FETAL HEART RATE MONITORING DURING PREGNANCY FOR ASSESSING THE WELL-BEING OF THE FETUS

Muhammad Ibn Ibrahimy
Department of Electrical and Computer Engineering
International Islamic University Malaysia, 53100 KL, Malaysia
Email: ibrahimy@iium.edu.my

ABSTRACT

Long-term fetal heart rate (FHR) monitoring is necessary to ensure that any FHR abnormality, which may appear at any time during pregnancy and labor, can be detected. An ambulatory electrocardiogram (ECG) recorder employing three abdominal surface electrodes has been developed towards achieving such a monitoring. The difficulties encountered in determining the FHR from the maternal abdominal signal are mainly the interference due to the electromyogram and motion artifact, and relatively small amplitude of the fetal ECG compared to that of the maternal. Thus improvement to existing abdominal signal processing algorithm is necessary to increase the percentage of successful monitoring. A real-time algorithm has been developed for the simultaneous measurement of the fetal and maternal heart rates from the abdominal signal. The algorithm is based on digital filtering, adaptive thresholding, statistical properties in the time domain, and differencing of local maxima and minima. A filtering technique has been utilized in the proposed algorithm to extract the fetal signal from the maternal abdominal signal. This is an alternative to a previous method which subtracts the maternal complexes from the abdominal signal with a need to overcome the problem of matching a template to the complexes. The proposed algorithm is capable of continuous ambulatory FHR monitoring either off-line, by using recorded signals, or on-line by a clinician during antenatal examination. The performance of the algorithm has been evaluated of the heart rates tracing processed from the abdominal signals. The resulting average accuracy is 83% for the FHR detection. The detection of the FHR from the maternal abdominal signal by the developed algorithm has also been compared with a short-term monitoring commercial instrument IFM-500 for the assessment of the reliability of the algorithm. The performance achieved from the comparison shows non-significant differences of means, low error percentages and linear correlation coefficient. A portable system based on the developed algorithm has the potential for increased percentage of real-time FHR detection thus enabling successful long-term fetal monitoring.

Keywords: Fetal heart rate, electrocardiogram, long-term monitoring.

INTRODUCTION

The variations in the fetal heart rate (FHR) observed during pregnancy and labor has widely been used by clinicians to assess the well-being of the fetus (Crowe et al. 1997). Despite providing only an indirect measure of the fetal status, monitoring of FHR has been proven to be a useful diagnostic tool for the obstetrician. The physician can use the information contained in the FHR pattern to check whether the development of fetus is progressing as desired. FHR is usually found normal even for pregnant women with high risk of prematurity and miscarriage. FHR abnormalities may however occur at any time. The ability to perform long-term monitoring of the FHR would thus provide more information on the fetal condition.

Currently, efforts are being made to gain a better interpretation of the FHR patterns by researchers. It is widely believed that improvement in the predictive value of the FHR records could be achieved by introducing long-term monitoring (Brown & Patrick 1981). Research is also being carried out to identify the most appropriate timing for collecting FHR data from a pregnant woman. Such investigation would be facilitated by the availability of a suitable algorithm for a portable system capable of conducting long-term FHR monitoring and processing in real-time.

PHYSICAL AND TECHNICAL ASPECTS

The well-being of a fetus during pregnancy and labor is dependent upon sufficient perfusion and oxygen supplies to vital organs namely the central nervous system and the heart. FHR monitoring is based on the fact that variations in the fetal respiratory status are expected to have specific influence on the FHR patterns. The variations in the FHR are found to be under the complex influence of many physiological factors which include changes in the blood pressure and the oxygen tension (Wood & Dobbie 1989). Thus, FHR patterns have been used as indicators of the neurological function and oxygen availability of the fetus, and to some extent, its growth and maturity (Schifrin & Clement 1991).

Interpretation of FHR is the pivotal aspect of fetal monitoring. A baseline FHR range in between 110 and 150 beats per minute (BPM) is considered normal, while a rate below 110 BPM is termed bradycardia and a rate above 150 BPM is termed tachycardia (Schifrin 1990). Possible etiologic factors of tachycardia are fetal hypoxia, maternal fever, parasympathetic drugs and sympathetic drugs. Bradycardia of lesser than 110 BPM suggests fetal distress. FHR acceleration and deceleration are a rise and fall of the FHR respectively, lasting less than 10 minutes either in connection with uterine contraction (periodically) or independently (sporadically). Changes of FHR for a duration of greater than 15 minutes are considered baseline changes. Baseline rate is elevated with maternal anxiety, maternal fever or immaturity of the fetus.

A non-invasive procedure would allow physicians to obtain heart rate and other electrophysiological information throughout the pregnancy without rupturing the membranes. From this information, the status of the fetus can be determined similar to the invasive procedure. Electrodes placed on the maternal abdomen can pick up the fetal ECG complex but the signals are generally very weak. The signal amplitude is at most 60 μV and can often be less than 10 μV (Behrer et al. 1968). At this level, the fetal ECG can be lost in a sufficiently high level of electrical noise. Thus the major disadvantage with the technique is that the acquisition of the fetal ECG cannot be guaranteed and often has a very low signal to noise ratio. A typical abdominal fetal electrocardiogram is shown in Figure 1 along with a direct fetal electrocardiogram taken from a scalp electrode and the maternal electrocardiogram taken from a chest lead. In the abdominal ECG, fetal heart beats are indicated by F and maternal heart beats by M.

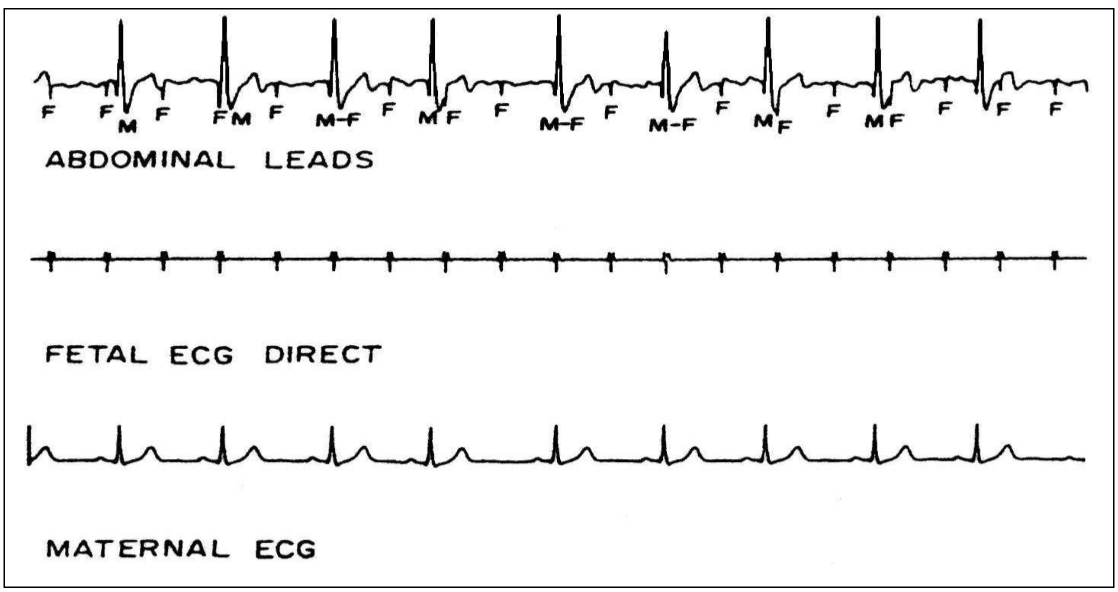

Figure 1: An example of an abdominal ECG obtained from maternal abdomen

The overall objective of this research is to lay down the groundwork for a good quality, simplified signal processing algorithm that may lead to an efficient ambulatory FHR monitoring system. At this end, we look at the basics required for such algorithm having the real-time extraction ability of the fetal and maternal heart rates. To develop this approach the following specifications have been taken into account:

- Able to process the single-lead abdominal signal and continuously detect both the maternal and fetal R waves for the measurement of the MHR and FHR respectively.
- Able to perform long-term (e.g. 24 hours) monitoring of the fetal condition during pregnancy and labor in presence of motion artifacts and interferences.

- Effective in resolving the FHR when the fetal R wave and that of maternal are overlapped.
- Capable of running either off-line, using recorded signals, or on-line by a clinician during antenatal examination.
- Have the possibility of greater accuracy than that of the previous methods in measurement of both the FHR and MHR.
- Cost-effective implementation of the algorithm in actual use for long-term monitoring.

ALGORITHM DEVELOPMENT

A QRS detection algorithm has been developed with the ability to process a single-lead abdominal signal by using filtering in the frequency domain to identify maternal and fetal ECG. Two sets of digital filters are used for the detection by utilizing the basic characteristics of the ECG. The incoming signal is first passed through a digital bandpass filter (cut-off 10 & 40 Hz) for reducing the power line interference, baseline drift, muscle noise and motion artifacts so that both maternal and fetal R waves are enhanced. The maternal QRS complexes are then detected by thresholding the maxima of the matched filter output and an updated maternal ECG template is formed from successively detected maternal ECG complexes using the R peak as the fiducial point. This point is also used to make an average to reduce the maternal contribution from the first digital-filtered abdominal signal. The remaining signal is then passed through another bandpass filter (cut-off 30 & 40 Hz) to enhance the fetal QRS complexes.

A flowchart of the algorithm is as shown in Figure 2. The figure shows two almost similar sets of operations used to enhance and then detect the maternal and fetal QRS complexes respectively. The detection of maternal QRS is performed by cross-correlating the signal with an average template which is first formed in an initial routine and then continuously updated with the detection of acceptable R peaks. The differencing of local maxima and minima routine is used for the detection of fetal QRS complexes with 2 sec delay in the fetal R wave search operation. The threshold used in the detection is first set up in the initial routine and then adapted based on the running average of the signal as compared to the running average of the noise. The search interval for the detection is limited on the basis of the averages of previous RR intervals.

To test the possibility of performing in real-time, the program was written using PIC17C44 microcontroller assembly language instruction and designed for operation with 500Hz sampling frequency. The real-time processing requirement is met by implementing the intensive processing routines over a number of sampling intervals.

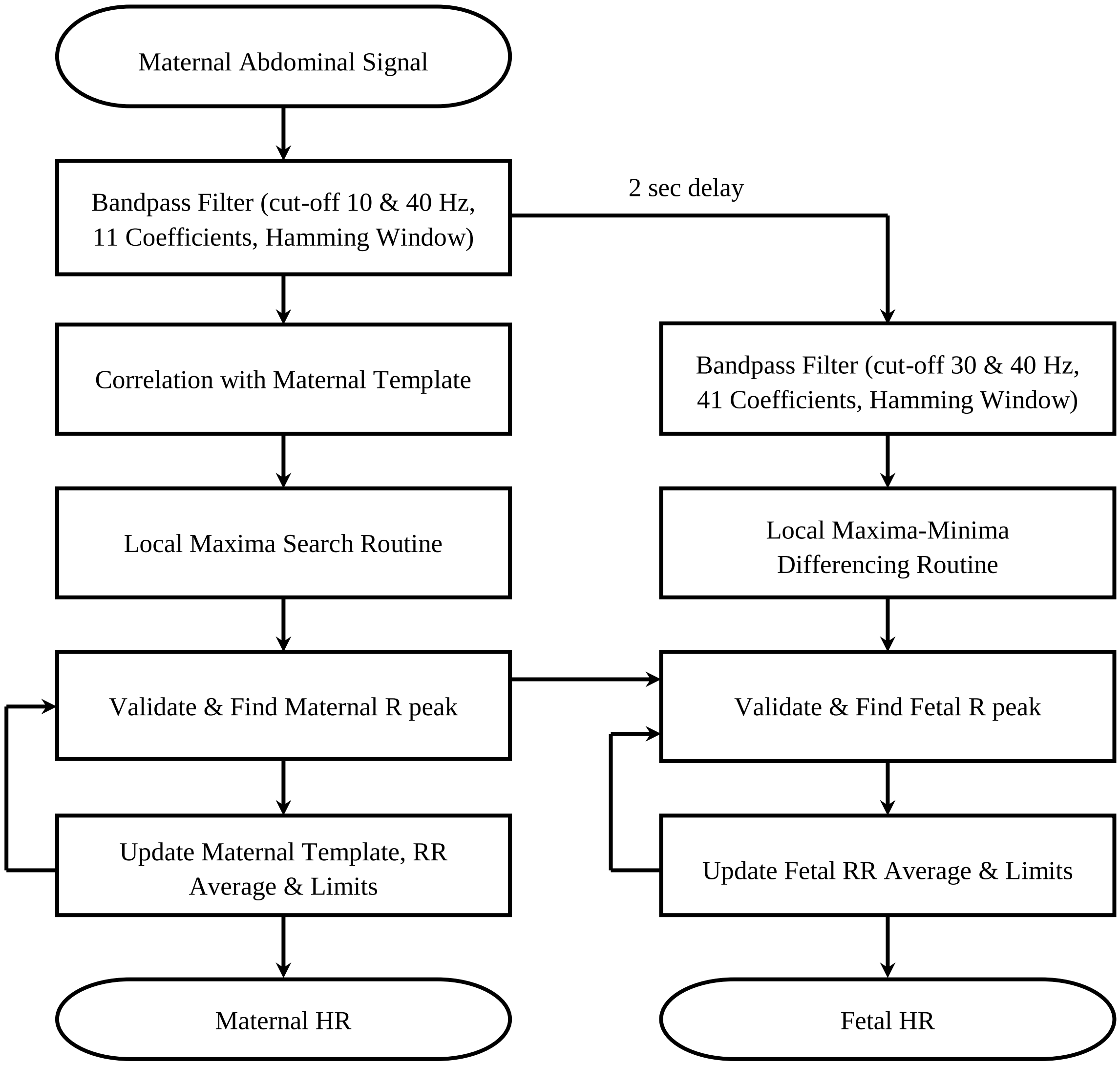

Figure 2: Flowchart of the algorithm

A microcontroller-based system is constructed to test the real-time capability of the developed algorithm required to extract FHR and MHR from the abdominal signal of pregnant women. First, the abdominal signal sensed by the single pair of electrodes is amplified and digitized. Then the digitized data is received by the microcontroller and subsequently processed for detecting the R peaks of both the fetal ECG and the maternal ECG to measure the RR intervals. Both fetal and maternal RR intervals are then stored in the external RAM and downloaded into a PC through an RS232 interface for analysis.

RESULTS AND DISCUSSION

The performance of the program based on the developed algorithm has been tested using the recorded abdominal ECG data containing different signals conditions and has also been compared with a short-term monitoring commercial instrument IFM-500 for the assessment of the reliability of the algorithm. A summary of the statistical comparison between 4,164 heartbeats, derived from both techniques, is shown in Table 1. Since the statistical comparison showed non-significant differences of means, low error percentages (3.31 % - 6.63 %) and linear correlation coefficient from 0.84 to 0.93, it can be concluded that the proposed algorithm of the developed system to detect the FHR from the maternal abdominal signal gives reliable values even with the simple processing methods used for easy implementation.

Table 1: Statistical analysis of the FHR measured from the IFM-500 Fetal Monitor and the PIC17C44 microcontroller board

Patient	Week of Gestation	Valid Heartbeat No.	MEAN ± SD (RANGE)		PRD (%)	LINEAR REGRESSION		
			IFM-500 (BPM)	PIC17C44 (BPM)		Slope	Intercept	Correlation Coefficient
M	35	862	151.4 ± 6.4 (140-169)	152.7 ± 7.9 (104-202)	6.63	0.68	48.40	0.84
N	36	995	148.7 ± 5.5 (136-168)	145.4 ± 6.9 (126-169)	3.82	0.86	20.64	0.93
O	38	840	145.7 ± 7.3 (132-166)	147.9 ± 6.8 (122-161)	5.81	0.91	12.03	0.92
P	39	550	136.2 ± 3.2 (130-147)	134.3 ± 4.6 (125-147)	3.31	0.78	29.42	0.86
Q	40	917	141.0 ± 6.4 (119-162)	143.6 ± 7.7 (126-187)	6.48	0.94	8.26	0.89

The FHR and MHR detection performance results, P4F and P4M respectively, of the thirteen data are listed in Table 2. The performances for the MHR traces are better because the patients in these cases were all at rest. However, slightly lower performances for J (36 and 37 weeks), K (37 weeks) and L (38 weeks) are attributed to the presence of large noise in some parts of the signal. The performances for the FHR traces are more or less good for all patients resulting in an average accuracy of 83 % (min. 68 %) for detecting the fetal heart rate. In early cases, weeks 36 and 37 of patients J and K have relatively poor performances. Some section of the signals did have high noise levels or small fetal complexes.

Table 2: Performance of the program on-line

Patient	Week of Gestation	Performances (%)	
		P4M	P4F
J	36	94.61	68.40
J	37	93.79	77.41
J	38	99.05	81.93
J	39	99.00	95.82
K	37	85.94	69.62
L	38	92.24	73.59
L	39	98.09	89.33
L	40	99.29	96.41
M	35	98.94	79.26
N	36	99.16	92.59
O	38	99.05	93.82
P	39	98.24	78.16
Q	40	98.99	83.62

The performances achieved for the heart rate measurements from the abdominal data show that both rates can be successfully extracted during 35 weeks of gestation to labor. The fetal complexes have to be consistently present above the worst noise level sufficient for detection by the adaptive threshold after being match-filtered. The ratio of the fetal R peak to that of the maternal must not too be low to avoid having to eliminate large maternal complexes. Their sizes must also not be comparable to allow for the proper detection of the maternal R peak. The above conditions are usually possible during the later weeks of gestation and sometimes during the earlier weeks as well.

With maternal activity, the above conditions will degrade accordingly and the continued success of the fetal R peak detection will depend on its average size. The noise involved with vigorous movement will also affect the MHR and in this case correct detection of the fetal R peak will not be possible. However, the algorithm has been designed to be able to resume correct detection when the signal to noise ratio improves. The only restriction of the algorithm in this respect is that the signal must be reasonably clean to start with to enable the initial routines. The use of the clinical data produced more results of the algorithm’s capabilities and showed its ability to measure heart rates over longer duration with the signal directly acquired from the abdomen.

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