

STUDY AND ANALYSIS OF FETAL HEART RATE MONITORING SYSTEM**Amna Abd Al-Hussain Nassar**University of babylon, Faculty of Engineering,
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Abstract: Analysis of FHR variability, together with uterine muscle contractions and fetal movement activity, subject to cardiotocographic monitoring, currently play a fundamental role in fetal assessment. The strength of cardiotocography lies in that normal ranges of the results of the FHR signal analysis almost always (>95%) confirm fetal wellbeing. Unfortunately, questionable or abnormal signal features may indicate both fetal distress and its absence. The classic fetal heart rate variability analysis consists in determining the FHR baseline and then in identifying bradycardia/tachycardia, acceleration/deceleration patterns as well as the type and amplitude of oscillations. A more advanced FHR analysis is aimed at evaluating instantaneous FHR variability, especially with beat-to-beat approach, which is very important in fetal condition assessment. The most common technique of recording the FHR signal is the Doppler ultrasound method, which makes it difficult to correctly estimate the instantaneous heart rate variability because the measurements are averaged. On the other hand, instantaneous heart rate variability plays a crucial role in the diagnosis of fetal condition [1]. The increased interest in monitoring the fetal cardiac bioelectrical activity is due to the fact that the analysis of the fetal electrocardiogram ensures high efficiency and accuracy of the heart rate measurement even on a beat-to-beat level. The first fetal electrocardiogram was recorded as early as in the 1960-ies by means of a special spiral electrode enabling direct signal registration from a fetal head. Due to the way the electrode is placed, its use is limited only to the advanced labour stage [1].

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Introduction

Fetal heart rate monitoring is a procedure used to evaluate the well-being of the fetus by assessing the rate and rhythm of the fetal heartbeat [2]. During pregnancy, the development of the different organs usually follows phases that start in different weeks. Among these, the heart begins to work at the fourth week of life, so, from this stage, the fetus starts to use its own bloodstream. The fetal heart activity can be monitored from the seventh week using specific devices, such as ultrasound-based ones. Starting from the 20th week, the fetal heartbeats can be heard without amplification, and the corresponding Fetal Heart Rate (FHR) normally ranges from about 110 to 160 beats per minute (BPM). It is important to monitor the heart activity as soon as possible and with accurate and reliable systems, especially by using ultrasound techniques, in order to timely detect any abnormal behavior (e.g., cardiorespiratory disease) [3].

For fetus heart rate measurement, FHR monitor devices or combined cardiotocography (CTG) monitors are usually adopted. The CTG (These combine measurements by one tocographic (TOCO) and at least one ultrasound probe usually recorded in the last pregnancy trimester period) allows both early diagnoses of uterine disorders and hypoxemic changes that can compromise the fetus growth (e.g., twins or triplets) [3]. The fetal ECG (FECG) contains information about the state of the fetus and is very useful for clinical diagnosis of the fetus during pregnancy and during labor. The analysis over long periods of time or even better continuous monitoring is a powerful tool in detecting the problems occurring during pregnancy. The use of Doppler ultrasound, extensively used nowadays is not suitable for long periods of monitoring. That is why researchers have focused lately on the processing of the abdominal signals to obtain information on fetal heart rate (FHR) and uterine contractions. Fetal monitoring using abdominal signals, a noninvasive recording technique allowing long-term fetal monitoring, can be implemented when the signal is processed properly. Beat-to-beat information about the FECG is contained in the abdominal signal. The P-Wave can also be detected in the averaged FECG after processing the abdominal signals. The abdominal signals contain not only the signal of interest, i.e. the FECG, but also other signals that have amplitudes much larger than that of the signal coming from the heart of the fetus. When the FECG is detectable, the maternal ECG (MECG) can have an R-Peak seven times the R-Peak of the FECG. Therefore, the MECG is the most important source of disturbances. Other disturbing signals that must be considered are the baseline, the myoelectric signals, and the uterine contractions, especially during labor. After removing all these signals, the FECG is still overwhelmed by electrical noise and the signal-to-noise ratio is very poor [4].

The fetal heart rate monitoring can be carried out as a standalone application developed on a smart phone using a cheap portable Doppler ultrasound device connected to the phone, owing to the huge distances that women in these remote communities have to travel to reach health centers and hospitals, many do not get proper medical care to address prenatal issues [5].

Anatomy of the fetus:

- **amniotic sac:** a thin-walled sac that surrounds the fetus during pregnancy. The sac is filled with amniotic fluid (liquid made by the fetus) and the amnion (the membrane that covers the fetal side of the placenta), which protects the fetus from injury and helps to regulate the temperature of the fetus [2].
- **anus:** the opening at the end of the anal canal [2].

- **cervix:** the lower part of the uterus that projects into the vagina. Made up of mostly fibrous tissue and muscle, the cervix is circular in shape [2].
- **fetus:** an unborn baby from the eighth week after fertilization until birth [2].
- **placenta:** an organ, shaped like a flat cake, that only grows during pregnancy and provides a metabolic interchange between the fetus and mother. (The fetus takes in oxygen, food, and other substances and eliminates carbon dioxide and other wastes) [2]. -**umbilical cord** : a rope-like cord connecting the fetus to the placenta. The umbilical cord contains two arteries and a vein, which carry oxygen and nutrients to the fetus and waste products away from the fetus [2].
- **uterus (Also called the womb.):** the uterus is a hollow, pear-shaped organ located in a woman's lower abdomen, between the bladder and the rectum, that sheds its lining each month during menstruation and in which a fertilized egg (ovum) becomes implanted and the fetus develops [2].

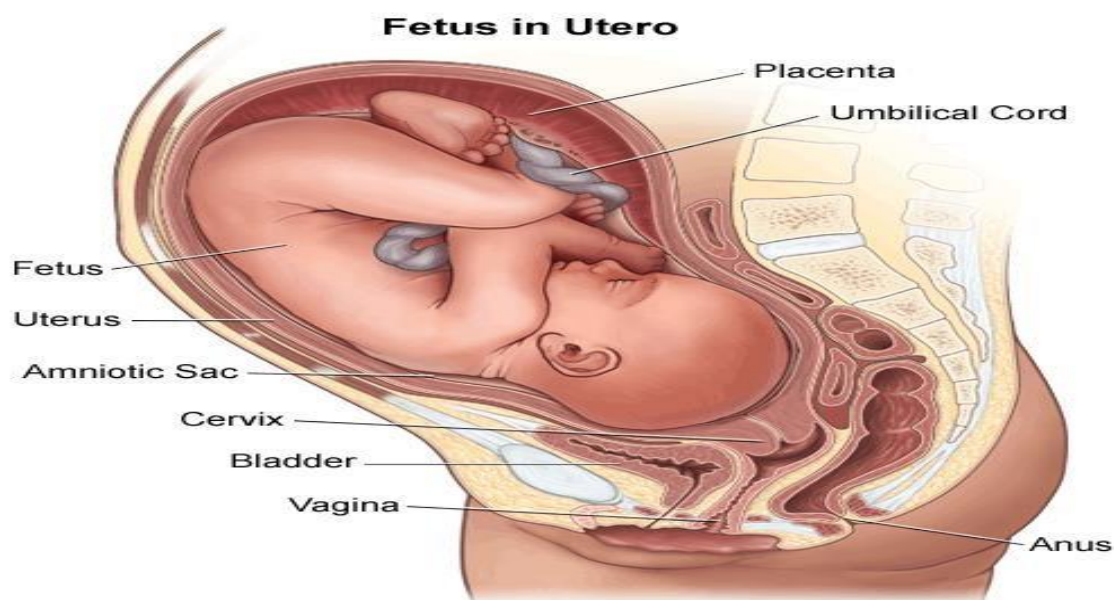


Figure 1-1 Anatomy of the fetus [2]

Reasons for the procedure:

Fetal heart rate monitoring is especially helpful for high-risk pregnancy conditions such as diabetes, high blood pressure, and problems with fetal growth [2]. Situations during labor which may affect the fetal heart rate and for which fetal heart rate monitoring may be used include [2]:

- uterine contractions
- pain medications and/or anesthetic agents given to the mother during labor
- procedures performed during labor
- pushing during the second stage of labor

Risks of the procedure:

There is no radiation used and generally no discomfort from the application of the transducer to the abdominal skin. The elastic belts that hold the ultrasound and pressure transducers in place around your abdomen may be slightly uncomfortable. These can be readjusted to help you feel more comfortable. You must lie still during some types of fetal heart rate monitoring. You may be required to stay in bed during labor [2]. Measurement and analysis of the fetal component in the abdominal recording is, in general, complex problem [6]. There are several reasons for this difficulty:

1. Electrical signals from the fetal heart, when measured at the mother's abdominal surface, are [6] : - very low in amplitude - often less than 10V.
2. -They may be weaker than myoelectric signals produced by movement of the mother, particularly during labor.
3. The strongest signal picked up at the maternal abdominal surface is the maternal electrocardiogram, which may be anywhere from 5 to 1000 times higher in amplitude than the fetal signal [6].
4. Researchers differ on whether or not the medium of electrical conduction of fetal signals to maternal abdominal electrodes should be considered even approximately homogeneous.
5. This complicates the analysis of the fetal electrocardiogram even if one can be measured [6].
6. Fetal positions in utero vary with time and from patient to patient. The location of the site of placentation (which may be responsible for at least part of the electrical conduction of fetal heart signals to the mother's abdominal surface) also varies across patients. a reliable abdominally obtained fetal electrocardiogram may be used to assess fetal heart rate variability in the antepartum period of gestation when it is not possible to obtain a fetal scalp lead electrocardiogram. Electronic instrumentation and computers are now being used in attempts to enhance and gather useful information from the abdominal fetal electrocardiogram [6].

Before the procedure:

1. Your physician will explain the procedure to you [2].
2. You may be asked to sign a consent form that gives your permission to do the procedure, The consent form for fetal heart rate monitoring may be included as part of the general consent for your labor and birth.[2].
3. you may be asked to eat a meal before the procedure, this can help increase fetal activity [2].
4. Although the gel applied to the skin during the procedure does not stain clothing, you may wish to wear older clothing or a hospital gown, as the gel may not be completely removed from your skin afterwards [2].

During the procedure:

1. Depending on the type of procedure, you may be asked to expose your abdomen,
<https://journal.silkroad-science.com/index.php/JMGCB> - 202

undress from the waist down, or undress completely and put on a hospital gown [2].

2. You will lie on your back on an examination table [2].
3. A clear gel will be applied to your abdomen (the gel acts as a conductor) [2].
4. The transducer will be pressed against the skin and moved around until the fetal heartbeat is located. You will be able to hear the sound of the fetal heart rate with Doppler or an electronic monitor [2].
5. During labor, the fetal heart rate may be monitored intermittently or continuously, depending on your condition and the condition of your fetus [2].
6. For continuous electronic monitoring, the transducer will be connected to the monitor with a cable. A wide elastic belt will be placed around your back to secure the transducer in place [2].
7. The fetal heart rate will be recorded in the medical record. With continuous electronic monitoring, the fetal heart pattern will be displayed on a computer screen and printed onto graph paper [2].
8. You may or may not be allowed to get out of bed with continuous external fetal heart rate monitoring [2].
9. Once the procedure has been completed, the transducer will be removed and the gel will be wiped off [2].

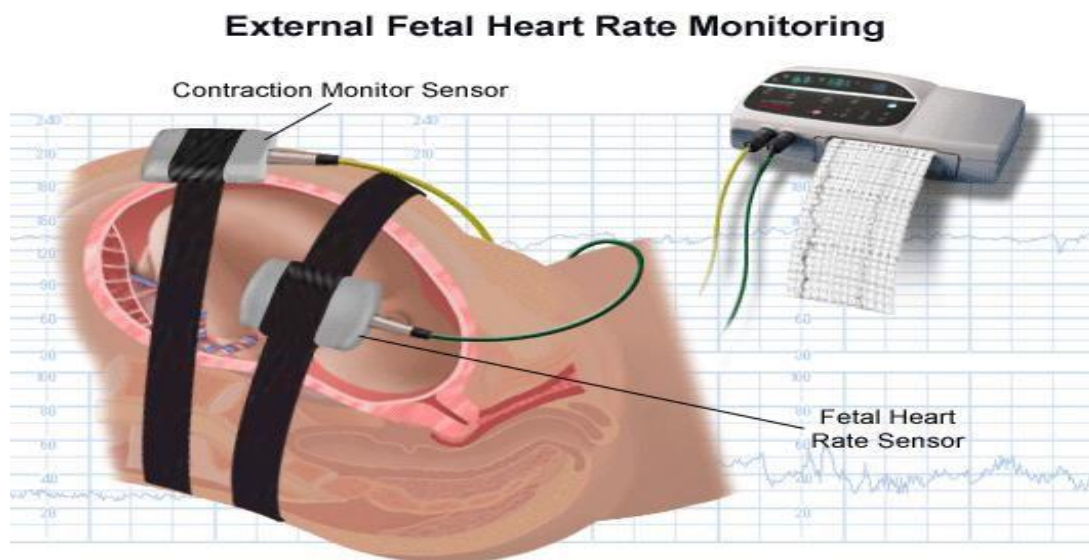


Figure 1-2: External fetal heart rate monitoring [2]

After the procedure:

There is no special type of care required after external fetal heart rate monitoring. You may resume your normal diet and activity unless your physician advises you differently [2].

Literature survey

approaches have been used. Longini et al. have described a computer algorithm that makes use of the fact that the maternal component in the abdominal recording can be estimated from near-orthogonal maternal ECG recordings obtained from the maternal chest [6].

Azevedo and Longini have described filtering methods for enhancing the fetal signals after removal of the maternal component, such as narrow band-pass filtering, local peak differencing, autoregressive filtering and matched filtering [6].

Bergveld et al. have described a different approach for suppressing the maternal ECG. Their technique is based on an optimization procedure applied to multiplication coefficients of six independent abdominal signals which are added together [6].

Bemmel has described a procedure for detecting weak fetal electrocardiograms based on band-pass filtering [6].

Autocorrelation techniques for detecting the fetal electrocardiogram have also been described by **Favret et al.** [6].

Ferrara and Widrow have demonstrated the use of time-sequenced adaptive filtering for enhancing the fetal signals in the abdominal ECG. Their method requires the use of two or more abdominal channels, and assumes that the noise in the abdominal recordings is uncorrelated between these channels [6].

Oldenberg et al. have extended the concept of adult vectorcardiography to abdominally obtained fetal electrocardiographic recordings [6].

Methods of the fetal heart rate monitoring:

An FHR Simulator (FHRS) designed and developed to be able to test the correct and accurate functionality of an FHR monitor the device consists of different elements, such as a power supply, a binary counter, a block of gates, an amplification stage, and an actuator, i.e., sided by a light panel indicator to monitor its specific state. The connections among all the elements are schematized in the block diagram reported in Figure 2-1,[3]

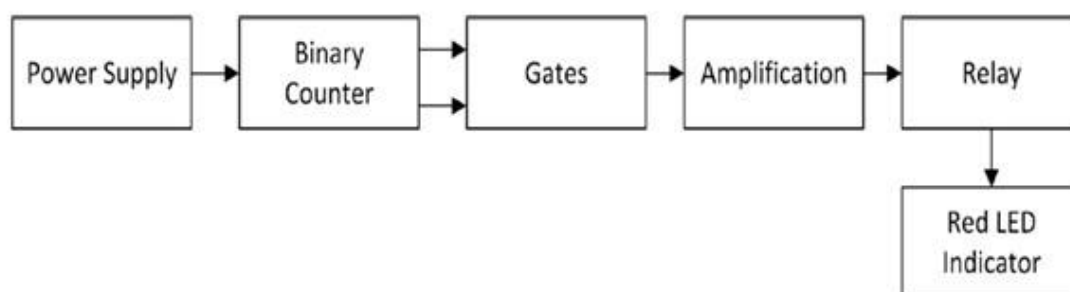


Figure 2-1 Block diagram of FHRS [3]

a binary counter is used as a frequency divider to obtain submultiples of two from a main driving clock of a 20-ms period (i.e., obtained from the 50-Hz AC power supply). In this way, it is possible to obtain, among all the possibilities, the two stable clocks

whose frequencies are used to drive the actuator in simulating the heartbeats occurrences. The accuracy in generating the periodic waveforms depends on the accuracy in counting the driving waveform pulse. the generated frequency accuracy depends on the driving waveform accuracy, that is related to the power supply. integrated circuit, consisting of **four two-input NAND gate** (i.e., four Schmitt trigger circuits), is used to combine the frequency divider output and to produce a signal that flips between the two frequencies: in this way, the simulation of the FHR frequency and the disturbing phenomena, which CTG must distinguish, is obtained. The resulting signal is amplified by a transistor without modifying its frequencies. Consequently, **the relay** driven by this signal, will switch according to its frequencies. **A red LED** has been added to the circuit to have a visible indicator light of the relay activations. The LED is placed parallel to the relay winding indicates tripping and protects the collector against overvoltage [3].

To test an FHR monitoring device, an ultrasound gel is placed on the relay and the probe of the device is positioned on it. In this way, the switching of the relay can be detected by the generated Doppler effect [3].

A transformer is used as power supply for the circuit. Then, a voltage stabilizer which produces a stable +5 V DC voltage from 12 V, is used to power the binary counter and the NAND gates IC. the 50 Hz signal is used to provide a frequency fixed signal to the binary counter, using a resistor to reduce the amplitude. A second power transistor is then used to activate the relay, which presents a low resistance. For the signal amplification, the two further transistors are used while a third one adopted for switching the relay. Components that were used in the design are wild spare electronic components. The Zener diode generates from 13.5 V AC impulses 5 V/ 0.5 V for all the counter excitations.to adjust the voltage for the different components and to proper condition the signal in the circuit, different resistors and capacitors are used. A three-way switch is employed as user interface. The astable flip-flop input part is realized with the combination 100-nF capacitor and 100 kohm resistance that produces impulses 60 ms width simulated chamber contraction time. This is time interval was confirmed by measures achieved during the test on the FHRS. when testing CTG, different signals can be used to test the device, such as a single frequency signals or a combination of both given by the gates, which as described are connected such that the two signals alternate. Thus, CTG and artifacts, which normally occur during the pregnancy observation, are simulated. Indeed, the CTG pregnant woman includes both the heart signal related to the fetus and the one related to the mother [3]. There are two methods for fetal heart rate monitoring, external and internal, In our research, we will discuss externally monitoring the fetal heart rate [2] .

External fetal heart rate monitoring:

This method uses a device to listen to or record the fetal heartbeat through the mother's abdomen. A fetoscope (a type of stethoscope) is the most basic type of external monitor. Another type of monitor is a hand-held electronic Doppler ultrasound device. These methods are often used during prenatal visits to count the fetal heart rate. A fetoscope or Doppler device may also be used to check the fetal heart rate at regular intervals during labor. Continuous electronic fetal heart monitoring may be used during labor and birth [2].

• How to perform an external examination?

An ultrasound transducer placed on the mother's abdomen conducts the sounds of the fetal heart to a computer. The rate and pattern of the fetal heart are displayed on the

computer screen and printed onto special graph paper [2].



Figure 2-2 External examination for fetal heart rate monitoring.

Types of external fetal heart rate monitoring:

-Doppler ultrasound

Doppler ultrasound refers to the use of a relatively focused ultrasound beam to determine the fetal heart rate. A weakly focused beam of ultrasound of around 1.5 MHz is used to insonate the fetal heart with the reflected ultrasound then detected within the same transducer [7]. The Doppler shift is the change in frequency of a wave for an object moving relative to the source of the waves. Thus, sound waves reflecting off moving tissue, such as the pulsing heart and coronary system will exhibit Doppler shift, whilst those reflected off stationary organs will not. The reflected sound waves that undergo Doppler shift are used to construct a time varying amplitude signal in which heart beats are evident as peaks. The monitor outputs the Doppler shift heart amplitude signal as an audible mono waveform through a headphone jack [5].

Monitoring FHR using Doppler ultrasound is a mature technology forming the basis of virtually all commercially available cardiotocographs. From the user's viewpoint many mothers find the transducer cumbersome and the belt used for attachment uncomfortable.

These factors, render the method unsuitable for long-term monitoring [7].

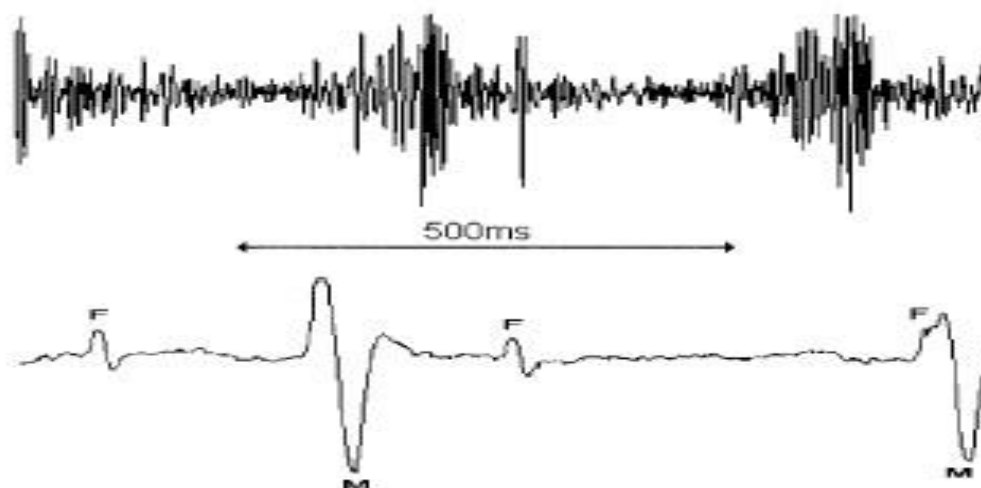


Figure 2-3 Simultaneously recorded Doppler audio (top) and transabdominal signals (which includes both maternal and fetal ECGs). Each fetal ECG is accompanied by a Doppler signal and this begins before the fetal QRS complex representing atrial activity.

-ultrasound M-mode analysis

Ultrasound M-mode analysis describes a technique in which a single ultrasound transection is plotted against time, thus allowing an estimation of cardiac time intervals. M-mode analysis allows an estimation of atrial and ventricular coordination, as well as an estimation of PR intervals. Atrial contraction is recognizable by the movement of the atrial wall towards the atrial septum or aortic root. Ventricular contraction is recognized by the opening of an arterial valve or the start of the ventricular wall movement towards the ventricular septum. Due to the technical difficulties encountered with fetal electrocardiography and through the years the inability to determine P-waves reliably, M mode analysis has become the, albeit limited, standard for assessment of fetal arrhythmias. Bradycardias, supraventricular tachycardias, extrasystolies are readily diagnosed with the aid of M-mode ultrasound but, as the images are often not easily read, it will always remain an indirect assessment of cardiac electrical activity [7].

-Fetal electrocardiogram

The fetal ECG obviously has the potential to provide FHR data with beat-to-beat accuracy. The major benefits of the fetal electrocardiogram: - it can provide unobtrusive, long-term, risk-free ambulatory monitoring via small recording units that are simple enough to be used for domiciliary monitoring by the mothers themselves [7].

Fetal electrocardiography involves the use of electrodes placed on the maternal abdomen to pick up the potential differences on the maternal body surface resulting from the currents flowing within the fetal heart. In essence, it is comparable to normal electrocardiography.

The fetal ECG is only of the order of around 10 μV , whilst the recorded signal always also contains the maternal ECG (of magnitude around 100 μV). Consequently, low noise amplifiers must be used to successfully detect the fetal ECG with its processing including a stage in which the maternal and fetal ECGs are separated [7].

That the fetal ECG could be detected has been known for many years. However, it

has yet to become accepted as a standard clinical technique, primarily because of the well documented fact that the signal cannot be detected reliably. This is due to many factors: The signal is small to begin with, can be buried within electromyographic noise from the abdominal muscles or other noise sources, is of variable size throughout gestation and usually becomes smaller around the 28th to 32nd weeks gestation due it is generally assumed to the insulating effect of the vernix caseosa which covers the fetus around this time [7].

The fact that acquisition of the fetal ECG cannot be guaranteed, together with its low quality for morphological analysis has led us to concentrate our efforts on the production of a 24-hour continuous fetal heart rate monitor. The unobtrusive nature of fetal ECG acquisition lends itself to long term domiciliary FHR monitoring, with our most recent 'Walkman' sized recorder allowing up to 24 hours of raw abdominal fetal ECG signal to be recorded on PCMCIA card for subsequent. Examples of FHR traces obtained from fetal ECG are shown in Figure 2-4 together with the simultaneously recorded Doppler ultrasound derived trace shown for comparison [7].

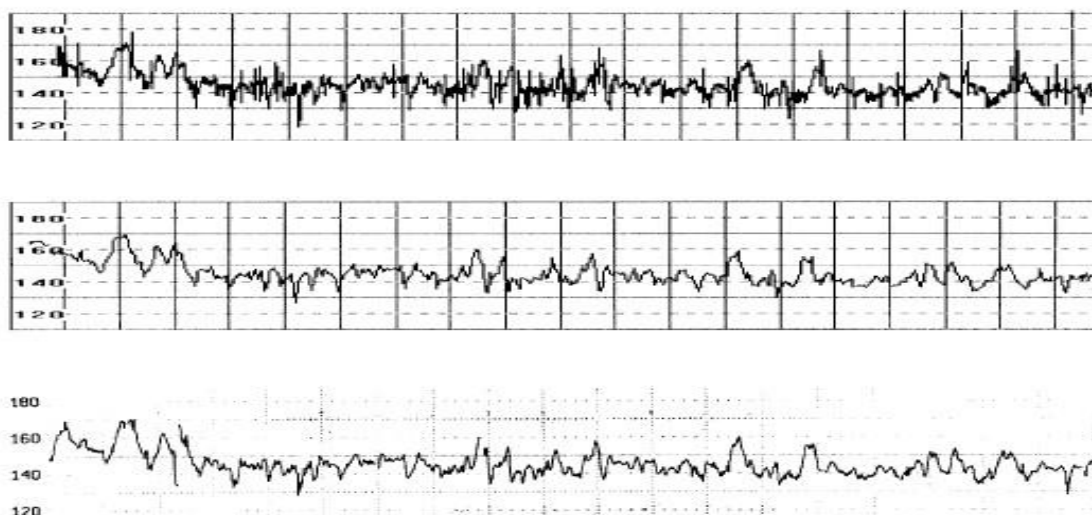
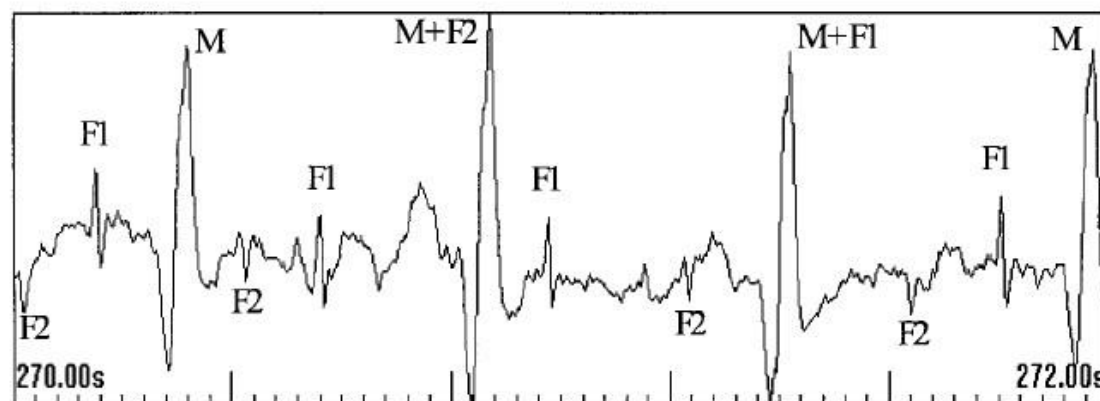


Figure 2-4 Minute heart rate trace obtained via the fetal ECG and displayed as both a beat-to-beat (top) and 2 second averaged (middle) record. Also shown (bottom) is the



heart rate obtained simultaneously using a Doppler ultrasound based fetal heart monitor.

Figure 2-5 Transabdominal signal recorded from a mother carrying twins. The

maternal ECG plus those from both twins are clearly visible. The differing morphology of the ECGs from the twins indicates clearly how the fetal ECG morphology is dependent upon fetal lie relative to electrode positioning.

-Fetal magnetocardiogram

The fetal magnetocardiogram (MCG) can be recorded reliably from the 20th week onward and can be used to classify arrhythmias such as heart blocks and atrial flutter. Moreover, it can be used to diagnose a prolonged QT-syndrome. The duration of the PR and RR intervals and that of the QRS-complex can be used to define what is normal. This opens the possibility to study fetuses with congenital heart diseases by means of fetal MCG [7]. The amplitudes of the various waves depend on the distance between the fetal heart and the position where the magnetic field is measured, and the electrical properties of the tissues surrounding the fetal heart. Since the distance to the fetal heart and conductivity distribution are unknown, as a consequence the amplitudes cannot be used for diagnostic purposes. This is also the case for the fetal ECG both ante-and intrapartum [7].

The disadvantage of fetal MCG is the size, cost and complexity of the instrumentation required [7]. Arrhythmic activity, including premature beats, conduction blocks and tachycardia have been reported to occur in 11 % of 60 otherwise normal pregnancies studied using the fetal MCG [7].

Fetal magnetocardiograms are recordings of the magnetic fields generated by the currents flowing within the fetal heart. These magnetic fields are extremely weak (10^{-12} tesla). By comparison, the magnetic field of the earth is a million times stronger (5×10^{-5} tesla). The only sensor that is sensitive enough to monitor such weak fields is a SQUID (superconductive quantum interference device) and currently these SQUIDs have to be cooled by liquid helium. In use the dewar containing the sensors and helium is held above the maternal abdomen. In case of a fetal MCG recording, the magnetic field measured at some distance from the maternal abdomen is subtracted from the magnetic field measured near the abdomen. This enhances the signal-to-noise ratio since the fetal signal is largest near the abdomen and is decreased at a greater distance whilst the noise is very much the same at both distances. Usually, a fetal MCG is measured within a magnetically shielded room although it has been shown that this is not a necessity. To acquire a signal in which the different stages of the depolarization and repolarization of the heart (the PQRS complex) the fetal heart signal can be averaged over a number of beats [7].

As fetal magnetocardiography provides cardiac waveforms of good quality, it is used for the detection of fetal cardiac conduction disorders. In addition, it provides help in acquiring a fetal ECG map on the maternal abdomen by providing a trigger, with which the fetal ECG can be averaged. Such a map may pinpoint a good measuring position for the fetal

ECG as well as providing insight into the fetal abdominal conduction pathways of the fetal ECG. An example of a simultaneous recording of fetal ECG and MCG is given in Figure 2-6 [7].

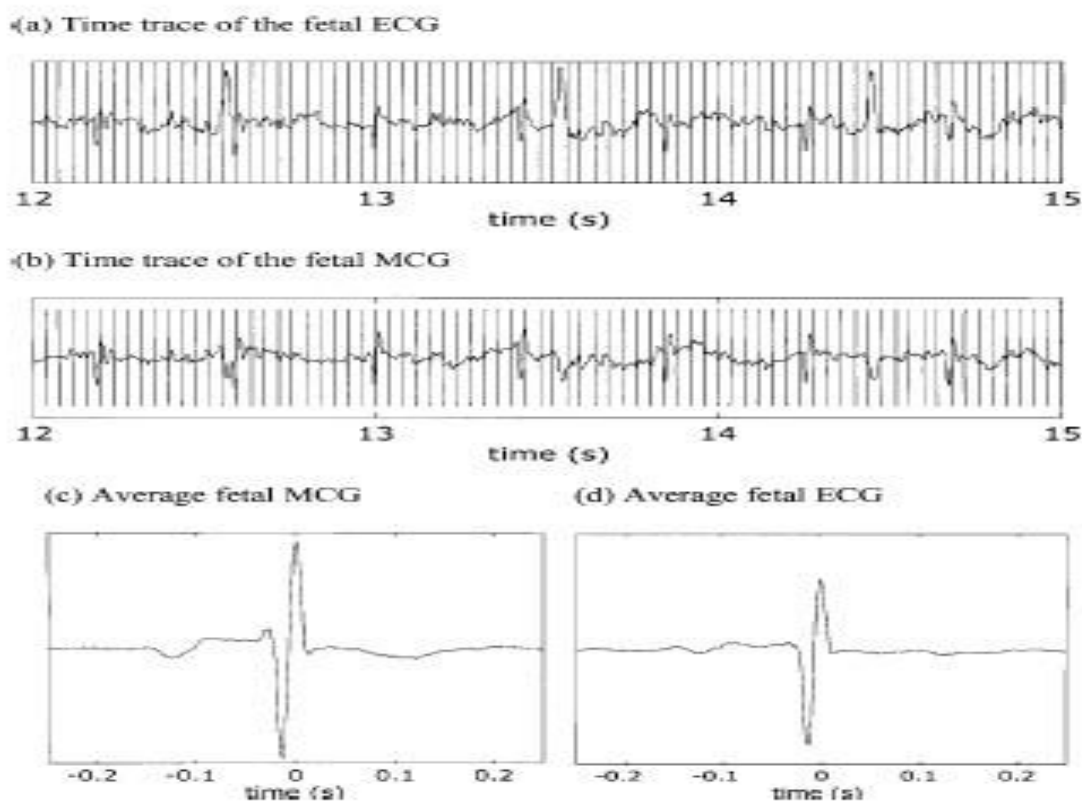


Figure 2-6 Simultaneous recording of fetal ECG and MCG and the average cardiac complexes of both fetal ECG and MCG.

The electric trace is the best of twenty ECG channels, whereas the fetal MCG signal is compromised by an increase of noise due to the simultaneous electric recording. In this case the fetal ECG is of excellent quality, however such a signal cannot be guaranteed and at times the fetal signal will be hardly recognizable. However, using an additional MCG channel as trigger, it proved to be possible to obtain a map of averaged fetal ECG waveforms in those cases as well. In figure 2-7 two fetal MCG recordings are shown the upper time trace recorded in the 36th week of gestation shows a premature atrial contraction (indicated by the arrow). As P-waves are identifiable in the MCG, the cause of arrhythmia could be localized to be of atrial origin. In the lower trace a fetal MCG of a twin pregnancy is shown (32 weeks of gestation), the R-peaks of both fetuses are seen [7].

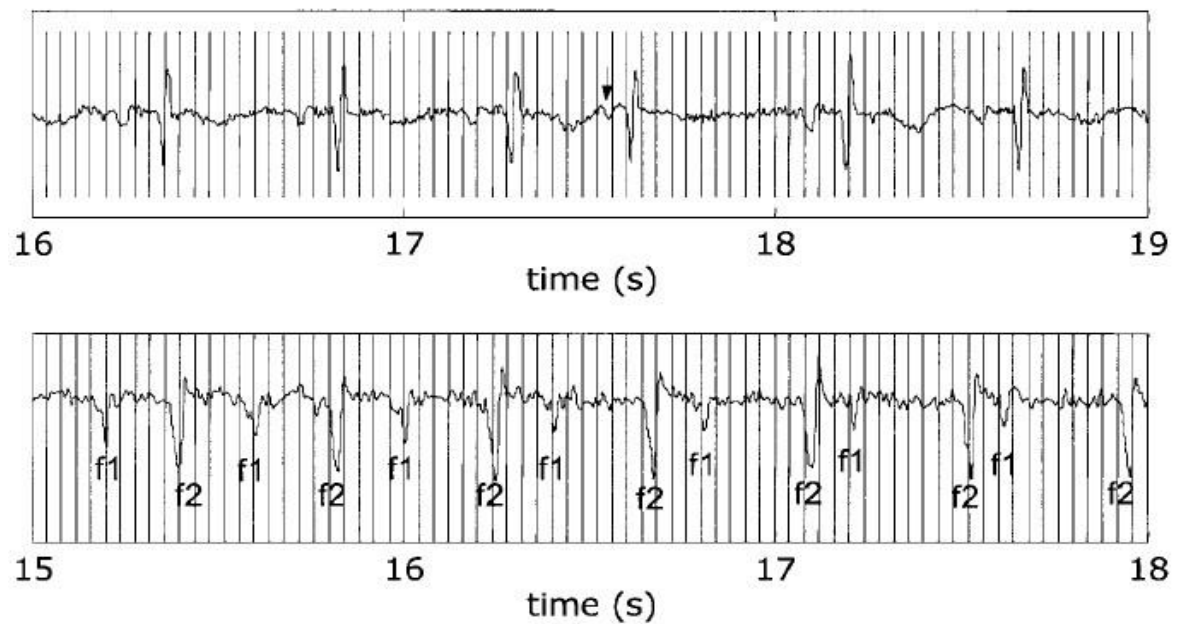


Figure 2-7 Two examples of fetal MCG. The upper trace shows a premature atrial contraction and the lower trace shows a twin pregnancy.

This illustrates like in fetal ECG that the amplitude and shape of the fetal MCG depend on the position of the pickup coil relative to the position of the fetal heart. At measuring positions that proved to be a good position for obtaining a fetal MCG of one of the twins, the trace of the other twin was hardly recognizable [7].

Recording procedure and data preprocessing:

The data are recorded using a Portis-32/ASD system. For the representation of the digitized values, we use 22 bits. The sampling frequency is 400 Hz [4].

The signals are recorded using the unipolar measurement and 12 electrodes are placed on the belly as given in Figure 2-8 [4].

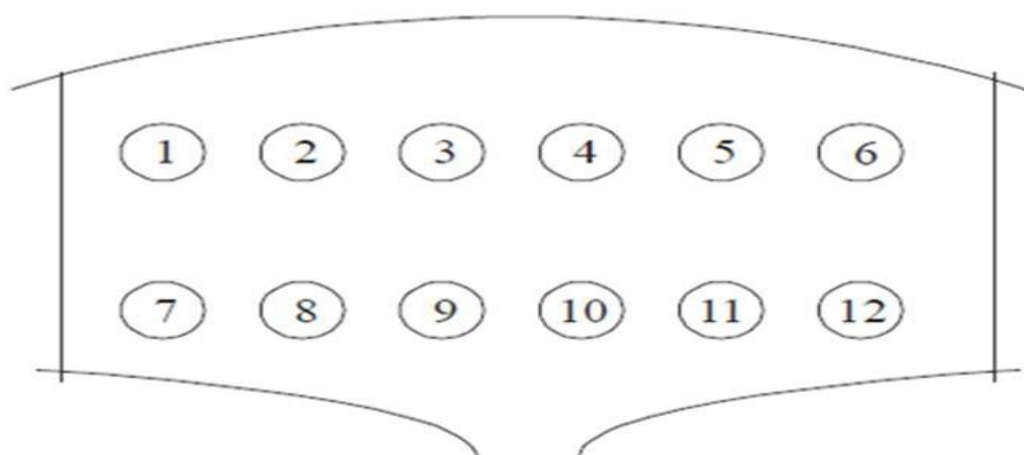
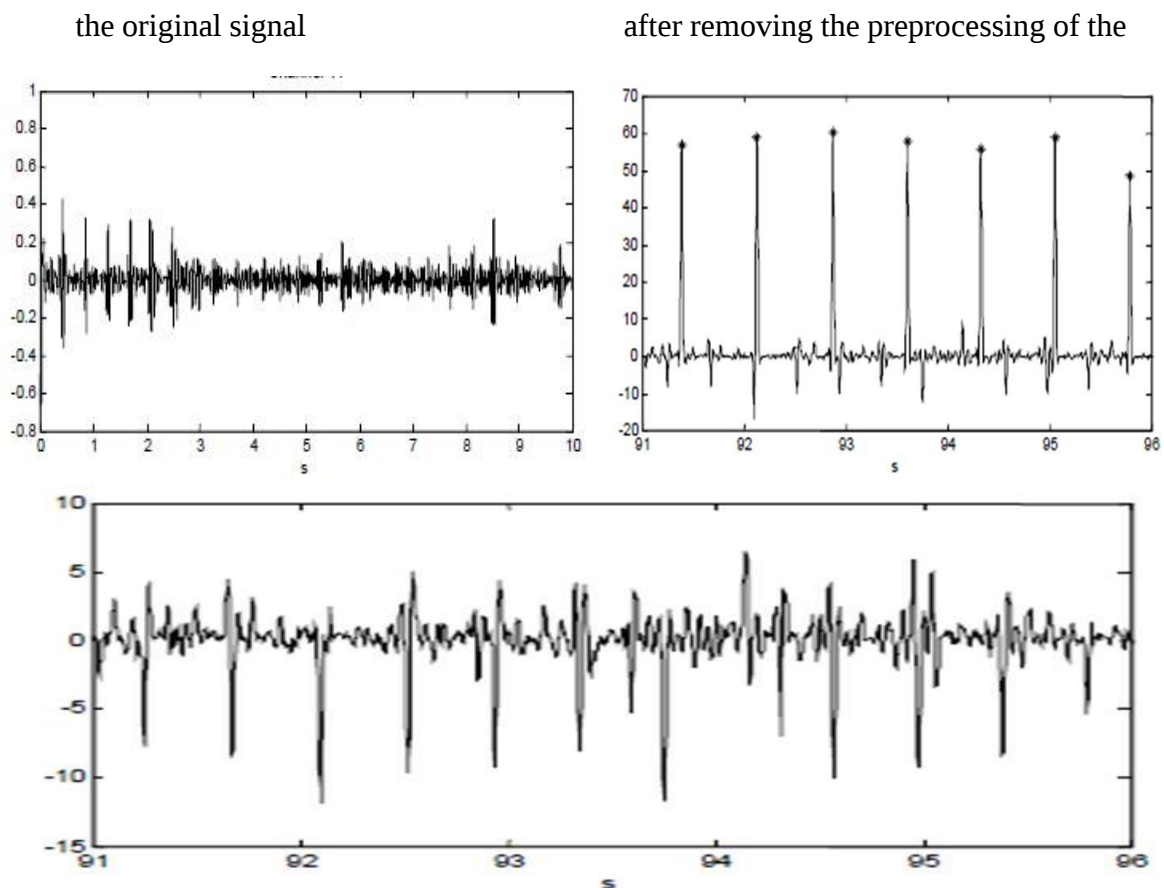


Figure 2-8 position of the electrodes

The recorded data are preprocessed in several steps in order to remove the power line interference, the baseline fluctuations, and the MECG [4].

- 1) A moving averaging with a window of 8 samples is performed to remove the 50 Hz power line interference [4].
- 2) In order to extract the fetal ECG, the baseline and the uterine contractions are approximated using a median filter with a window of 75 ms [4].
- 3) The P- and T-Wave of the MECG are also removed by this procedure [4].

The obtained signal contains information about MECG, FECG and random noise. The MECG is removed using a coherent averaging procedure, i.e., the averaged MECG segment is subtracted every time an R-Peak corresponding to the ECG of the mother is detected [4]. Due to the fact that the QRS complexes differ within the signal, an optimization is applied to the averaged template, so that the MECG subtraction from the abdominal channel is improved



abdominal signal

after removing the MECG

Figure 2-9: Signals obtained after removing the MECG in the original recorded signal and in the interpolated signal.

Fetal heart rate monitoring using smart phones:

A simple block diagram for the proposed system is given in Figure 2-10. The proposed system consists of two main components - a front-end application on the smart phone and a back-end system on a remote server [5].

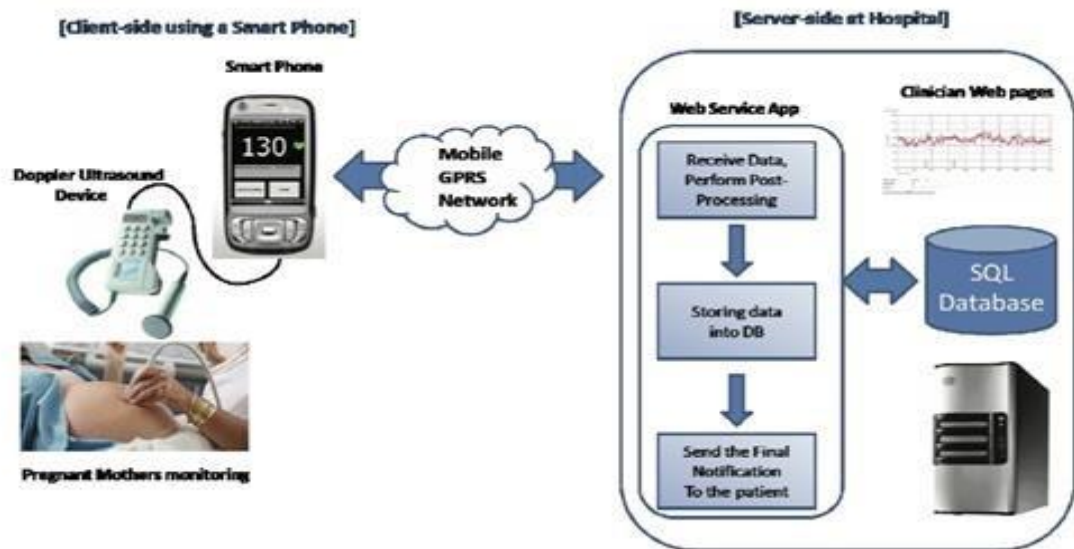


Figure 2-10: The system by using smart phone [5]

Smart phone:

During actual monitoring, a Doppler ultrasound signal from the Doppler device is fed into the in-built microphone (USB headset input) of the smart phone via an audio cable. Thus, the input Doppler signal is processed on the phone directly to estimate fetal heart rates using our application program. Figure 2-11 shows the Doppler Handheld device and the smart phone used for this research [5].

Figure 2-11 The FD2-P Doppler ultrasound device and the TyTN II smart phone.

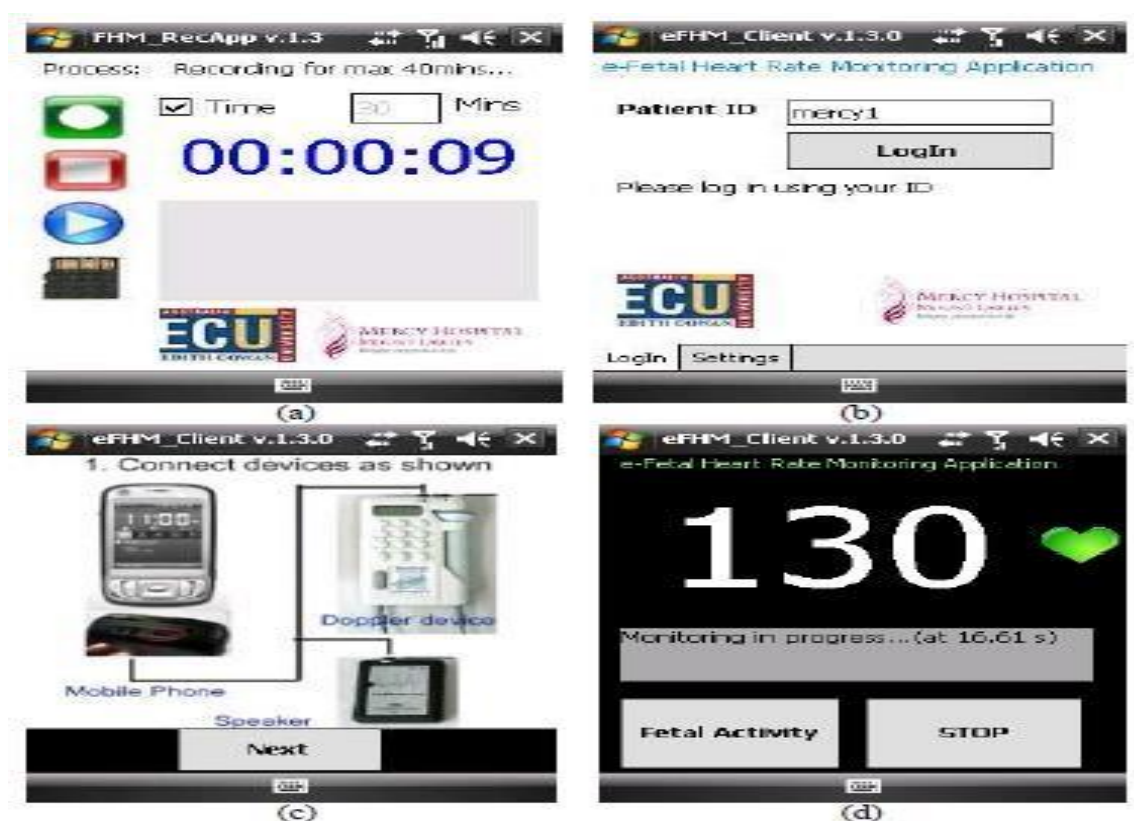


(Photo by Getty Images for Microsoft Research) [5]

• Implementation of smart phone:

The actual application for fetal heart monitoring was designed to be 'user friendly' for end users, such as pregnant mothers, so that they can monitor their pregnancy at home without assistance. Therefore, the user interface of our application is limited to several simple functionalities; a user log-in, fetal heart rate monitoring, fetal activity tracking, and data uploading to a back-end server. The application provides user-friendly interface with graphical instructions by illustrating images regarding how to set up the system and how to measure fetal heart rate. After displaying instructions, the actual fetal heart monitoring starts to estimate fetal heart rates. During monitoring, fetal activities can be recorded by pressing the fetal activity user-event button [5].

Figure 2-12: Screenshot images of developed applications. (a) The recording application to collect real fetal heart data. (b) Log-in of the e-Fetal Heart Rate Monitoring



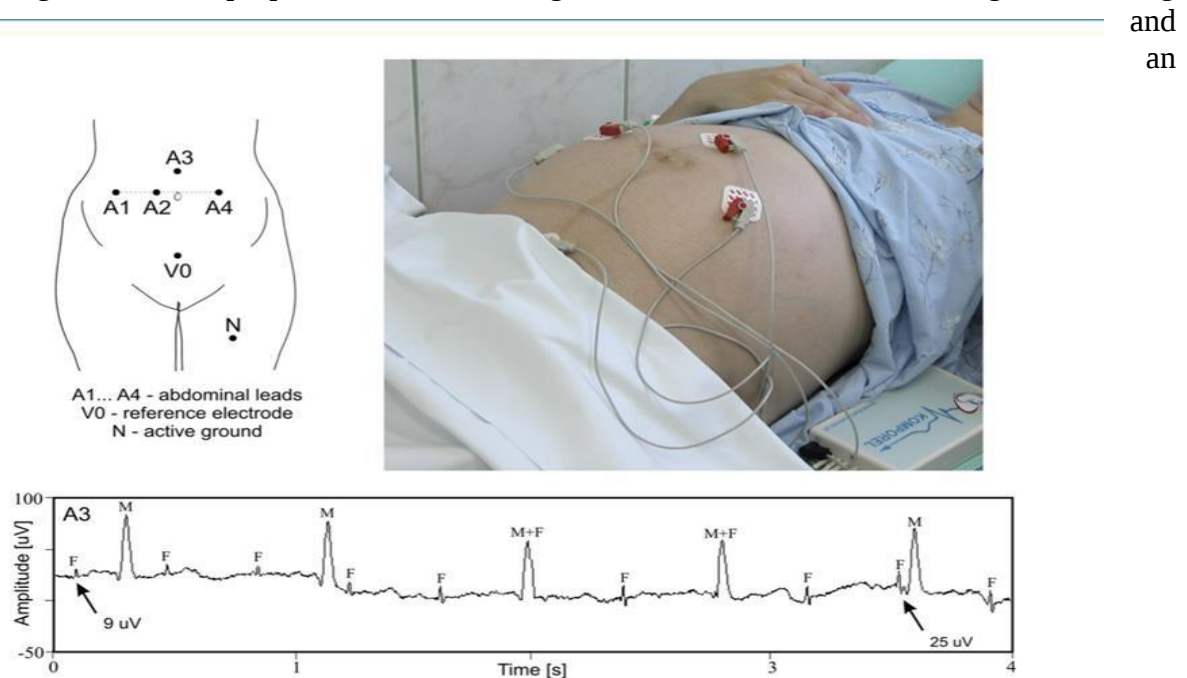
Application. (c) Graphical instructions for end-users after the log-in process. (d) Fetal heart monitoring using our application [5].

Results and Discussions:

Data collection

The developed instrumentation for recording signals was used to collect research material including four-channel records of bioelectrical fetal heart activity obtained from electrodes placed on the maternal abdominal wall. Pregnancy signals were recorded between the 32nd and 42nd week of pregnancy. Labour signals were obtained in an advanced stage of labour. They consisted of four-channel records of bioelectrical fetal heart activity from abdominal electrodes. Additionally, a direct FECG signal was recorded simultaneously from the fetal head. Labour was monitored between the 38th and 42nd week of gestation [1].

Figure 3-1: The proposed electrode configuration for the indirect FECG signal recording and an



example of a signal recorded on the maternal abdomen (M, F – QRS complexes, maternal and fetal, respectively) [1].

Recording protocol

The developed KOMPOREL System for monitoring the bioelectrical activity of a fetal heart was used for recordings. The system consists of a signal recorder module and a portable computer. The recorder module enables simultaneous acquisition of four signals from the maternal abdominal wall as well as one FECG signal directly from the fetal head (during advanced labour only). The recorder exhibits a low level of inherent noise (below 1 μV), a high value of common interference suppression factor (CMRR = 115 dB) and provides signal amplification from the level of several dozen microvolts to several volts. The amplifiers and filters ensure that the FECG band is obtained in the range from 0.05 to 150 Hz. Optionally, power line interferences can be additionally suppressed. If strong low frequency noise occurs, the cut-off frequency of the high-pass filter increases to 1 Hz. Moreover, the recorder module makes it possible to check the loss of electrode contact, mark fetal movements perceived by the mother, as well as control the charge level of the batteries [1].

The electrode configuration consists of four measuring electrodes A1 - A4, evenly placed around the patient's navel line. As a result, signals are recorded relative to one common reference

electrode V0 located above the pubic symphysis. Additionally, a common mode reference electrode N (with active-ground signal) is placed on the patient's left leg. Owing to the appropriate preparation of the abdominal skin removal of the upper stratum corneum of the epidermis) in the place of application of the measuring electrodes the level of muscle noise or slow-changing noise was significantly reduced. However, the recorded signals still exhibit low-frequency interferences caused by fetal and/or maternal movements, as well as by impedance changes between the measuring electrodes and maternal skin [1].

Data processing:

All abdominal signals, with sampling frequency of 500 Hz, were initially filtered to suppress power and slow-changing interferences. A simple filter with multiple notches, located every 50 Hz was used [1]:

$$H(z) = z^{-50} - \frac{1}{36} \left(\frac{1 - z^{-60}}{1 - z^{-10}} \right)^2$$

The first cutoff frequency is equal to approximately 5 Hz, which assures effective suppression of low frequency noise. The top-band between 45 Hz and 55 Hz results in successful elimination of the powerline interference. In the case of a direct FECG signal, the initial noise suppression was carried out in a similar way, with the filter parameters adjusted to the sampling frequency of 1 kHz [1].

Technical validation:

Direct FECG registration, due to its invasiveness and application limited only to the advanced labour stage, has not been widely used [1].

An alternative method is to record the FECG indirectly – from electrodes placed on the surface of the maternal abdomen. This method is non-invasive and can be used both during pregnancy and labour. The method cannot be applied on a wider scale owing to the poor quality of the FECG signal recorded in the presence of numerous interferences. Undoubtedly, the evaluation of its usefulness requires, above all, the effectiveness of the FQRS detection to be measured, which directly affects the continuity of FHR signal determination. It depends on the entire abdominal signal processing channel: interference filtering, maternal electrocardiogram suppression and FQRS complexes detection

Several different indicators have been defined to assess the effectiveness of the FQRS complex detection. The most objective ones are as follows: Performance Index (PI), Accuracy (Acc), Sensitivity (Se or S+), Positive Predictive Value (PPV or P+) and their harmonic mean F1 defined as follows [1] :

$$PI[\%] = \frac{N - FP - FN}{N} \cdot 100$$

where:

N – is the total number of the reference QRS complexes

TP – is the number of true positive detections (correctly identified)

FP – is the number of false positive detections (extra detected QRS complexes) FN – is the number of false negative detections (missed QRS complexes)

$$Acc[\%] = \frac{TP}{TP + FP + FN} \cdot 100$$

$$Se[\%] = \frac{TP}{TP + FN} \cdot 100$$

$$PPV[\%] = \frac{TP}{TP + FP} \cdot 100$$

$$F1[\%] = 2 \cdot \frac{PPV \cdot Se}{PPV + Se} = 2 \cdot \frac{TP}{2TP + FN + FP} \cdot 100$$

a comprehensive evaluation of non-adaptive FECG extraction methods based on the model of blind source separation by means of the Principal Component Analysis (PCA) and Independent Component Analysis (ICA). With the PCA method, the QRS detection efficiency for the labour dataset (B2) was F1 = 98.56% (Se = 98.27%, PPV = 98.86%, Acc

= 97.17%) while for ICA it amounted to F1 = 98.55% (Se = 98.23%, PPV = 98.87%, Acc = 97.13%) [1].

Conclusion

This project presents different methods and several analysis tools to fetal heart rate detection. FHR signals were recorded through CTG in normal and in intra uterine growth restricted (IUGR) fetuses, with the goal of demonstrating that fetal monitoring can be strongly improved by new analysis techniques and parameters related to pathophysiological fetal states. The work evidenced some important points. First, FHRV signal carries a lot of information about fetal condition during pregnancy and CTG, being the most employed technique supporting the diagnostic process along the final part of the pregnancy, and allows extracting this information through an accurate analysis. We tested time domain, frequency domain, and nonlinear approaches and results showed that time domain and nonlinear indices significantly separate the two groups allowing a clear classification. This is very important as early identification of IUGR condition allows proper intervention reducing life-threatening events.

Various cases were considered on the basis of this study, that is, those that do not require a precise estimate of the fetal heart rate and those for which accuracy is critical. The accuracy of fetal heart rate estimation in the first case is not important but the false negative rate should be as low as possible. For example, if the goal of a monitoring system is simply to verify that the fetal heart rate is in the normal range (110–160 bpm), very high accuracy is not needed. In this case, an error of estimation of 0.8 bpm is sufficient. Many computations showed that for an error of estimation of 0.8 bpm, a zero false negative rate in the zones when the rhythm is quasi-constant could be ensured. In the second case, an error of estimation of 0.25 bpm is required for a system in which the goal is not only to estimate the heart rate, but also to evaluate fetal wellbeing. It is important to note that this error of estimation was guaranteed for a quasi-constant heart rate. This is not a constraint for such a system, since the variability of fetal heart rate must be evaluated in these ranges to predict fetal distress.

In case of a fetal MCG recording, the magnetic field measured at some distance from the maternal abdomen is subtracted from the magnetic field measured near the abdomen. This enhances the signal-to-noise ratio since the fetal signal is largest near the abdomen and is decreased at a greater distance whilst the noise is very much the same at both distances.

Usually, a fetal MCG is measured within a magnetically shielded room, although it has been shown that this is not a necessity. To acquire a signal in which the different stages of the depolarization and repolarization of the heart the fetal heart signal can be averaged over a number of beats.

As fetal magnetocardiography provides cardiac waveforms of good quality, it is used for the detection of fetal cardiac conduction disorders. In addition, it provides help in acquiring a fetal ECG map on the maternal abdomen by providing a trigger, with which the fetal ECG can be averaged. Such a map may pinpoint a good measuring position for the fetal ECG as well as providing insight into the abdominal conduction pathways of the fetal ECG. The fetal ECG is of excellent quality; however, such a signal cannot be guaranteed and at times the fetal signal will be hardly recognizable

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