulse oximetry, doppler ultrasound

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1. Introduction

Biomedical research aims to continuously improve diagnostic devices and to develop new, less invasive and less annoying methods. Upgrading existing inexpensive techniques is also of great interest since most research is mainly directed by cost reduction [1].

Fetal heart rate (FHR) was first introduced in the 17th century. It is an important parameter that can be monitored during pregnancy and/or labor; and in some cases the only available source of information. During pregnancy, it provides information regarding the fetal heart rate and waveform which are significant in determining the fetal well-being, fetal development and the presence or absence of any congenital heart disease [2] while during labor it can help reduce newborn acidemia and other problems.

FHR can be monitored using multiple techniques that can be categorized as: invasive or non-invasive; auscultation methods (such as Doppler ultrasound and the fetoscope) or electronic fetal monitoring methods. The latter can be further divided as external devices (including Doppler ultrasound and tocodynamometer) and internal devices (including direct fetal electrodes and intrauterine pressure catheters) [3].

The earliest method to measure the fetal heart rate was the fetal stethoscope which further developed into the fetoscope in 1917 [4,5]. There are two different types of fetoscopy: internal (endoscopic fetoscopy) and external. Internal fetoscopy uses fiber optics inserted into the uterus either trans-abdominally or trans-cervically for multiple

purposes while external fetoscopy resembles a stethoscope to listen to fetal heart sounds. The latter method requires trained personnel and therefore its accuracy depends on the skills of the practitioner. As early as 1906, fetal heart rate was recorded using abdominal and intravaginal ECG leads and for half a century this was primarily used to assess fetal life. In 1958, a continuous FECG monitor was proposed by Edward H. Hon who has measured the time intervals between successive R waves in the recorded heart beat signal to calculate the heart rate [5,6,7,8]. A few years later in 1964, efforts made to monitor the FHR and to assess the fetal heart motions non-invasively led to the development of Doppler ultrasound monitor by Callagan [9]. It is performed by transmitting an ultrasound beam through the maternal abdomen and measuring the frequency of the reflected signal [10]. As Doppler ultrasound is not suitable for continuous monitoring, cardiotocograph (CTG), or more commonly known as the electronic fetal monitor (EFM), has been developed in 1968 by Hon to monitor the FHR and the uterine contractions simultaneously during pregnancy and/or labor. The main drawback of the CTG monitors is that they are subjective and difficult to interpret due to complexity which sometimes leads to unnecessary surgery [4,9,11]. In 1972, Hon introduced an invasive yet accurate FHR measuring device called the fetal scalp electrode (FSE) [9]. FSE method includes the insertion of an electrode through the birth canal and attaching it to the fetal scalp. It is a dangerous technique as it may cause injuries in the fetal scalp and/or uterine infection. Non-invasive FHR monitor using optical techniques was then introduced in the 19th century. It is performed by placing

the electrodes on the maternal abdomen. An example of the method is photoplethysmography (PPG). PPG uses a light source and a photo detector to measure blood volume changes in small blood vessels in order to measure FHR. PPG has the advantage of non-invasiveness and can be used for continuous real-time monitoring. Another non-

invasive technique called fetal magnetocardiography (FMCG) makes use of magnetic fields produced by the electrical activity of the heart. Unlike fetal MRI, FMCG does not emit magnetic fields making it safe. FMCG is highly reliable and can record beat-to-beat data but has a complex hardware design [12,13].

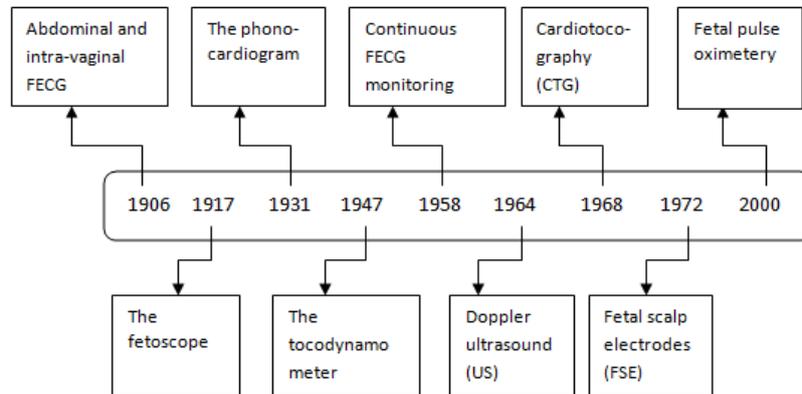


Figure 1. Chronology of fetal heart rate monitoring development [5,9]

2. Background on Fetal Heart Rate

The heart and circulatory system are among the first organs to develop in the fetus and they normally appear during the 3rd or 4th week of life [14]. From there the heart gradually becomes more specialized and the heart rate rhythm becomes more regular. The pumping action of the fetal heart is similar to that for an adult in which a myocardial stimulation caused by the sino-atrial (SA) node is transferred to the Purkinje fibers through the atrio-ventricular (AV) node and the bundle of His causing myocardium contractions. International guidelines recommend that the normal fetal heart rate baseline ranges from 110 beats/minute (bpm) to 160 bpm [3]. FHR decreases gradually throughout gestation on an average of 0.4 bpm per week [15]. The National Institute of Child Health and Human Development (NICHD) stated definitions of terms regarding the fetal heart rate such as acceleration, baseline, baseline fetal heart rate variability, bradycardia and decelerations [3].

A number of methods for measuring the fetal heart rate have been studied and used; they include the fetoscope, Doppler ultrasound, fetal scalp electrodes (FSE), intrauterine pressure catheter (IUPC) and other methods. Fetal heart rate can be monitored using Doppler ultrasound in the 7th to 9th weeks and the heart beat can usually be heard using a stethoscope at 20 weeks [14]. Some of the non-invasive fetal heart rate monitoring techniques is discussed in the following five sections:

Fetal Electrocardiography (FECG)

Non-invasive fetal electrocardiography (FECG) is a method used for measuring the electrical activity of the fetal heart using surface electrodes placed on the maternal abdomen. FECG can be monitored during pregnancy and/or labor and is used to detect abnormal fetal heart rates (FHR) or patterns; such as FHR acceleration, bradycardia or tachycardia, which may result from ischemia or other pathological reasons. Although FECG monitoring using FSE is the most accurate method for monitoring the FHR, it is highly invasive, relatively expensive and can only be used during labor [16], making the non-invasive FECG a more acceptable option.

The accuracy of trans-abdominal FECG can be determined by comparing it to results acquired using FSE. A recent study performed by G. Clifford et al. [17] evaluated the accuracy of a FECG device by comparing the results to data acquired from FSE. An E-TROLZ electro-physiological platform was used to record data from 32 laboring women in their first and second stages of labor. Standard ECG electrodes were placed in a standard configuration based on anatomic landmarks as shown in Figure 2, while the number of electrodes was chosen based on the recording device capacity. A QRS detector was then used to locate the R peaks in the extracted abdominal signals and the FHR was calculated based on the following formula:

$$\text{FHR (bpm)} = \frac{1}{\text{median RR-interval}} * 60$$

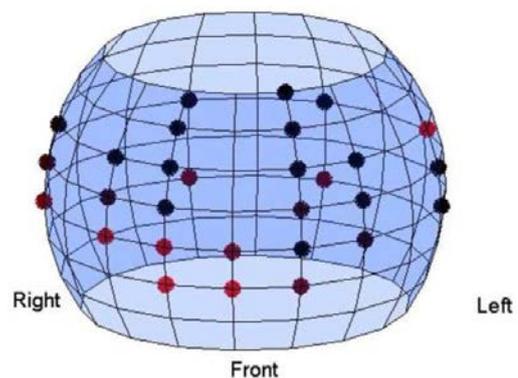


Figure 2. location of abdominal electrodes [17]

The signal quality differs according to fetal positioning; therefore signal quality measures were used to automatically determine the sensors with the most contribution to the output signal. The study has resulted in an average correlation of 0.96 between results obtained by FSE and abdominal electrodes over a complete beat, a root-mean-square (RMS) error of 0.36 beats per minute (BPM) and a standard deviation of 15.4 BPM. Maternal obesity increases health risks for both the mother and the child during and after pregnancy. In addition, its effect on

diagnosis performance should be assessed. In a study proposed by EM Graatsma et al. [18], a portable FECG monitor was used to take fifteen hour recordings (mostly overnight to minimize interference due to abdominal muscle activity) of 150 women between 20 and 40 gestational weeks and one hour recordings of 22 women going through labor. The AN24 fECG monitor was used to take the recordings, where five electrodes were placed in a standardized manner on the maternal abdomen. The RR-intervals of the maternal and fetal ECG signals were processed to calculate the maternal heart rate (MHR) and FHR respectively. Medians of FHR in addition to short term variability were then compared with simultaneous FSE recordings to assess the accuracy of the device. The results have shown that 82% of the recordings from the antenatal group and 77.3% of the intrapartum group had a good recording quality and were not influenced by the body mass index (BMI) of the mother. Another study [19]

has evaluated the effect of BMI on trans-abdominal fetal ECG monitoring using the AN24. In a population of women with a BMI range (16-50.7 kg/m²) and between 20-41 gestation weeks, 204 overnight monitoring sessions were performed and the relationship between recording quality and BMI was studied, the results of the study have stated that the correlation coefficient between BMI and the recording quality (RQ) was 0.35 (GA between 20-25 weeks), -0.08 (GA between 26-33 weeks) and -0.2 (GA \geq 34 weeks) (Figure 3). Lower conductivity of the fetal ECG signal in the gestational age between 26 and 34 weeks was previously related to interferences from the vernix caseosa and the relatively increased amniotic fluid volume; BMI has thus no significant effect on the recording quality (RQ) except in the periviable period (20-26 gestational weeks). Since FHR monitoring is uncommon in early stage of pregnancy, and the overall recording quality is high, this finding is considered as not clinically relevant.

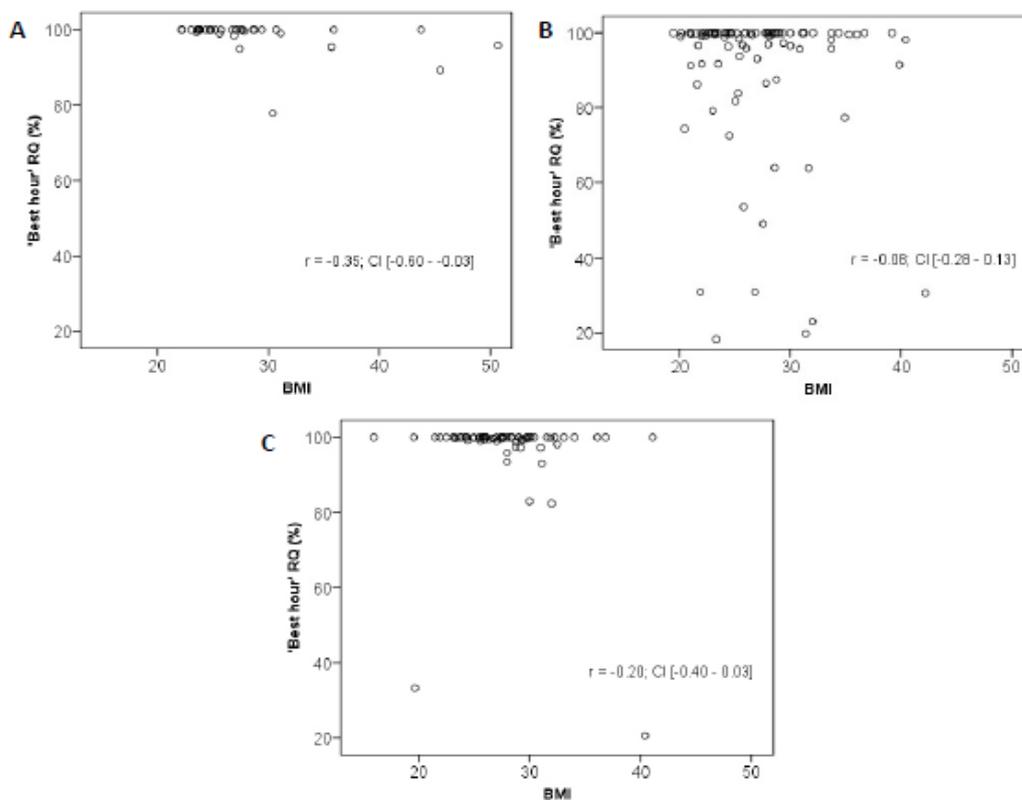


Figure 3. relation between BMI and recording quality. Figure A is related to the group with GA between 20-25 weeks, figure B is for GA between 26-33 weeks and figure C is for GA > 34 weeks [19]

Since obesity affects the RQ of ultrasound methods, FECG can be considered a suitable alternative to Doppler CTG during a restful state in high-risk pregnancies [19].

Electrode positioning is one of the main factors that should be studied in order to get a reliable FECG signal. A device called the Monica AN24 Monitor, which is the first non-invasive FECG monitor, uses five electrodes placed on the maternal abdomen [16]. Electrode placement is based on anatomic landmarks and therefore the distance between electrodes is dependent on the maternal abdominal girth [17]. An approach used five disposable electrodes placed in a standardized manner, regardless of the fetal position, two electrodes along the midline, one on each side of the uterus, and a ground electrode [18].

Trans-abdominal FECG has the advantage of being completely non-invasive, relatively cheap, easy to handle,

suitable for long-term recordings and has the potential for beat-to-beat variability monitoring [12,18]. However, a number of difficulties are associated with trans-abdominal FECG measurements: signal interferences due to maternal ECG (MECG, which normally has a magnitude of 10 times higher than FECG), motion artifacts, maternal muscle noise, fetal brain activity, electrode contact noise, power line interferences and other sources of noise. It is therefore necessary to have a signal processing system with high signal to noise ratio [2]. Another problem arises as a result of the dependency of the trans-abdominal FECG signal on the orientation of the fetus relative to electrode positioning [12].

When it comes to FECG signal processing, it is not convenient to use regular filters to extract the desired FECG signal from the continuously changing maternal

ECG signal, which brings out the need for an adaptive filter to adjust its coefficients according to one or more reference MECG signals [14,20]. A good way to start the processing is to convert the signal into its wavelet transform which is most suitable for non-stationary signals [14,21,22]. A study performed by EC Karvounis et al. [23] has used three pairs of electrodes placed on the maternal abdomen, while the complex continuous wavelet transform (CCWT) principle was used to extract the desired FECG signal, the procedure included 4 stages (Figure 4): stage 1 included averaging of the signals coming from all three leads to get a distinguishable fetal R wave, in stage 2 the wavelet transform coefficient values were calculated and the maternal QRS complex detection using a threshold of 60% of the mean of the maternal highest value, stage 3 included the fetal QRS complex detection including misdetections fetal QRS points but not

overlapped fetal QRS points with the maternal signal, after that stage 4 included detecting the overlapped QRS and rejecting the misdetections QRS points using a heuristic algorithm and therefore the FHR [23].

Another study [24] has proposed using multivariate singular spectrum analysis (MSSA) which was applied to a simulated FECG, MECG and random noise to separate fECG signals. This method overcomes limitations associated with nonlinearity and non-stationarity of signals, and it decomposes a signal into its components to eliminate the noise component. The basic SSA method is composed of two stages: in the first stage the signal is decomposed to separate the MECG component from the composite signal which requires one signal taken from the maternal abdomen and at least one signal taken from the thorax. In the second stage it is reconstructed to be used for further analysis (Figure 5).

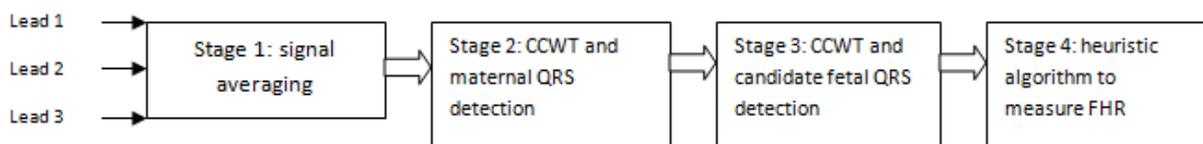


Figure 4. The proposed 4-stage Fetal Heart Rate (FHR) extraction method

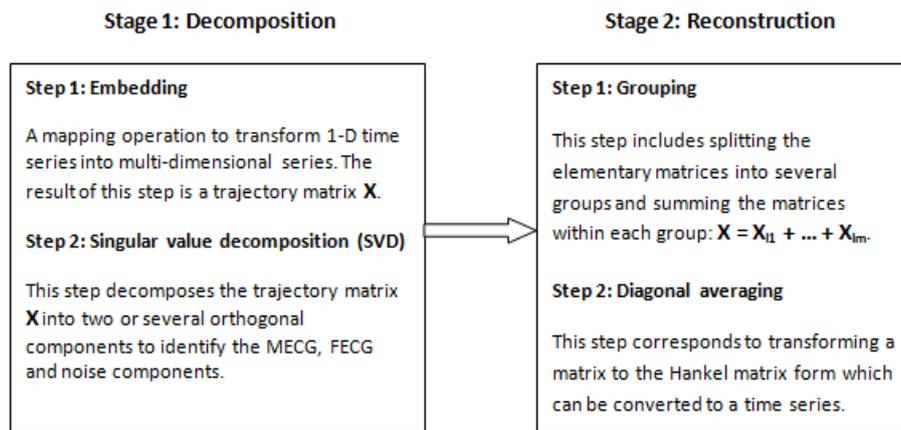


Figure 5. Proposed processing steps

A recent study by Zhongliang et al. [25] proposed FECG extraction method via a combination of blind source separation and empirical mode decomposition. First, FECG is extracted from the abdominal electrodes and the recursive least squares (RLS) blind source separation algorithm is used. Second, the FECG signal is decomposed by empirical mode decomposition; and its intrinsic mode functions (IMF) are adjusted. Finally, the clear FECG signal is obtained after IMF reconstruction. Experimental results show that the algorithm can rapidly and efficiently extract FECG and greatly eliminate noise; it is therefore considered as an efficient FECG extraction method.

One area that many people are concerned about is detecting FECG in case of multiple pregnancies. A study [26] has tested the feasibility of using 12 electrodes for singles and twins and 16 electrodes for triplets evenly placed on the maternal abdomen with a reference electrode placed on the right ankle. The electrodes were connected to a 12-bit multi-channel digital recorder and high pass and low pass filters with cutoff frequencies of 1-2 Hz, 150 Hz were used, respectively, and the data were then separated into multiple source signals to extract

fECG. The results have shown that- out of 199 subjects of single pregnancies- P, Q, R and S waves were detected in all subjects while the probability to detect the T wave was higher for gestational age of 24 weeks or more. In twins, out of the 58 subjects that have been tested, 72% of the twin signals were separable. For triplets, signals were separable in 93% of all 15 subjects.

Another area of concern is the size and portability of the FECG measuring device. A study [27] suggests that using a single lead abdominal electrode could be used to miniaturize the FECG device. The proposed method process is composed of two parts: the first part is concerned with eliminating the MECG from the abdominal signal and the second part is concerned with the enhancement of the fECG from the resulting signal. The proposed algorithm requires three steps: R-peak detection using wavelets transform, re-sampling, and comb filtering to extract periodic signals. Comb filtering alone cannot be used with ECG signal because of small variation in RR-intervals (heart rate variability), to overcome this, re-sampling (step 2) is used to unify the number of samples in each RR-interval. This solution is convenient since it would allow FECG monitoring in a

non-clinical environment with high simplicity. The results have also shown an improved robustness and capacity of real-time applications. 78% of the obtained signals were considered of good quality.

3. Photoplethysmography (PPG)

Photoplethysmography (PPG) which was first introduced in the 1930's is an optical, non-invasive method used to detect volume changes in the blood vessels and therefore measure the heart rate based on the changes in light absorption in the tissues at a specific red or NIR wavelength [28]. This method can also be used to measure the fetal heart rate through the maternal abdomen. The acquired PPG signal is composed of an AC component which represents blood volume changes, and a DC component which represents the heart rate baseline and low frequency noise components [29,30].

Fetal heart rate is measured non-invasively by transmitting near infrared (NIR) light of wavelength ranging between 650–950 nm that can penetrate the human tissues with the peak penetration being at 890 nm [31,32] via a photo detector to measure the reflected light. In 2000, a study proposed using four halogen lamps, 20 watts each, and two tungsten lamps, 0.575 watts each, as light sources with two photomultipliers as photo detectors [31]. This technique requires high power usage, generates heat, expensive and difficult to implement. To overcome the mentioned drawbacks, and since the main concern in fetal monitoring is temperature rise, another method using low-power light emitting diodes (LEDs), with a maximum power of 68mW, as light source was proposed. The latter method uses a low-cost silicon photo detector that is placed directly on the maternal abdomen [31].

The received light beam at the photo detector is modulated by both the maternal and the fetal blood pulsation; and in order to extract the desired FHR signal, a reference signal from the mother is required. The required signal is usually taken from a PPG probe attached to the maternal index finger. The signal acquired at the maternal abdomen (primary signal) is passed through a pre-

amplifier [33] and it is simultaneously digitized with the reference signal in preparation for the next signal processing stages which include digital synchronous detection, preprocessing and adaptive noise cancellation [32,34,35]. Gan et al. [32] proposed that the digital synchronous detection includes passing the primary signal from the maternal abdomen through a 710-740 Hz band-pass filter and then multiplying it by the reference signal, the resultant signal is then low-pass filtered at a cut-off frequency of 15 Hz. In the preprocessing stage the primary signal is down-sampled to 55 Hz to reduce the processing time. It is then passed through a high pass filter at a cut-off frequency equal to the fundamental frequency of the reference signal to remove low frequency noise sources such as the respiration artifact [32]. In this stage the reference signal is also down-sampled to 55 Hz and passed through a 0.6-15 Hz band-pass filter to remove the respiration artifact and high frequency noise [32]. Both of these signals are then fed into an adaptive filter in order to extract the desired FHR signal (Figure 6).

The PPG method has the advantage of using low power levels that are harmless to either the mother or the fetus. PPG is hence suitable for continuous monitoring; and the NIR light used is non-ionizing. It is also suitable for real time signal acquisition due to its fast response. The PPG system can be designed to be portable, robust and at low cost. On the other hand, there are a few concerns regarding this method. The first concern is the dependency of the signal quality on the source-detector (S-D) separation which in turn depends on the type of source and photo detector. The Monte Carlo technique findings indicate that an S-D separation of 4 cm results in 70% optical power from the fetal heart beat. Second concern is the signal quality that depends on the fetal depth from the abdominal surface. When the fetus is at a depth of greater than 2.5 cm the acquired signal has low SNR [31]. Third concern is the dependency of the signal quality on the fetal position in-utero, with the best signal being acquired when the probe is close to the fetal heart. Finally, the presence of motion artifacts and muscle contractions affects the signal accuracy [32].

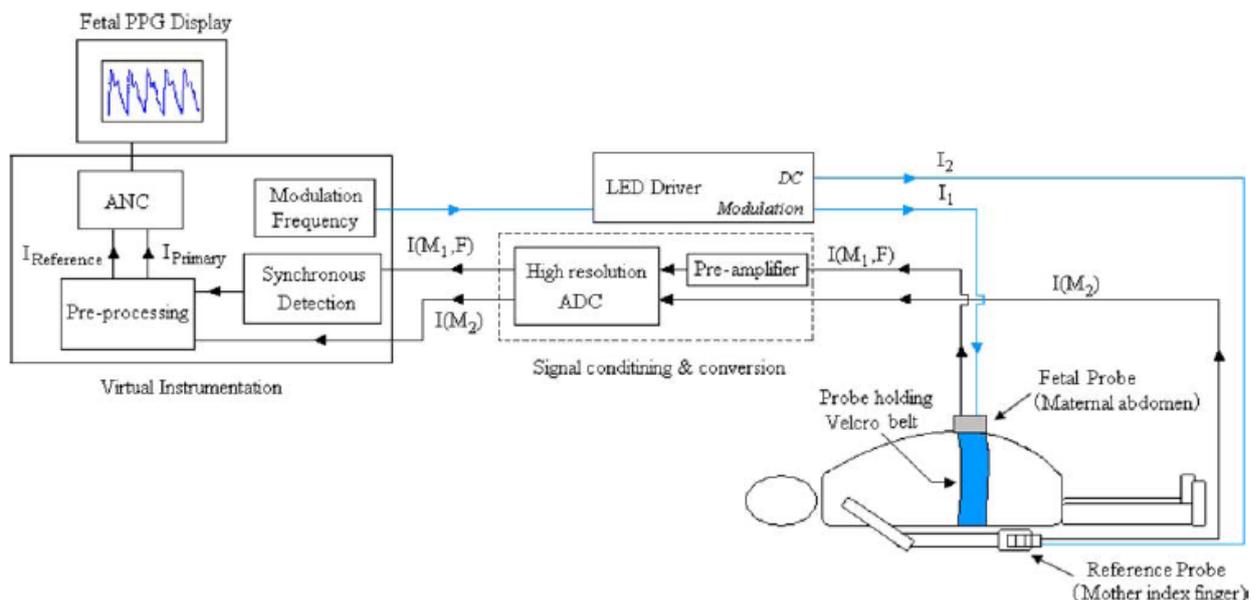


Figure 6. optical fetal heart rate detection system [32]

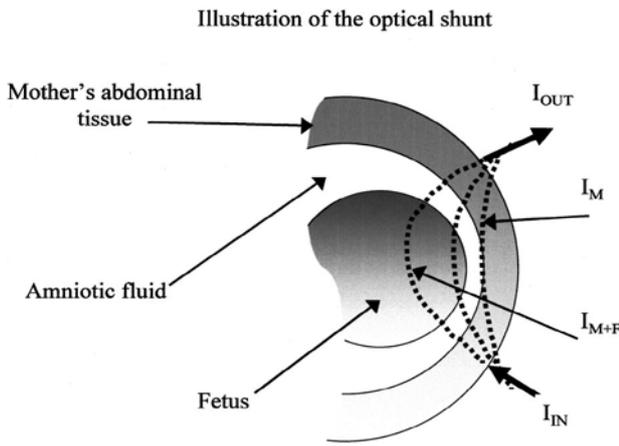


Figure 7. Illustration of the optical shunt problem [36]

A problem that arises when using an optical source and a photo detector at a small S-D separation to measure the fetal PPG is the optical shunt problem which occurs when the transmitted signal reaches the detector without passing through the fetus. A study about trans-abdominal fetal pulse oximetry proposed by Zourabian [36] has used the Monte Carlo simulation technique to measure the optical shunt between the source and the detector in the maternal layer at different S-D separation distances; 2.5 cm, 5 cm and 7.5 cm. Simulation results have shown that the highest fetal signal intensity occurs at an S-D separation of 5 cm, moreover, at the same S-D separation, the shunting signal passing through the maternal and the amniotic layers without reaching the fetal layer was 35% (65% of the detected signal reaches the fetal layer) (Figure 7).

Another study proposed by Ramanujam et al. [37] has studied photon migration through the fetal head in-utero using NIR light and laboratory tissue phantoms. A continuous wave spectrometer was used to make NIR measurements on 19 patients (whose average gestational age was 37 weeks) at 760 and 850 nm and at two S-D separation distances: 10 cm and 2.5 cm on the maternal abdomen directly above the fetal head. Similar NIR tests were performed on laboratory tissue phantoms with variable optical properties -obtained using different concentrations of India ink and Intra-lipid in water- and variable physical geometries -obtained using glass containers of different shapes and sizes [37]. The NIR measurements obtained from laboratory tissue phantoms have then been compared to the results of using NIR

measurements on the maternal abdomen in order to determine which tissue phantom best resembles the photon migration path through the fetal head in-utero. Results have shown that NIR measurements from the maternal abdomen can be obtained with a good SNR, approximately 50:1, at both the large and small S-D separations. A study performed by Gan et al. in [38] has considered a two-channel PPG system where the effect of having one LED and two photo detectors on the FHR signal was studied. One detector was placed at an S-D separation of 1.5 cm and the other at 4 cm. Both channels were set to have the same gain. Results have shown that at a trans-impedance gain of 1 Mohm the DC optical signal received at an S-D separation of 1.5 cm was higher than that at 4 cm, while if the trans-impedance gain was increased to 10 Mohm (to compensate for signal loss due to scattering, absorption or diffusion) the DC optical signal received at an S-D separation of 4 cm was higher. By passing the acquired signal through a band-pass filter, the DC component was removed and the AC component remained representing blood pulsation. The advantage of using a 4 cm S-D separation is that the transmitted light is able to reach deeper tissue levels. A study by Jumadi et al. using a 3-layer tissue model and the Monte Carlo simulation technique [39] has proposed three optical sensor array configurations to determine the most suitable configuration which can automatically select the signal with the highest SNR depending on the fetus position. The three configurations were the square using eight photo detectors, the diamond using four photo detectors and the star using five photo detectors (Figure 8). One emitter with a wavelength of 890 nm was placed in the center and the photo detectors were placed around it in a standardized manner. The initial S-D separation distance used was 4 cm as has been proposed earlier [32]. The sensor array was placed on the middle of the maternal abdomen during practical implementation so that the photo detector nearest to the fetus could receive the reflected signal. The most suitable configuration was chosen based on the strength on the irradiance, which can be calculated by dividing the flux received at the photo-detector by the area of the detector. Results have shown that the diamond is the most suitable sensor array configuration. The star shape has also given good results but (due to its shape) the S-D separation was set to less than 4 cm which might reduce the SNR.

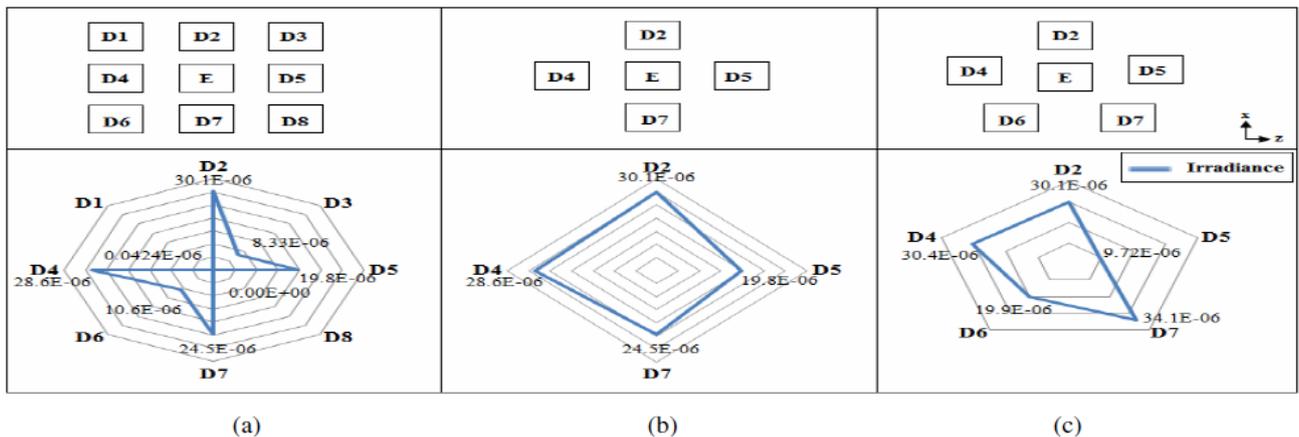


Figure 8. Optical sensor array configurations; (a) square, (b) diamond and (c) star [39]

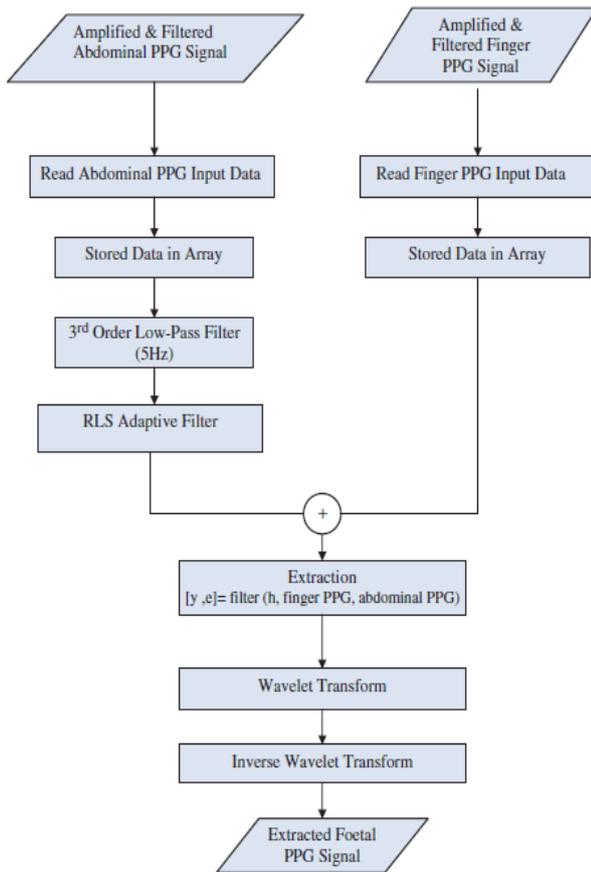


Figure 9. The algorithm used for fetal PPG extraction [40]

Another non-invasive optical system has been proposed by R. J. Oweis et al. [40], the approach consists of an abdomen circuit, a PPG circuit and a personal computer (PC). It is used to extract a fetal PPG signal with high SNR. The system uses the wavelet transform, which decomposes the signals at eight levels to eliminate noise related problems, and a recursive least squares (RLS) based adaptive filter. The abdomen circuit is composed of a transmitter circuit and a receiver circuit. The transmitter circuit consists of an astable 555 timer that generates a square wave of 725 Hz frequency, to be used for amplitude modulation (AM), and an IR light source at a wavelength of 880 nm. The receiver circuit consists of an IR detector to receive the modulated fetal PPG signal, a current to voltage (I/V) converter, a 710-740 Hz band-pass filter, an envelope detector to demodulate the maternal and fetal heart rate signals from the carrier signal, a national instruments data acquisition (NIDAQ) card to transfer the data from the envelope detector to the personal computer (PC), and a PC equipped with MATLAB to extract the FHR. The PPG circuit consists of a 1000 gain amplifier and a band-pass filter to prepare the signal for software processing. Software application consists of applying the wavelet transform to the extracted finger and abdominal PPG signals, passing the signals through an RLS based adaptive filter and finally applying the inverse wavelet transform to reconstruct the desired fetal PPG signal. The proposed system has proven to overcome problems related ambient light and power-line interferences. The test was performed on eight women and results have shown a correlation coefficient of 0.978.

4. Cardiocography

Cardiocography (CTG), which was first introduced in the 1970s by Dr. Konrad Hammacher, is one of the most subtle noninvasive pre-natal diagnostic techniques in clinical practice used to monitor fetal health and to record the measurement of the fetal heart rate and uterine contractions during both antepartum and intrapartum periods [41,42,43] (Figure 10). Antepartum fetal surveillance constitutes an essential component of the standards of care in managing high-risk pregnancies including maternal hypertensive disorders, intrauterine growth restriction, reduced fetal movement and other maternal and fetal pathophysiological conditions [18,44].

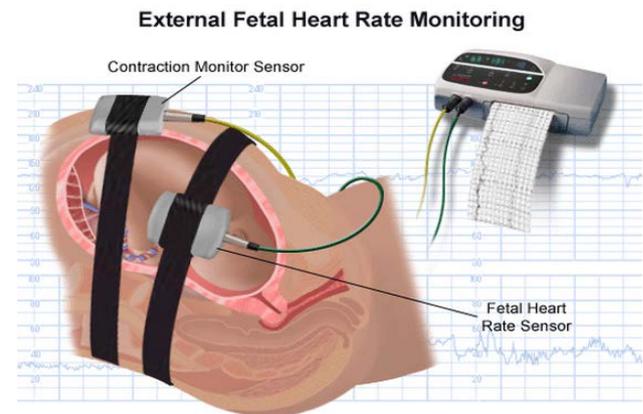


Figure 10. An external fetal cardiocography (CTG) monitor

It is noteworthy to mention the two types of CTG that are applicable in the field. First, external cardiocography is used for continuous or intermittent monitoring of the fetal heart rate and the activity of the uterine muscle. The latter is detected by two transducers placed on the maternal abdomen: one above the fetal heart level and the other at the fundus. Doppler ultrasound provides the information which is recorded on a paper strip known as a cardiocograph (CTG) [45]. The second type called internal cardiocograph uses an electronic transducer connected directly to the fetal scalp. A wire electrode is attached to the fetal scalp through the cervical opening and is connected to the monitor. This type of electrode is sometimes called a spiral or scalp electrode. Internal monitoring provides a more accurate and consistent transmission of the fetal heart rate than external monitoring because factors such as movement do not affect it. Internal monitoring may be used when external monitoring of the fetal heart rate is inadequate, or closer surveillance is needed [46].

Interpretation of a CTG tracing requires both qualitative and quantitative description of uterine activity, baseline fetal heart rate, baseline FHR variability, presence of accelerations, periodic decelerations and finally changes or trends of FHR patterns over time [47]. While issues concerning the interpretation of CTG are widely adverse, recent years have shown a consensus formed by the Royal College of Obstetricians and Gynecologists with the Society of Obstetricians and Gynecologists of Canada issuing statements on standardized nomenclature for fetal heart rate patterns.

Moving on to the market, many commercially available CTGs provide a continuous CTG tracing printed on a

strip-chart and, in addition, an evenly sampled FHR and UC series of digital outputs [41].

Errors commonly observed in CTG interpretation are directly related to the quality of the data acquisition and the presentation by the CTG machine. It is therefore crucial that all obstetricians and midwives understand the reasons for erroneous recordings and recognize the limitations of the technique [42]. Tests were applied to CTG findings reliability and significance in women presenting with reduced fetal movement (RFM) at the third trimester (28 weeks gestation or more). One study [48] was based on maternal perception of RFM (if there were less than 10 movements in any 12-h counting period). Therefore CTG was performed within 1-h for duration of 1-h and repeated after 1-h if the fetal heart pattern was initially un-reassuring. A reassuring CTG was defined as having 110-160 as a base line with two fetal heart rate accelerations exceeding 15 beats per minute sustaining for at least 15 second in a 20 minute period. If there was no acceleration, it will then be considered non-reassuring while fetal heart rate deceleration was deemed abnormal. The study was performed on 524 women that are above 28 gestational weeks, the main outcome measures included: obstetric intervention and perinatal outcome. 92% of the 524 women had initial reassuring CTG, and 3% was reassuring after a repeat tracing within 1 h. 5% of the women had non-reassuring/abnormal CTG, this group had significantly higher rates of emergency caesarean deliveries, neonatal resuscitation and NICU admissions. These results show that non-stress CTG is a discriminating test in women presenting with RFM at the third trimester and that abnormal pregnancies were more common for women with initial abnormal or continuously non-reassuring CTG [48].

Several studies were made to compare different prolonged FHR recording methods to show which methods were more efficient than others. A noteworthy study was made to compare between the uses of CTG vs. fECG concerning prolonged FHR recordings [18]. During the study several problems arose with using CTG for prolonged fetal heart rate monitoring and were due to the discomfort, poor signal quality and prolonged exposure to ultrasound [42] while fECG showed that it can obtain approximately 8 hours of qualitatively good FHR records without the necessity of interference of any caregivers from 20 weeks of gestation onwards [18]. Other studies concerning CTG problems states that It is widely accepted that suspicious fetal heart rate (FHR) patterns lack specificity; and false positive FHR tracings often result in unnecessary interventions [42,49].

Another significant use of CTG findings was correlated with how fetal pulse oximetry behaves in various cardiotocographic (CTG) tracings and its association with neonatal outcome. Previous studies have shown that using the wavelet analysis with CTG recordings for intra-partum fetal monitoring provides useful information on the fetal response to hypoxia. 318 women entered the trial during labor at the 'Aretaieion' University Hospital labor ward. They were monitored with external CTG and fetal pulse oximetry. 50 women out of 318 delivered operatively because of abnormal CTG patterns. After the application of wavelet analysis and neural networks to the pulse oximetry and FHR variability readings of these 50 women, it has been shown that the system had a sensitivity of 85%

and a specificity of 93%, while false negative and false positive rates were 15% and 7%, respectively. This shows that computerized FHR and FSPO2 monitoring have excellent reliability in interpreting non-reassuring FHR recordings [49].

An additional study [50] mainly shows how CTG was used to record variable or persisting late decelerations in a total of 156 pregnant women undergoing the active phase of labor with a gestational age of 32–42 weeks. All subjects were monitored by CTG alongside fetal pulse oximetry, which were recorded using a Nellcor 400 and an FS14 sensor for at least 30 minutes using wavelengths of 735 and 890 nm. The CTG patterns after the delivery were divided into three groups as reassuring FHR patterns (50%), late decelerations (10.3%) and variable decelerations (39.7%). Fetal acidosis was significantly more frequent with late decelerations (23.1%). A multiple logistic regression model was used to demonstrate that the most predictive variable of neonatal well-being was the initial pulse oximetry reading during active labor [50].

As for a more recent study [41], M. Cesarelli et al. have taken a different perspective by developing an algorithm that is used to recover the unevenly spaced FHR series from the CTG series recorded by the device. The output FHR values were first converted into RR-intervals. They are often subjected to a zero order interpolation which affects the frequency content of the signal. To eliminate the FHR spectrum alterations related to zero-order interpolation, a pre-processing algorithm was developed. There are three main steps for the proposed algorithm as follows:

(a) *Choice of the first sample*: this is considered to be the first change of value detected in the RR series (not duplicated sample).

(b) *Block identification*: The RR series are divided into blocks containing samples of equal value where the first sample of each block is stored.

(c) *Evaluation of the number of not duplicated samples in each block*: RR series are series of RR-intervals, sampled unevenly at the occurrence of R-waves. The RR series have an important characteristic which is that the cumulative sum of the samples equals the elapsed time from the first sample.

About CTG related labour problems, a recent study found that electronic fetal heart rate monitoring may be used selectively based on an admission test [51]. Fetal blood sampling may be of help to reduce unnecessary operative delivery. In centers where these facilities are available most problem are due to poor understanding of FHR patterns and inappropriate and delay in action because of lack of consideration of the clinical picture. The proper evaluation of the risk to individual fetus by incorporating the overall clinical picture and appropriate action should avoid intrapartum morbidity and mortality [51].

A Cochrane systematic review has not found evidence to state that CTG is useful for antepartum fetal assessment and shows a trend that women being managed with CTG had an increased perinatal deaths. Continuous CTG is associated with an increasing number of caesarean sections and no significant differences in infant mortality or other standard measurements of neonatal wellbeing. Dawes and Redman have developed a computer algorithm

to eliminate observer variability and to increase the accuracy of CTGs [52].

Another common labour problem that was worth studying is the Misidentification of maternal heart rate as fetal on CTG during the second stage of labor [53]. A retrospective observational study was used to measure the rate of accelerations during external and internal monitoring as well as decelerations for a 60 minute period prior to delivery, in addition to that, the role of fetal ECG in differentiating between MHR and FHR trace was also studied [53]. CTG recordings of 100 fetuses were studied and the results have shown that decelerations were the most common and have occurred in 89% of CTG recordings during the second stage of labor. Accelerations were found in 28.1 and 10.9% of cases recorded by an external ultrasound transducer as well as internal scalp electrode, respectively. Accelerations coinciding with uterine contractions occurred only in 11.7 and 4% of external and internal recording of FHR, respectively. Acceleration coinciding with uterine contractions was less than half in fetuses monitored using a fetal scalp electrode [53].

A study which was done by James C. Dixon et. Al. [54] was included due to its prevalence to pregnancy issues. Investigations were made to see the relationship between intestinal atresia and fetal growth, intrapartum cardiotocograph abnormalities and staining of the amniotic fluid in gastroschisis pregnancies. 115 pregnancies were studied with babies that were complicated by gastroschisis and delivered after 30 weeks of gestational age. CTG abnormalities recorded were tachycardia, late decelerations, variable decelerations, reduced baseline variability or bradycardia. The presence or absence of intestinal atresia was confirmed. The measurements were taken according to birth weight, intrapartum cardiotocograph abnormality, staining of amniotic fluid, and Apgar score. It was found that for gastroschisis cases with or without atresia, there was no significant difference between the Apgar scores or the frequency of amniotic fluid staining. Patent bowel gastroschisis was associated with more CTG abnormalities and reduced growth, when compared with cases with intestinal atresia [54].

Inter- and intra-observer variability has an influence on the interpretation of CTGs recordings, which is why the subjectivity of CTG interpretation should be taken into consideration. Using modified definition of a fetal heart rate deceleration compared with consultant interpretation as the Gold Standard, it has been demonstrated that a minor modification in the standard definition of fetal heart rate deceleration enables midwives and trainees in obstetrics to identify decelerations with improved accuracy, using analysis by five consultant obstetricians as the everyday Gold Standard [55,56]. Some studies [57,58] were made based on the opinion of midwives and doctors of the use of CTG and their perception of it. A survey was conducted among 1086 midwives to assess their attitudes towards the use of CTG machines. The data were analyzed and compared using several categories, and the results have shown that midwives reject the idea of them being dependent on machines in their practice [57]. As a result of these studies, future education of midwives is recommended to maintain competence of skills in natural birth as well as high-tech birth [57,58].

5. Doppler Ultrasound

The Doppler principle was first discovered in 1842 by the Austrian physicist Christian Doppler and describes the relationship between the velocity of the objects and received wave frequencies. This method is used for measuring mechanical activity of the heart like the opening and closing movement of valves during each cardiac cycle to estimate the fetal heart rate signal [59]. Doppler ultrasound technique depends on generating ultrasound beam with frequency of 1 or 2 MHz (the most common frequency are used in the range (1-2.3MHz) [60]. The beam is generated by an ultrasound (US) transducer placed on the maternal abdomen, penetrates tissue to reach internal body structures and is the reflected echoes are received by the US transducer; these echoes are then demodulated to obtain information regarding movements in the form of differential frequencies [10]. In the demodulated signal the useful components are located in acoustic frequency band (200-1500 Hz) so band pass filtering is used to separate the useful components of the signal [12] (Figure 11).

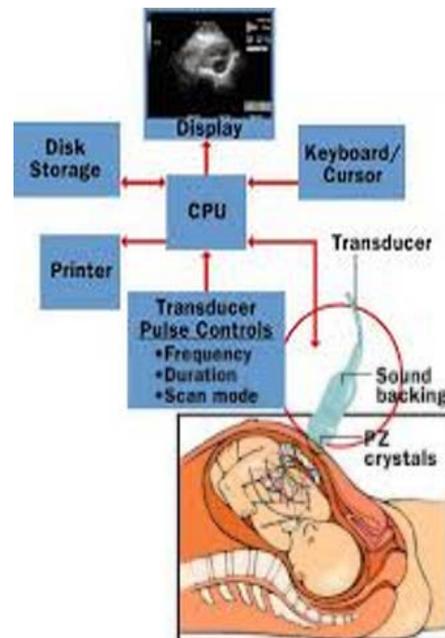


Figure 11. Doppler ultrasound system

The major limitations of using Doppler ultrasound are its sensitivity to movement and that it is not suitable for continuous monitoring [2], it also gives the averaged HR and cannot give the beat-to-beat variability [61]. Doppler ultrasound generally is not used in the first trimester and not always reliable as a result of signal complexity and the effects of fetal and maternal breathing [33].

There are many methods to measure the fetal heart rate by using Doppler ultrasound. One of these methods is pulsed Doppler ultrasound; this method is to estimate the true beat-to-beat value of the FHR signal through multiple measurement of a given cardiac cycle in the ultrasound signal and consists in three steps [10]:

The dynamic adjustment of autocorrelation window; which allows for the determination of the periodicity of the Doppler signal, under the condition that the established window contains at least two corresponding mechanical activity occurrences.

The peak detection algorithm.

Determination of beat-to-beat interval within the given time window.

The shape of the signal and locations of peaks are continuously varying during heart activity. Therefore, the location of the heart beat cannot be accurately defined and beat-to-beat measurements are complex. For that reason, autocorrelation function (AF) is used. The main problem when using Doppler ultrasound to measure the fetal heart rate is the detection of consecutive heart beats as a reason of fetal movement. In Peak detection, for high signal quality, the position of maximum AF directly indicates the signal periodicity. Low AF peaks indicate low signal quality, which means there is an error in the measurements resulting from signal artifacts coming from maternal blood vessels. When the signal quality decreases, the amplitude of the AF peaks goes below a certain threshold ($R_{\max} = 0.6$). AF correction is applied (triangular window function) using Interval validation to reduce large errors in the measurements caused by signal interferences that have not been removed [10]. This method increases the accuracy where the continuous Doppler ultrasound technique provides the fetal heart rate with limited accuracy. The research material was collected from three patients during labor with total recording time 68 minutes (total of 8945 intervals detected in fECG) and the results have shown increasing in the accuracy of time interval and short-term FHR measurements [10].

Two methods of fetal heart rate estimation based on Continuous Doppler ultrasound were used in the study: One was the classical method based on the analysis of the autocorrelation coefficient of the envelope of the band

pass filtered Doppler signal [62,63], and the other was based on analysis of the autocorrelation coefficient of the envelopes of the wavelet reconstruction products of the Doppler signals [64].

A study about the accuracy of Doppler US compared to electrocardiography (fECG) [65], the study included collecting US data (FHR_{US}) and comparing it to data acquired using fECG (FHR_{REF}) by the use of electrodes penetrating the fetal head from 5 women with a total recording duration of 185 minutes. The results obtained have shown that the data acquired from Doppler US monitors is sufficient for visual monitoring but not for the beat-to-beat level analysis [65].

The study [60] shows the sensitivity to fetal movement through the continuous Doppler ultrasound. The researchers used a 2 MHz continuous Doppler system with two ultrasonic sensors with diameter (25 mm) and thickness (6 mm). One of the two sensors is called fetal heart and thorax sensor, while the other one is fetal legs sensor. Both transducers were excited using the same emitter and the two reception transducers were connected to two different channels, the signals were then processed as shown in Figure 12). The data collected from 23 women at gestational age from 26 to 40 weeks with recording length of 30 minutes for each record. They detected 96% of fetal rolling movement, 100% of fetal flexion movement, 97% of fetal legs movement, 100% of fetal head movement and 83% of fetal arms movement. The average sensitivity of mother to fetal movement detected by Doppler fetal (Dopfet) system is 27% for this small sample [60].

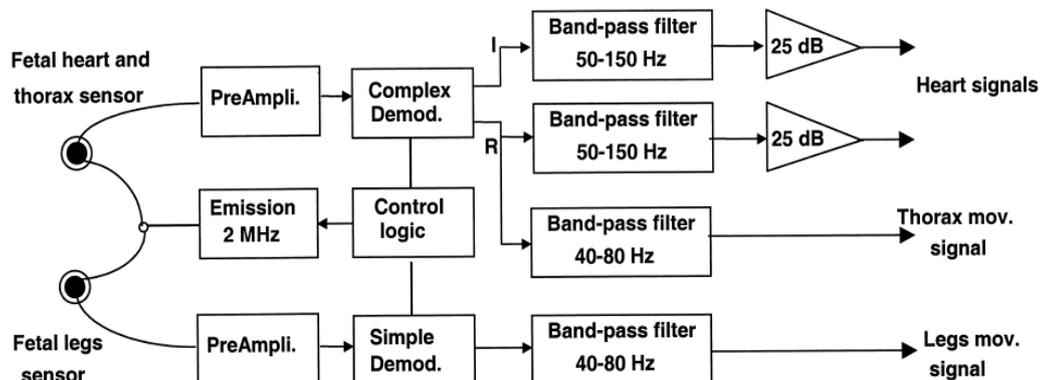


Figure 12. Block diagram of the electronic module [60]

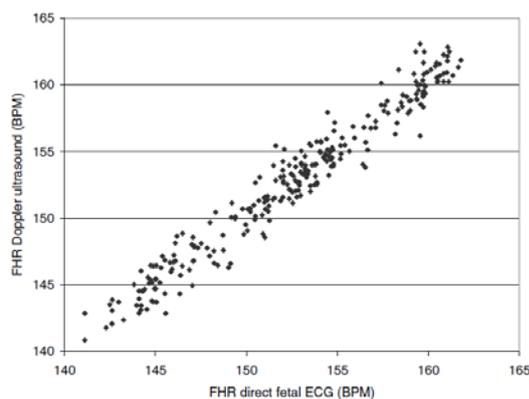


Figure 13. FHR calculated using the Doppler US algorithm compared to FHR obtained using direct fECG [66]

A study proposed by Chris H L Peters et al. [66] showed the detection of beat-to-beat through CTG monitoring by using Doppler ultrasound. The calculation algorithm consisted of two steps: in the first step, an estimation of the time when the heart cycle shows up is made; this is achieved by applying a low-pass filter with 2 Hz cutoff frequency to the envelope signal, peak detection is applied to the resulting signal in order to estimate the locations of heart cycles. The second step calculates the autocorrelation in the frequency domain to obtain the heart rate. The data was collected from women at gestational age of 40 weeks; and the results were shown in the time domain and frequency domain. In the time domain the signal with a time interval of 100s was taken. The results from the CTG using Doppler ultrasound and direct ECG cardiocography were illustrated in a graph. The best fitted

line was ($Y=1.002X$), R squared was then =95.43%, and the correlation coefficient was 0.977 ($p < 0.001$). In the frequency domain, the data was resampled at 4Hz. 256 points of fast Fourier transform were calculated. The results from the CTG using Doppler ultrasound and direct ECG cardiocography were illustrated in a graph. The best fitted line was then calculated. It was ($Y=1.068X+b$), R squared then =98.24%, and the correlation coefficient was 0.991 ($p < 0.01$) [66] (Figure 13).

6. Fetal Magnetocardiography

Fetal magnetocardiography (FMCG) is a non-invasive technique for recording the magnetic field generated by the electrical field of the heart. FMCG does not emit magnetic fields or energy therefore it is a safe technique [67]. Kariniemi et al. recorded the first (FMCG) using a superconducting quantum interference device (SQUID) in 1974 [68]. FMCG is a weak signal on the order of 10^{-12} tesla [12], much smaller than environmental magnetic signals; such as the earth magnetic field. Because of that, it is detected in shielded room [67]. FMCG can be used for fetal monitoring during labor, identification of fetal state, monitoring of fetal arrhythmia, automatic detection of fetal movement, and can be used to monitor the fetal heart rate. FHR can be monitored by CTG, but it is a short time measurement with limited accuracy, and by ECG but due to artifacts and low signal to noise ratio, can be applied later in pregnancy. On the other hand, FMCG can be used to monitor the fetal cardiac activity at the beginning of the second trimester [69]. In FMCG monitoring, no part of the magnetometer system is in contact with the body; this means that the magnetic fields from the fetal heart are not significantly affected by the electrical impedance of tissues making FMCG a more accurate method than FECG [70]. FMCG is not affected by the insulating effect of the vernix caseosa [71] and it can be used to detect true beat-to-beat measurements although the QRS complex is easily detectable in raw signals and P and T wave can be detected in averaging signal [12]. However, FMCG has some drawbacks such as size, cost, complexity of magnetometer system and it needs to minimize subject movement [71]. The fetal heart rate monitoring based on FMCG requires low computational complexity and low processing delay and must detect rapid changes in the heart beats [72]. The recording of FMCG depends on: fetal gestational age (GA), fetal behavioral state, fetal presentation, fetal movement and fetal respiratory rate [73].

The superconducting quantum interference device SQUID system used can detect very weak bio magnetic fields from picotesla (pT) to femtotesla (fT). There are two different SQUID systems: SQUID magnetometers for measurements in super magnetically shielding room (MSR) and SQUID gradiometers with different antenna shapes for measurements in moderate MSR or unshielded environments [74]. The more successful system used to detect FMCG includes an array of (SQUID) sensors, automated signal acquisition and control electronics [77]. Using the multi-channel SQUID array for FMCG detection is better than using the single channel SQUID system, it can cover a larger area of the maternal abdomen and it has large signal to noise ratio [75].

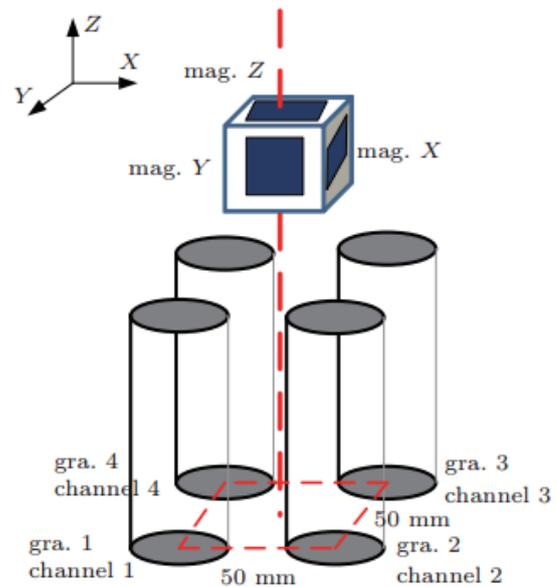


Figure 14. Arrangement of gradiometers and magnetometers [76]

One of the most promising techniques for the fetal MCG measurements is Multi-channel SQUID bootstrap circuit (SBC); it consists of four SBC magnetometers and three reference SBC gradiometers (Figure 14). It is fabricated by connecting a first order axial gradient pick up coil to an SBC chip, and fast ICA logarithm is used to separate the FMCG signals [76]. The FMCG device must be as close as possible to the maternal abdomen since the fetal signal is largest near the abdomen and it decreases at greater distance while the noise is the same at both distances. The amplitude and shape of FMCG depends on the distance between the fetal heart and the position where the magnetic field is measured [12].

The signal processing used to detect the FHR and averaged fetal PQRST complex is illustrated in Figure 15.

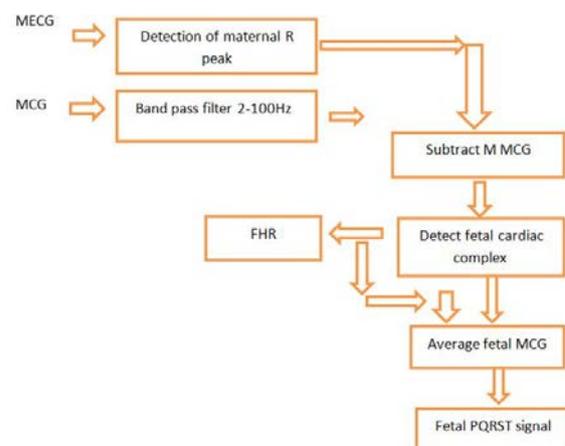


Figure 15. Signal processing used to detect FHR and averaged fetal PQRST complex [77]

MEKG is used to detect the time when R peaks occur, this time indicates when the maternal R peaks appeared in the recorded magnetic signals. It can be found by averaging the maternal complex in magnetic signals, maternal cardiac complex, and then complex subtraction from the FMCG. The fetal R peaks are detected by mean threshold set as 65% of the median of the R peak amplitude, and a matched filter. The R peak is used to drive a graph of FHR and for averaging fetal PQRST

complex [77]. The first step in FMCG extraction uses the band pass filter. To find the optimal filter, different frequency ranges are tested. For high pass filter, cut off frequency of 2Hz and 4Hz are tested and for low pass filter, cut off frequencies of 100Hz, 75Hz and 50Hz are tested. The result shows that a cut-off frequency less than 100Hz for the low-pass filter has an effect on the shape of the cardiac wave. The same is true for the high-pass cut-off frequency higher than 2Hz. Therefore, a bandwidth of 2Hz – 100Hz is chosen as an optimum solution. The FMCG signal used in this investigation is taken from a 38-weeks-old fetus and has high signal-to noise ratio [78].

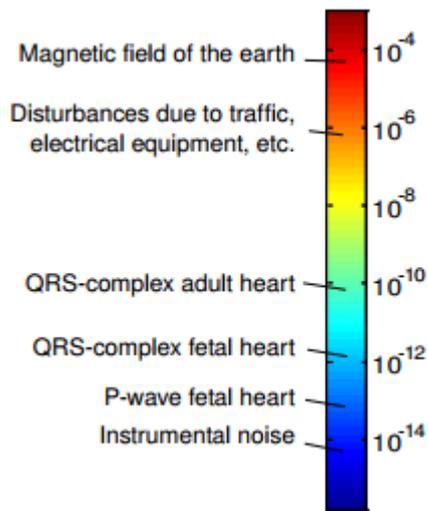


Figure 16. Magnitudes of FMCG signals in Tesla [77]

A study performed by D. Gutiérrez et al. [72] presented an algorithm that separates FMCG signals from maternal MCG (mMCG) signals adaptively based on a multi-channel filter, as well as dynamically selecting the channel the highest FMCG signal component. Recordings were made using 151-channel SQUID array covering the whole maternal abdomen. Group of channels in the upper part are used as a reference channel containing the maternal component. An adaptive filter is then used to estimate the maternal signal and subtract it from the whole signal and then estimate the fetal signal. The steepest descent algorithm is used to keep the mean square error minimized for fetal signal. For accurate removal of maternal signal this calculation must be done with the peak produced by the maternal heart. When this peak is detected by an R-detector the only first reference channel passed through the detector. This fast and reliable method for extraction of FMCG can be dynamically selected as the channel with high content of fetal component [72].

When FMCG is used in multiple pregnancies, signal processing methods for separation and identification of the cardiac signal of mother and her fetuses must be used. The maternal component is easily identified because it has the largest cardiac cycles. The QRS for the fetuses can be detected until if the fetuses have similar cardiac cycles. S Comani et al. [79] have proposed a method which can be used to separate FMCG signals, this method can also be used to detect fetal arrhythmias and in all cases of discordant fetal growth. FMCG was performed on a 23-year-old woman with a bi-zygotic pregnancy at GA of 27 weeks. Both fetuses and the pregnancy were normal. The first fetus was in a longitudinal position while the second

fetus was in a transverse position. Each magnetic sensor was a low temperature dc-SQUID. 55 sensors covered an area of 415 cm² and 55 mixed FMCG and mMCG signals were recorded. The signals were reconstructed using fixed point independent component analysis (fastICA), which was chosen for its effectiveness and consistency. When each independent component was retrieved, they were each assigned to their source. A number of parameters were calculated, such as fetal heart rate (FHR) and its evolution over time, RR-intervals, the standard deviation of all normal sinus RR-intervals and an estimate of FHR variability [79].

There are two signal processing methods: template matching (based on the spatio-temporal correlation in the signal), and independent component analysis (ICA) (on the basis of decompose the signal into statistically independent component). In signals with higher SNR, the identification by both methods was successful, but in signals with lower SNR the ICA found large number of beats in few data sets while the template method needed many data sets to found few beats. Therefore, ICA is more successful when the fetuses have different heart rates [80].

In post processing methods, fetal RR-interval extraction is used. Filtering method used to detect the time when R-peak occurs. The signal is filtered by a band pass filter of 10-40 Hz because most R-peaks are found in this frequency [75,78]. Hilbert method acts similar to the high pass filter. It is the best method to extract RR-intervals and can be used to automate the extraction of the fetal heart rate with 99.6% efficiency, independent component analysis (ICA) shows a large number of error and gives either excellent result or poor result. About the coupled ICA-Hilbert, the Hilbert can be added to improve the signal quality [75].

In the data acquisition system using SQUIDS, two different procedures, Fourier based filtering method and Wavelet based filtering method were used. Wavelet method has two steps, a baseline drift correction method and a filtering method to decrease the biological noise. The Fourier technique can determine the frequency content of the MCG. This technique allows the identification of the noise sources. The Fourier based filtering procedure can remove a large part of interferences from a fetal signal recorded in undesirable conditions. The wavelet based filtering method reduces only the biological noise but it is very active when there are magnetic interferences higher than MCG [81].

A study performed by Adam Adamopoulos et al. [82] used another method for the analysis of the FMCG by applying the clustering algorithms on the reconstructed multi-dimensional phase space of the fetal heart dynamics. First, to derive the multi-dimensional phase space from the one-dimensional FMCG signal, a technique based on theory of non-linear dynamics and chaos is used. Second, an especially developed clustering algorithm is applied to detect and estimate the number and the features of clusters in the dynamics of the FMCG [82].

7. Summary

In Summary, Table 1 shows a comparison between the discussed non-invasive FHR monitoring systems based on previous studies:

Table 1. Comparison between non-invasive FHR monitoring systems

Method	Advantages	Drawbacks	Gestational Age	Energy type
FECG	Low cost, easy to handle, suitable for long-term recording, beat-to-beat variability monitoring	Complex design requirements, dependency on fetal orientation in-utero	20-40 weeks	electrical
PPG	Low cost, low power consumption, harmless, easy to handle, suitable for long-term recording, suitable in a clinical setting, can be designed to be portable, can be used in an MRI environment	Dependency on S-D separation, dependency on fetal orientation in-utero		optical
Doppler ultrasound	Low cost, easy to handle, can be used during labor	Short-term variability cannot be observed, not suitable for continuous monitoring	20-40 weeks	Ultrasonic
CTG	Measures uterine contractions, provides continuous FHR tracings	Short-term variability cannot be observed, difficult to interpret, limited accuracy		Ultrasonic
FMCG	Not affected by tissue impedance, relatively accurate	High cost, large size, complex system design, requires minimized subject movement	20-40 weeks	magnetic

8. Conclusions

Fetal heart rate monitoring devices are becoming more popular day by day and they are taking place in almost every pregnancy and/or laboring procedure, especially in high risk pregnancies. A number of devices have been proposed since the beginning of the 20th century; such as the fetoscope, the fetal scalp electrode, Doppler ultrasound in addition to a few others. FHR monitoring via abdominal ECG electrodes has widespread clinical acceptance as it has the advantages of being relatively cheap, easy to handle and suitable for long term recordings with the ability for beat-to-beat variability monitoring but has complex design requirements. The use of Doppler ultrasound to monitor the FHR was soon proposed in the 1960's and is still being used on a daily basis till present for its low cost and simplicity although it is not suitable for continuous monitoring. Later in the same decade the first commercial CTG monitor was introduced by Hewlett Packard which has the ability to continuously monitor FHR tracings and maternal contractions simultaneously but has the disadvantages of having low accuracy and being difficult to interpret. The fetal magnetocardiography has solved the accuracy problem seen in the previous devices but is relatively expensive, has large size, complex design requirements and requires the mother to have minimal movement. Almost all of the previously mentioned drawbacks have been solved with the most recent FHR monitoring device, taking advantage of light properties, which is the photoplethysmography. This device meets all of the important criteria which are being easy to use, not overly large, having low power consumption, not using ultrasonic waves, being completely non-invasive, being safe for both the mother and the fetus and last but not least being suitable for long-term monitoring. All of these advantages have made the PPG a very interesting method and deserves to have the most attention in future biomedical research.

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