ELSEVIER

A portable recorder for long-term fetal heart rate monitoring

Firoz Ahmed[a,*], Muhammad I. Ibrahimy, Mohd Alauddin Mohd Ali, Edmond Zahedi[b]

[a]*Department of Electrical and Electronic Engineering, University of Tenaga Nasional, 43009 Kajang, Selangor, Malaysia*
[b]*Department of Electrical and Electronic Engineering, National University of Malaysia, 43006 UKM, Selangor, Malaysia*

Abstract

A PIC17C44 microcontroller development board and a real-time algorithm were developed with the capability of monitoring the fetal heart rate (FHR) as well as recording both the FHR and maternal heart rate for long-term. This paper describes the development of the microcontroller board and implementation of a real-time algorithm which were used to develop the portable recorder. Two set-up were developed. One setup was used to implement the algorithm in the PIC17C44 microcontroller board. Second set-up was developed for the assessment of the reliability of processed heart rates. A large number of clinical tests have shown the very good performance of the developed monitor in comparison with FHR curves simultaneously recorded with IFM-500 Doppler ultrasound fetal monitor. Statistical comparison was done and showed nonsignificant difference in mean ($p = 0.05$), correlation coefficient ($r = 0.8–0.92$) and low PRD (5–15). © 2002 Published by Elsevier Science B.V.

Keywords: Fetal heart rate; Fetal electrocardiogram; Portable; Fetal monitoring

1. Introduction

In order to diagnose variation in the Fetal heart rate (FTR) such as caused by fetal hypoxia, continuous FHR monitoring is recommended. However, the FHR is normal (120–150 beat per minute (BPM)) most of the time even for pregnant women with high risk of prematurity and miscarriage. Studies have shown that a home monitor combined with more patient awareness and more intensive nursing contact will reduce the incidence of prematurity and miscarriage [1,2]. These women can maintain normal daily activities at home as well as work, avoiding unnecessary hospital stay, with the use of 24 h monitoring of FHR. Portable FHR monitors have been developed, some using Doppler ultrasound [3]. For long-term monitoring, a system based on abdominal fetal electrocardiogram (FECG) is found to be the most appropriate because of Doppler ultrasound's sensitivity to movement making it unsuitable for long-term ambulatory monitoring [4]. Many methods have also been proposed for extracting the fetal QRS complexes from the abdominal electrocardiogram (AECG) signal. The straightforward approach employs averaging, digital filtering, spectrum analysis and autocorrelation analysis [5–7]. The above methods have proven inaccurate

for the very low signal to noise ratio (SNR) of the FECG. The techniques based purely on frequency spectrum are less successful due to some overlapping of the frequency contents of the maternal and fetal QRS complexes [8]. The most current methods for FECG detection and enhancement are the orthogonal basis, adaptive filtering and linear combination methods [9]. All these methods require at least eight electrodes which would not be comfortable to patients for long-term monitoring. Another new method is to extract the FECG from composite AECG by using wavelet transform [10]. But the computation time in this method is very long so that it is not possible to implement it in real-time.

The fetal complexes have been successfully enhanced by matched filtering techniques [11] to determine the FHR. This involves firstly cross correlating the AECG signal with the maternal electrocardiogram (MECG) template to enhance the MECG detection. Taking a few significant points on the QRS template alleviates this time consuming process [12]. Following MECG suppression, the fetal QRS complexes in the subtracted signal are enhanced by another cross correlation routine. A large number of QRS detection schemes have been developed for the adult ECG signal which has a better SNR. The algorithm based on amplitude and slope discrimination are most immune to muscle noise [13]. The performance of this algorithm was further
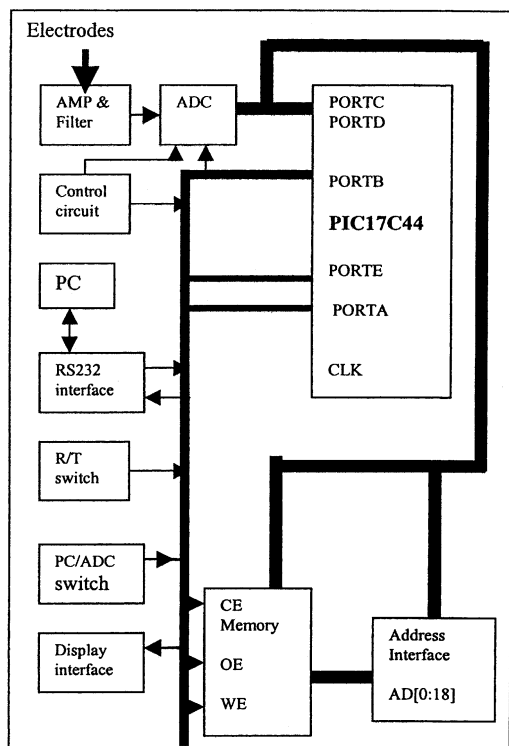
Fig. 1. Block diagram of the PIC17C44 microcontroller board.

Fig. 2. The memory map.

improved by the use of adaptive thresholds [14]. These schemes can be incorporated for the detection of both the maternal and fetal QRS complexes in the cross-correlated signal. A portable recorder based on the FECG system has been developed, capable of monitoring the FHR and recording of both the FHR and the maternal heart rate (MHR) for long-term. It uses only three skin electrodes to sense the signal from the abdomen of pregnant women. The recorder is based on low power PIC17C44 microcontroller board and a real-time algorithm. This paper presents the development of the microcontroller board, implementation of the algorithm and the resultant FHR and MHR.

2. Hardware development

The microcontroller board has been developed for a portable FHR and MHR recorder using the PIC17C44 microcontroller, which is capable of detecting the fetal and maternal QRS complexes for measuring the FHR and MHR in real-time. The FHR can be displayed on the liquid crystal display (LCD) and the maternal and fetal RR intervals can be stored in the memory of the microcontroller board up 24 h. The recorded RR intervals are downloaded to a PC through an RS232 interface circuit for measuring and analysing both the FHR and MHR. The block diagram of the PIC17C44 microcontroller development board is as shown in Fig. 1.

The hardware of the board and algorithm are developed so that the signal can be received either from the PC or the

analogue-to-digital converter (ADC). The hardware accommodates the PIC17C44 microcontroller chip, address interface, SRAMs, ADC circuit, amplifier circuit, power supply circuit, RS232 interface circuit and display interface circuit. The system uses 7 of the 8 I/O pins of PORTB which are available on the PIC17C44 chip for interfacing to peripheral devices and are correspondingly numbered in the figure as PB0 to PB7. A control circuit is used to clock and control the PIC17C44 chip and the ADC. PORTC and PORTD of the PIC17C44 are multiplexed address/data bus. These ports are used as a 16 bits data bus and lower 16 bits address of 19 bit address bus. PORTE is used for higher three bits address of the 19 bits address bus. PORTA is a 6-bit wide latch. The PA0/INT pin is used as an external interrupt, which is activated by the control circuit, when the ADC data is ready. PA1 is connected to a switch of control circuit which control the recording and transferring of the signal. PA2 and PA3 are connected to data terminal ready (DTR) of an RS232 port of the PC and ADC/PC switch of the control circuit, respectively.

The amplifier circuit consists of a low power, high-accuracy instrumentation amplifier chip (INA102) and a precision dual OP amp chip (TLC277C) which are operated from a ± 5 V supply. The circuit consists of an Intersil ICL7660S voltage converter configured to provide -5 V supply to the amplifier and ADC circuits, and a Phillips PCF1251P micropower voltage detector designed to light up an LED when the battery voltage falls below 4.4 V. The circuit is connected to four AA batteries in series supplying a nominal voltage of about 6 V. Four alkaline-manganese primary batteries are enough to operate the recorder up to 34 h. The national semiconductor ADC 1225 is used to convert the amplifier output into a digital data. It is a 12-bit plus sign and has the lowest power consumption. The ADC is clocked at 1 MHz which is supplied by the control circuit. The sampling clock of 500 Hz is provided by the programmable crystal oscillator of base frequency is 1 MHz. The sampling clock is also used to interrupt the PIC17C44. The PIC17C44 chip interrupt enable is positive edge triggered and this will cause a branch to an interrupt service routine.

The external memory is required to store the fetal and maternal RR intervals so that both the heart rates can be downloaded for further analysis. The ADC output is also stored in the memory of 8 s for notch and match filtering. Currently, the 128×16 Kbit static RAM is used, which is

```
{The Listing of Signal Proceesing  Algorithm}

     Set_system_Parameters;
     Set_data-Memory_address_label;
     START
          If_Selection_Record
          Then_GOTO_Record
          OR_GOTO_Transmitt;
     Record
          Initialise_Processor   ;
          Set_Constant;
          Set_External_memory;
          Set_Initial_Templates;
          Wait_For_First_Data;
          Search_First_Peak;
          Update_MQRS_Template;
          Search_First_Peak;
          Find_First_Maternal_R;
          Set_Maternal_Thresshold;
          Search_Maternal_R;
          Validate_&_Save_RR_Interval;
          Set_Maternal_Threshold;
          Set_Maternal_RR_Limits;
          Set_MECG_Template;
     Loop
          Search_Maternal _R;
          Validate_&_Save_RR_Interval;
           Average_Subtract_MECG_Template;
          GOTO    Loop;
     END
     Transmitt
          Initalise_Processor;
          Transmitt_RR_Intervals_To_PC;
           When_End_Data;
          END.
```

Fig. 3. The listing of the signal processing algorithm for the measurement of the RR intervals.

sufficient for operation and storage with the fetal and maternal RR intervals of about 10 h. The memory map is as shown in Fig. 2.

3. Software development

The AECG signal is sensed from the abdomen of pregnant women by using three surface electrodes. It is amplified by an amplifier with an analogue band-pass filter of 10–40 Hz of the development board. The signal is then digitised by a 12-bit ADC with a 500 Hz sample frequency. The band-pass filter reduces the influence of muscle noise, 50 Hz power line interference, baseline wander and T-wave interference. The digitised signal is then received by the PIC17C44 microcontroller for processing to measure the heart rates by using the real-time algorithm. The algorithm is written in PIC17C44 assembly language instructions. It detects the maternal QRS complexes by thresholding the maxima of the matched filter output and a MECG template is then formed from the detected MECG complexes using the R peak as the fiducial point. This point is used to align the subtraction of a scaled version of the template of the MECG from the AECG signal. The remaining signal is then match-filtered to enhance the fetal QRS complexes. The following sections present the implementation of the signal processing algorithm by using the PIC17C44 microcontroller board.

3.1. Signal processing algorithm

The signal processing algorithm, as listed in Fig. 3, consists of the initialisation procedures, procedures to search for the maternal R wave, validate and save the maternal RR interval, and average and subtract the maternal template. The initialise routine clears the processor data memory and select the recorder mode of operation. The algorithm then waits to receive the data either from the PC or the ADC, depending on the setting made before running the algorithm. During each sampling interval within these procedures, the receive data, cross-correlation and local maximum search routines are performed.

The initialisation procedure to detect the fetal signal commences after the first subtraction of the maternal complex. The cross-correlation and local maximum search routines are also performed during each sampling interval. Section 3.2 presents the brief description of the algorithm.

3.2. The cross correlation routine

The cross-correlation between the signal x and s is given by

$$y(n) = \sum_{k=0}^{N} h(k)x(n-k) \tag{1}$$

where

$$h(k) = \begin{cases} s(N-k), & 0 \le k \le N \\ 0, & elsewhere \end{cases}$$

The template is represented by $s(k)$ which has a duration of $(N+1)$ samples where $N = 8$ and 5 for the maternal and fetal templates, respectively.

Eq. (1) is implemented by storing and updating the template in a set of data memories in the PIC17C44 microcontroller and copying the respective multiplicand signal values from the external memory into another set of data memories.

3.3. The local maxima search

This routine first measure the slope of the matched filter output by

$$y'(n) = y(n) - y(n-1) \tag{2}$$

and assumes a maximum at sample $(n-1)$ when the slope changes from $y'(n-1) \ge 0$ to $y'(n) < 0$. This sample value and instant are saved as the local maximum if no larger maximum is found in the subsequent 20 ms of samples. This duration is assumed minimum fetal QRS duration [14]. The local maximum search routines are implemented separately for the maternal and fetal R waves.

3.4. Maternal R wave search

In the initial stage, the detection of the maternal R waves begins after 80 ms sample exclusion. The maternal sample count is initialised and the local maximum search routine is performed on the cross-correlation output of each sample for 1.024 s. The largest maximum value is then compared to an initial threshold (10 µV) and it is repeated for another 1.024 s if the threshold is not exceeded. The maximum value is assumed to be a maternal R peak if the threshold is exceeded. The initial correlation template is updated from the external memory of the controller board. The search routine is then repeated for 1.024 s to detect the most recent R peak. A routine is performed to decide the most recent R peak if the two R peaks are detected during the above search and taken as the first R wave. The threshold is then updated as

$$\text{th1} = \frac{V_s - V_n}{4} + V_n \tag{3}$$

where V_s and V_n are the signal and noise value, respectively.

This threshold is used to search the subsequent R wave. When the second R wave is found, the validate and save maternal RR interval procedure is performed. Then the MECG complex, associated with the second R wave, is copied from the external memory to its MECG template section. This template is of fixed duration, 160 ms before and 320 ms after the R peak instant. Finally, the thresholds are automatically adjusted to float over the noise and the search interval limits are calculated based on the method proposed by Pan and Tompkins [13]. Then the routine to detect the next peak is performed. The local maximum is checked with the first threshold and the validate and save maternal RR interval routine is performed if exceeded. If not exceeded, the local maximum is checked with the second threshold if the maximum search limit is reached. The program branches to signal loss subroutine if the local maximum is less than the second threshold before repeating the search routine for searching the next peak.

3.5. The procedure to average and subtract the MECG template

The subtraction of the MECG template from the abdominal signal is a very critical procedure since any slight shift in the subtracting template will produce residuals that obscure the fetal complex and may cause serious difficulties in fetal QRS detection. Care is taken to subtract the MECG template by fine aligning the peaks. The MECG template is matched with actual MECG in the abdominal signal by scaling it with the factor,

$$K = \sqrt{\frac{\text{Value1}}{\text{Value2}}} \tag{4}$$

where Value1 < Value2. These values are obtained from the cross-correlation of abdominal signal with maternal template and auto correlation of the maternal template. The square root is executed by the Newton–Raphson method. If the cross-correlation value is greater than the auto correlation value, then the abdominal signal is multiplied by the factor K and MECG template is subtracted, if not, MECG template is multiplied by factor K and subtracted from the abdominal ECG signal. The subtracted signal is stored into a rotating buffer of the external memory of the development board at the same address. In this routine, the MECG template and maternal template are updated by averaging the abdominal signal sample with the template sample using the Eq. (5) with $B = 32$.

$$A(b) = \{1 - k(b)\}A(b - 1) + k(b)C(b) \tag{5}$$

where

$$k(b) = \begin{cases} \dfrac{1}{b}, & b \leq B \\[2mm] \dfrac{1}{B}, & b > B \end{cases}.$$

3.6. Fetal R wave search routine

The cross-correlation of the subtracted signal with the initial fetal QRS template begins when the time marker limit which is initiated at the second accepted maternal R peak reaches 2.56 s. At the initial phase, the local maximum search routine is performed twice, similar to the maternal search routine. The search interval is 640 ms so that at least two fetal R peaks are found by assuming that the FHR does not exceed 187 BPM during the initial search routine. The search is repeated if the largest local maximum is coincident with a maternal QRS complex and the second largest maximum is small or is also coincident. The fetal and maternal QRS complexes are coincident if,

$$|t_f - t_m| < 64 \text{ ms} \tag{6}$$

where t_f and t_m are the fetal and maternal R peak instants, respectively. The range in Eq. (6) accounts for possible overlap of the two complexes which are assumed to have widths of 50 and 80 ms, respectively. The overlap is checked by relating the fetal R peak instant to the four latest maternal RR intervals which are maintained in the program. Once the first fetal R wave is established, the fetal QRS template is updated and the threshold is set similar to the maternal section. Finally, the next peak detection routine is performed in a similar way to the maternal R wave where two thresholds are used. When the second fetal R wave is detected the validate and save fetal RR interval routine is performed.

4. Results and discussion

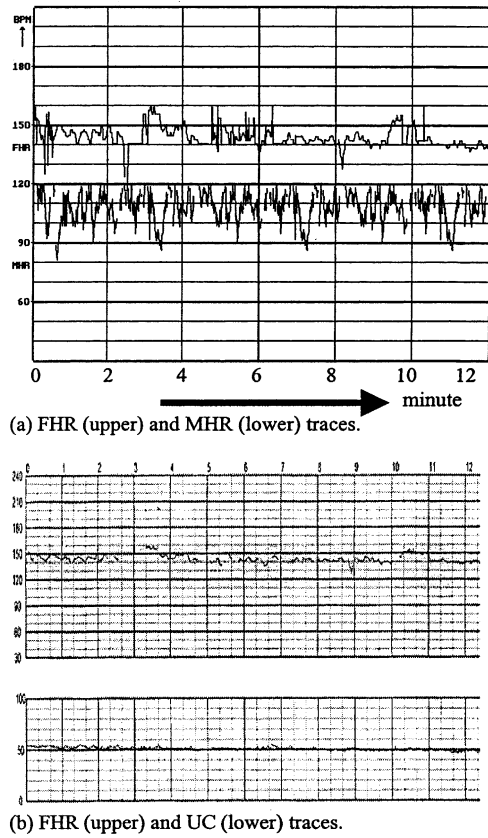The success of the portable recorder depends on the

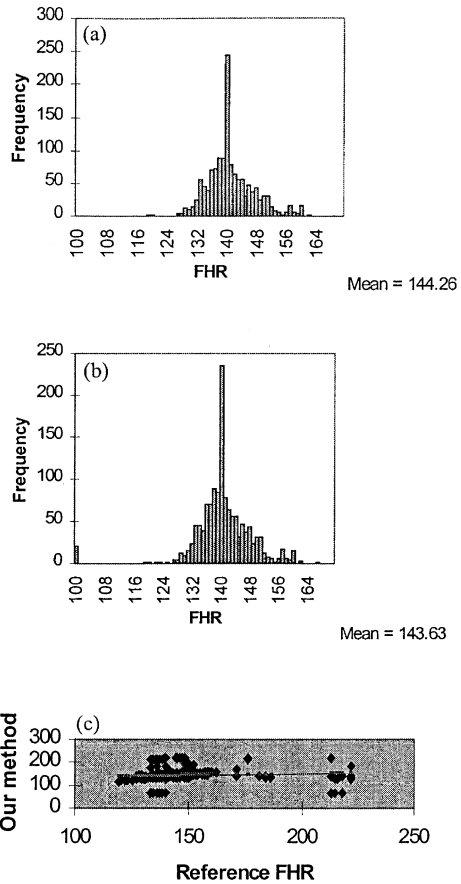Fig. 4. Traces from one patient (31 weeks) using simultaneously (a) portable recorder (b) IFM-500 Ultrasound fetal monitor.

Fig. 5. Histogram of FHR using (a) IFM-500 Ultrasound fetal monitor (b) Portable recorder and (c) Regression line between two methods.

ability of the algorithm to process the abdominal signal and continuously detect both the maternal and fetal QRS complexes for the measurement of the heart rates. The algorithm is written using the PIC17C44 assembly language instructions and debugged and assembled by using MPLAB integrated development environment (IDE) [15]. The object code is stored in internal EPROM of the PIC17C44 microcontroller. The power consumption by the recorder and using four AA size alkaline-manganese batteries, it is possible to operate the recorder al least 34 h.

The AECG signal which were recorded by using the portable signal recorder is received from the PC and both the calculated fetal and maternal RR interval are recorded into external memory. The AECG signal is received from the PC so that the detection of R peak by the algorithm could be compared with manual detection. The RR intervals are downloaded to the PC by using the RS232 interface, which

is included in the development board. The receiving and downloading software are also developed using the C++ language. The developed system has also been tested in the hospital by recording the heart rates from ten patients. A setup has also been developed for the assessment of the reliability of processed FHR by using the developed system. IFM-500 ultrasound fetal monitor [16] is used to record the FHR simultaneously with developed recorder for statistical comparison. Ten recordings have been done and analysed. The analysis consisted in the visual comparison of the FECG FHR curves with the measured ultrasound FHR diagram. Visual comparison is shown in Fig. 4. The histogram and regression lines are also given in Fig. 5 for graphical comparison. A summary of the statistical comparison between FHR, derived from both techniques, is shown in Table 1. The linear regression is used to signify the results with 95% confidence level ($p = 0.05$). Percentage RMS difference (PRD) [17] is also given to assess the developed system.

5. Conclusion

In an effort to develop a portable device for the long-term monitoring and recording of FHR and MHR, a system based

Table 1
Statistical analysis of beat to beat (RR) intervals

PRD	Linear regression		
5.054–15.79	Slope 0.126–0.74	Intercept 33–150	Correlation coefficient 0.78–0.92

on the abdominal FECG method was found to be the most appropriate. In order to extract both the fetal and maternal RR interval to measure the heart rates from the abdominal signal, a portable recorder has been developed. In most cases, good MHR traces were obtained by using the system. Successful measurement of the fetal RR intervals by the recorder depends on the consistency of the appearance of the fetal complexes above the noise level. Using the developed system, good FHR and MHR traces were obtained from abdominal signals with comparatively large fetal complexes designing the use of only two electrodes. This is desirable from the stand point of real-time long-term monitoring of the FHRs.

References

[1] M. Katz, P.J. Gill, R.B. Newman, Detection of pattern of uterine activity in labor by ambulatory monitoring, American Journal of Obstetric and Gynaecology 68 (1986) 773–778.

[2] J.D. James, F.F. Johnson, R.W. O'Shaughnessy, L.C. West, A prospective random trial of home uterine activity monitoring in pregnancies at increased risk of preterm labor, American Journal of Obstetric and Gynaecology 159 (1988) 595–603.

[3] M. Murakami, Y. Chiba, H. Horio, Y. Dawashima, A new system of home monitoring for fetal health care, Journal of Maternal–Fetal Investigation 2 (1992) 195–198.

[4] J.A. Crowe, A. Harrison, B.R. Hayers-Gill, The feasibility of long-term fetal heart rate monitoring in the home environment using maternal abdominal electrodes, Journal of Physiological Measurement 16 (1995) 149–152.

[5] W. Creoles, M. Restivo, M.A. Assadt, N. El-Sherif, Criteria for optimal averaging of cardiac signal, Journal of Biomedical Engineering, BME 33 (1986) 957–966.

[6] V.D. Sani, D. Maulik, Computerised detection of low-level fetal signals in the maternal abdominal electrocardiogram, Computers in Biology and Medicine 15 (1985) 81–93.

[7] P. Bergveld, A.J. Kolling, J.H.J. Peuscher, Real-time fetal ECG recording, IEEE Transactions on Biomedical Engineering 33 (1985) 505–508.

[8] J.H. Bemmel, W.H. Vander, Detection procedure to represent, IEEE Transactions on Biomedical Engineering 13 (1966) 175–182.

[9] S.L. Horner, W.M. Holls, P.B. Crilly, A robust real-time algorithm for enhancing a non-invasive fetal electrocardiogram, Digital Signal Processing: A Review Journal 5 (1995) 184–194.

[10] J.H. Nagel, Progress in fetal monitoring by improve data acquisition, IEEE Engineering Medical and Biological Magazine 3 (1984) 9–13.

[11] M.A. Mohd Ali, Development of a portable fetal and maternal heart rate recorder, PhD Thesis, Nottingham University, UK, 1994, p. 112.

[12] G.M. Friesen, A comparison of the noise sensitivity of nine QRS detection algorithm, IEEE Transactions on Biomedical Engineering 37 (1990) 85–98.

[13] J. Pan, W.J. Tompkins, A real time QRS detection algorithm, IEEE Transactions on Biomedical Engineering 32 (1985) 230–235.

[14] M.L. Lamkee, H.W. Huntington, R.R. Alvarez, Fetal electrocadiography: a study of the normal recording, American Journal of Obstetric and Gynaecology 83 (1962) 1622–1628.

[15] Microchip, MPLAB IDE, Simulator, Editor User's Guide, 1996.

[16] IFM-500 Doppler Ultrasound Fetal Monitoring System.

[17] R.G. Lee, H.S. Chen, J.H. Chen, Home telecare system using cable-television plants—an experimental field, IEEE Transaction on Information Technology in Biomedicine 4 (2000) 44.