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Fetal R-Wave Detection in the Ambulatory Monitoring of Maternal Abdominal Signal

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ABSTRACT

An algorithm for the real-time measurement of the fetal and maternal R-R intervals from a single-lead abdominal signal has been developed on a low power TMS32010 digital signal processor development system. The algorithm is based on a combination and modification of earlier techniques which have been proposed to perform similar processing. The performance of the algorithm is improved by the incorporation of validation procedures which enable the algorithm to continue operation despite temporary data loss during maternal movement. The reliability of the R-wave detection is determined from information tagged to the measured R-R intervals indicating the signal condition at the time of detection. These tags are then used as a basis for error correction and the measurement of the algorithm performance. The performance achieved from tests on active pregnant women shows the possibility of implementing the above system for ambulatory use.

ABSTRAK

Sebuah algoritma untuk mengukur dalam masa nyata selang R-R bagi janin dan ibu daripada isyarat perut ibu yang diperolehi melalui dawai tunggal telah direka bentuk dengan menggunakan sistem pengembangan pemproses isyarat digit TMS32010 yang berkuasa rendah. Reka bentuk itu diasaskan kepada gabungan dan pengubahsuaian teknik-teknik terdahulu yang telah dicadangkan untuk pemprosesan yang serupa. Prestasi algoritma ini telah diperbaiki dengan menambah prosedur pengesahan yang membolehkannya meneruskan pengendalian walaupun terdapat kehilangan sementara data semasa pergerakan ibu. Keboleharapan pengesanan gelombang R ditentukan daripada maklumat yang ditanda pada selang R-R yang diukur bagi mencerminkan keadaan isyarat semasa pengesanan dibuat. Tanda-tanda itu dijadikan rujukan dalam pembetulan ralat dan pengukuran prestasi algoritma tersebut. Prestasi yang diperolehi daripada ujian terhadap wanita hamil yang aktif menunjukkan kemungkinan sistem di atas digunakan semasa berjalan-jalan.

INTRODUCTION

Information from the monitoring of fetal heart rate (FHR) during pregnancy has been used by clinicians to assess the well being of the fetus. During this monitoring, the expectant mother is required to be in the recumbent position and limit her activity. More information on the fetal condition would be available with long term monitoring which requires the ability to continuously obtain FHR data from active pregnant women [1]. The FHR may be processed from either phonocardiograph, Doppler ultrasound or electrocardiograph (ECG) signal. The abdominal ECG technique would be the most suitable in a portable system for ambulatory use provided that difficulties associated with weak signal voltage could be overcome [2].

Efforts to extend the optimal conditions for FHR measurements by the abdominal ECG method include the determination of the optimum lead system and the development of better signal processing techniques. The signal processing algorithm attempts to improve whatever signal is available from the abdominal leads while a suitable lead system may increase the chances of obtaining a good signal from the fetal heart. For the production of a reliable fetal heart trigger in long term monitoring, the lead system requires at least eight electrodes to guarantee a clear fetal ECG (FECG) signal and an adequate suppression of the maternal ECG (MECG) [3]. By an appropriate choice of electrode locations on the maternal abdomen and thorax, and using the singular value decomposition (SVD) technique, an on-line algorithm has been developed to simultaneously eliminate the MECG and detect an optimal fetal heart signal [4]. However, the use of fewer electrodes would be necessary for a comfortable monitoring environment at the expense of a reduction in the reliability of fetal R-wave detection.

This paper describes a real-time algorithm for the detection of the fetal and maternal R-waves in signal acquired via only three surface electrodes on the maternal abdomen. The algorithm uses adaptive thresholding schemes and validation procedures to improve the reliability of the R-R interval measurements. The validation procedure involves tagging of the intervals when measured from noisy signals to signify the degree of confidence on the resulting FHR data. A postprocessing software was also developed to implement correction schemes on the FHR and maternal heart rate (MHR) traces and quantitatively evaluate them based on the above tags.

ABDOMINAL SIGNAL

An example of the desired abdominal signal is given in Figure 1 showing the maternal and fetal QRS complexes which have been enhanced by filtering between 8 and 40 Hz. These complexes are the Q, R and S waves of the ECG signals. The maternal signal with a maximum possible amplitude of 1 mV [5] is generally considerably larger than the fetal signal. The fetal signal amplitude is at most 60 μV and can often be less than 10 μV [6]. At this level, the fetal complexes can be lost in a sufficiently high level of electrical noise. After filtering, the main sources of interference are motion

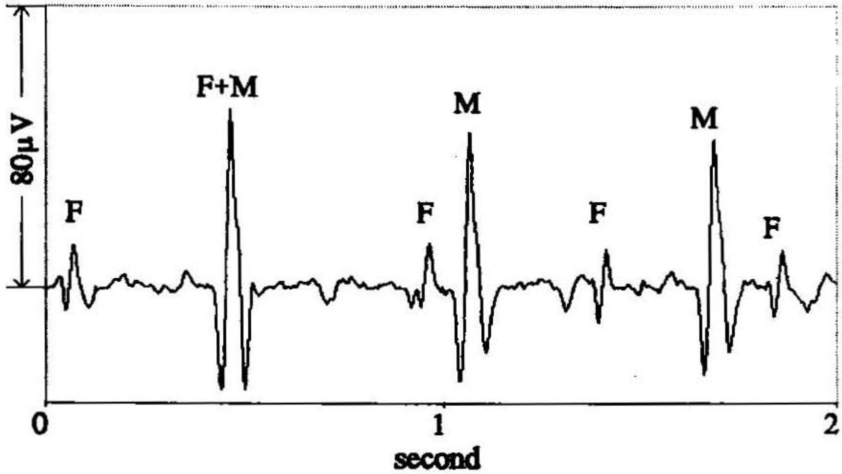

FIGURE 1. An abdominal signal with the fetal and maternal QRS complexes marked F and M respectively

artifacts and muscle noise arising especially during maternal movement. Sometimes, significantly large 50 Hz interference may also corrupt the abdominal signal. Motion artifacts are caused by changes in the electrode-skin impedance with electrode motion which appear as transient baseline changes resembling the QRS complexes [7]. Muscle noise generated by the body is recorded as the electromyogram (EMG) which has a baseline value in the microvolt range but muscle contractions can generate potentials up to the millivolt level. The noise ranges in frequency from about 10 Hz to several kHz [8].

The position and orientation of the fetal heart, being inside a mobile fetal body, within the maternal abdomen may change considerably as a function of time. The electrode positions on the maternal abdomen are chosen in order to obtain an FECG signal of adequate magnitude with minimal interference. The usual sites are in the midline, about 0.3 m apart across the umbilicus for the two 'sensing' electrodes, with the third electrode placed on either of the iliac crests acting as 'ground' to reduce the effects of mains interference. The electrodes in the midline often yield fetal complexes of maximal amplitude with the influences of the MECG and EMG at a minimum [9]. The recording of abdominal signal through a single channel, as in this case, means that the separation of fetal and maternal ECG's and subsequent detection of the R waves have to be completely performed by the signal processing algorithm.

REAL-TIME PROCESSING

The complete software for the real-time processing of the abdominal signal has been implemented by using the TMS32010 digital signal processor (DSP) codes. The abdominal signal is first filtered digitally to remove any remaining 50 Hz and low frequency noise before processing by the R-wave detection algorithm. The algorithm is based on the subtraction of a detected MECG by a scaled template which is produced by taking a running average of previously detected MECG complexes [10]. Currently, a 480 ms fixed width MECG template averaged from 32 complexes is used. The maternal R waves are localised by crosscorrelating the abdominal signal with the QRS samples of the above template consisting of 9 equally spaced points over 80 ms. After a 2 sec delay, the subtracted signal is crosscorrelated with the fetal QRS template which is made of 6 equally spaced points over 50 ms also formed from a running average of 32 complexes. The performance of the above steps is further described by the sketch in Figure 2.

Both the maternal and fetal R-waves are searched by using similar adaptive thresholding schemes which are based on the running average of the signal as compared to that of the noise. They also determine the R-wave search intervals by maintaining and updating two R-R interval averages and three R-R interval limits for each case [11]. The schemes enable the algorithm to deal with very low signal-to-noise ratios.

The above templates, averages and limits for the fetal and maternal cases are first set by the respective initial routines and then continually updated with the detection of reliable R peaks. In order to reduce the effects of muscle noise and motion artifacts on the detection, validation procedures based on a few logical rules are implemented before the detected peaks are accepted. The procedure include a continuation of the search for further maxima within the search limit to distinguish possible false detection. For the fetal case, a comparison is made between the locations of the fetal and maternal R-waves. Also, the signal to noise levels within the R-R interval of interest are represented by values which are tagged to the accepted interval. The tag values portray the level of confidence on the data and hence can be used to determine the reliability of the associated fetal R-R interval.

Figure 3(b) shows how the tag information appears on the display of the FHR trace following noisy condition in the MECG-subtracted abdominal signal. The round dot represents instance of coincidence of the detected fetal and maternal R-waves and the square dot represents the detection of an extra peak above the threshold within the search interval. The square dot appears in Figure 3 at the instant when the MECG subtraction residue had been detected larger than the actual fetal R-wave. This false detection explains the simultaneous appearance of the round dot and results in the FHR trace showing consecutive slow and fast rate.

The above software has been designed for operation with either 500 Hz or 1 kHz sampling frequency. The real-time processing requirement is met by implementing the intensive processing routines, such as the subtraction of the MECG template, over a number of sampling intervals. This has been tested on a TMS32010 DSP development system by using recordings of abdominal signal acquired via three surface electrodes [2]. The R-R intervals measured by the DSP system is further processed off-line on a microcomputer to evaluate the performance of the R-wave detection algorithm.

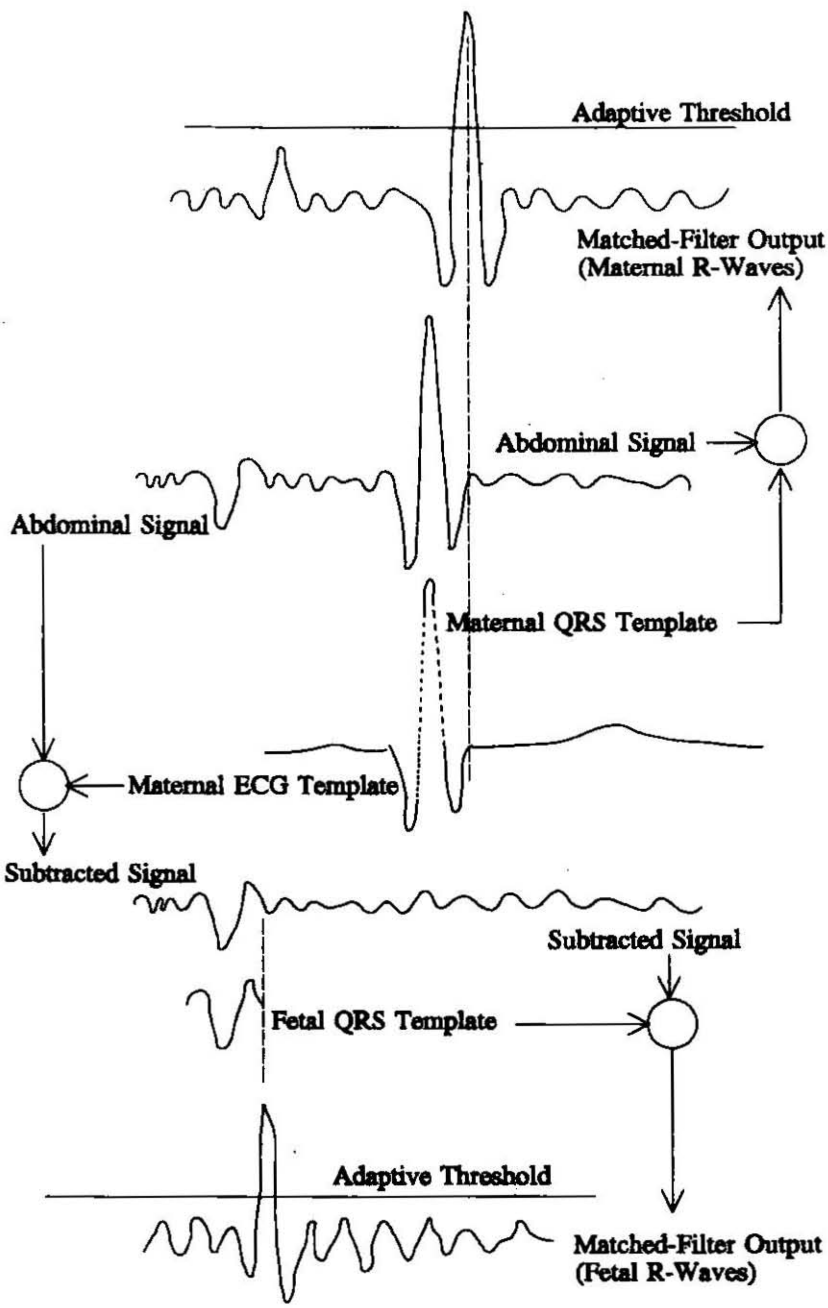

FIGURE 2. Enhancement of the maternal and fetal QRS complexes and subtraction of the maternal ECG

POSTPROCESSING

The postprocessing software has been developed to display both the FHR and MHR traces in beat per minute from the measured R-R intervals, perform corrections on the traces and output their

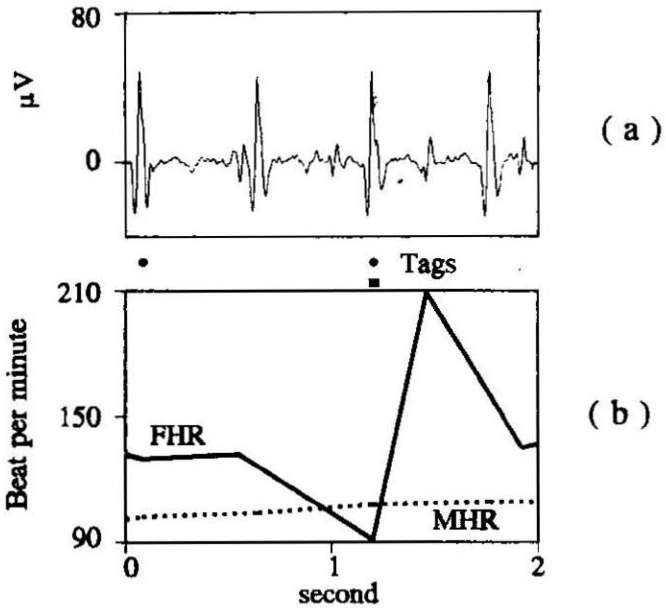

FIGURE 3. (a) An abdominal signal. (b) The heart rates display for the signal in (a) with the tags which arise from some of the RR-interval measurements

performance values. Two correction schemes are implemented based on the noise level tags, the coincidence of the fetal and maternal R-waves and the variation of the R-R intervals from their averages. The first scheme corrects errors which often arise within two consecutive R-R intervals such as previously shown in Figure 3(b). That particular case involves one missed beat and one false detection and can be corrected by replacing the two intervals by their average. From a list of possibilities for errors arising within two consecutive intervals, the total number of errors within a heart rate trace can be represented by the performance measure [12],

$$P_1 = 100 \times \frac{\#\text{Rwaves} - (\#\text{misses} + \#\text{false})}{\#\text{Rwaves}} \tag{1}$$

With activity and larger noise level, the above correction scheme will not be successful when errors may arise consecutively over more than two intervals. Further correction of errors over more intervals is possible based on the assumption that large variation in the heart rate does not normally occur over a few intervals [13]. In order to smooth remaining errors from the heart rate traces after the two-interval corrections, the second correction scheme is implemented. This scheme maintains a running average over 5 intervals and simply replaces any deviation exceeding 8 % of the average with the average value. The total number of errors, in this case, are represented by a similar performance measure, P_2. Both measures are used to evaluate and compare the results of processing by the real-time R-wave detection algorithm.

RESULTS AND DISCUSSION

The real-time algorithm has been tested on abdominal signal recordings of pregnant women during various weeks of gestation. Figure 4 shows an 8-minute display of FHR and MHR traces from a pregnant woman at 41 weeks who was initially at rest and then asked to rise and walk intermittently after 5 minute. The traces have been corrected according to the two schemes discussed above and the associated performance values, P_{1F}, P_{2F}, P_{1M} and P_{2M} (subscripts F and M for fetal and maternal respectively), are listed in Table 1. The table also gives minute-by-minute performance values for the second half of the recording.

TABLE 1. The performance values for the FHR and MHR traces of Figure 4

Minute	P_{1F}	P_{2F}	P_{1M}	P_{2M}
First 4	91.9	98.8	99.8	100.0
5th	95.2	97.3	100.0	100.0
6th	54.9	72.9	89.1	99.2
7th	72.3	89.9	98.2	100.0
8th	82.6	95.8	100.0	100.0
Overall	84.1	93.2	98.1	99.9

The performance values during the first 5 minutes show that very little smoothing is required and there are few errors occurring within two consecutive intervals. These indicate that the beat-to-beat measurement of both maternal and fetal R-R intervals are mostly reliable. During brisk movement, the motion artifacts swamped even the maternal R-waves and rendered the FHR trace unacceptable, as indicated by the performance values during the 6th minute. However, when the movement was intermittent and the signal-to-noise ratio improved, better performance values are again achieved.

The detection of the maternal R-waves are usually reliable and this permits the proper subtraction of the MECG. Successful measurement of the fetal R-R intervals by the algorithm depends on the consistency of the appearance of the fetal complexes above the noise level. In such case, although the FHR traces are lost or disrupted during vigorous movement and muscle activity, correct R peak detections can be resumed when the signal to noise ratio improves. This implies that with the presence of good fetal signals, such as in near-term pregnancies, the fetal R-R intervals can be measured over much of a long-term recording.

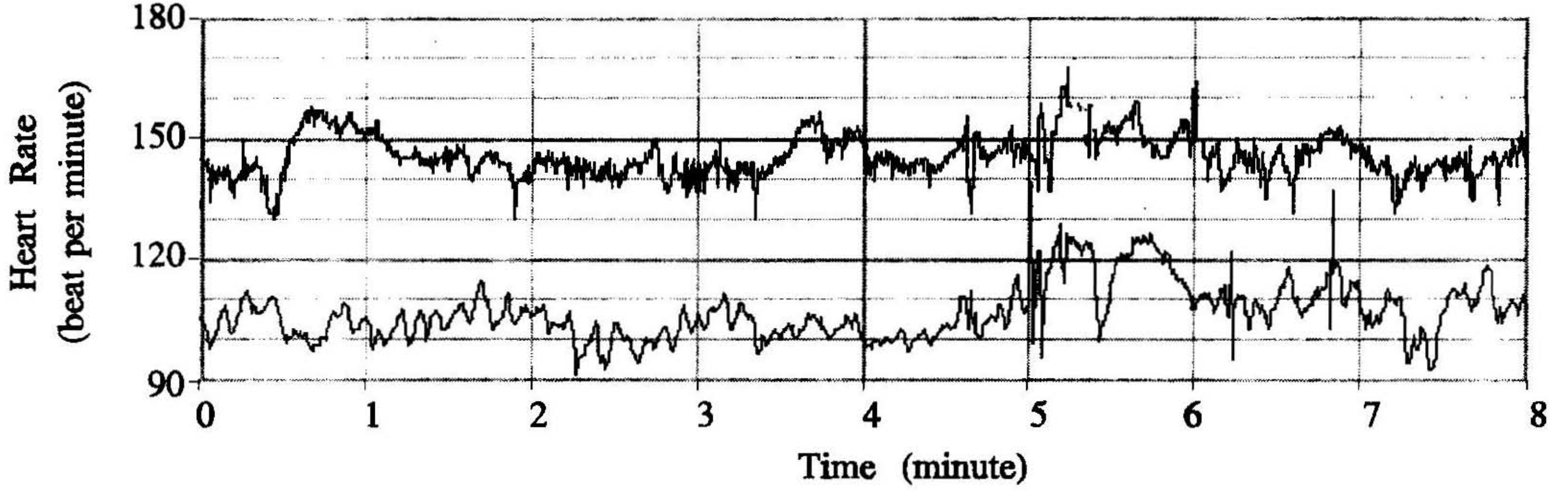

FIGURE 4. The FHR (upper) and MHR (lower) traces from a pregnant woman who was initially at rest and then walking intermittently after 5 minutes

CONCLUSION

The real-time algorithm developed on the DSP has been able to reliably measure from near-term pregnant women both fetal and maternal R-R intervals except during vigorous movement. The use of the two performance measures helps distinguish the reliability of the measurement. The implementation of the low power system for ambulatory use with the ability to generate both FHR and MHR traces over long period would improve understanding of the FHR pattern and its relationship to that of the MHR. The postprocessing part of the work could be implemented together with the real-time algorithm to enable an on-line display and correction of the heart rate traces as well as the indication of their reliability. The two performance measures may also be suitably combined to simplify the monitoring.

REFERENCES

1. H. Shono, et al., 1994, "Fetal Heart Rate Recorder for Long-Duration Use in Active Full-Term Pregnant Women," *Obstet. Gynecol.*, **83**, pp. 301- 306.
2. M.A. Mohd Ali, J.A. Crowe, B.R. Hayes-Gill and H. Yong, 1993, "Development of a Fetal and Maternal Heart Rate Recorder for Ambulatory Use," *Proc. IEEE Comp. Soc. Conf. Computers in Cardiology*, London, pp. 149-152.
3. A. Van Oosterom, 1989, "Lead Systems for the Abdominal Fetal Electrocardiogram," *Clin. Phys. Physiol. Meas.*, **10**, Suppl. B, pp. 21-26.
4. D. Callaerts, et al., 1989, "Description of a Real-Time System to Extract the Fetal Electrocardiogram.," *Clin. Phys. Physiol. Meas.*, 10, Suppl. B, pp. 7-10.
5. P. Bergveld, A.J. Kolling and J.H.J. Peuscher, 1986, "Real-Time Fetal ECG Recording," *IEEE Trans. Biomed. Eng.*, **33**, pp. 505-509.
6. M.R. Behrer, D.H. Glaeser, J.R. Cox and R.B. Woolf, 1968, "Quantification of The Fetal Electrocardiogram Through LINC Computer Processing," *Am. J. Obstet. Gynecol.*, **102**, pp. 537-548.
7. N.V. Thakor, 1988, "Electrocardiographic Monitors," in Encyclopedia of Medical Devices and Instrumentation, 2, J.G. Webster, Ed. New York: Wiley, pp. 1002-1017.
8. M.R. Neuman, 1988, "Fetal Monitoring," in Encyclopedia of Medical Devices and Instrumentation, **2**, Webster, J.G., Ed., Wiley, pp. 1271-1284.
9. M.L. Lamkee, H.W. Huntington and R.R. de Alvarez, 1962, "Fetal Electrocardiography: A Study of the Normal Recording," *Am. J. Obstet. Gynecol.*, **83**, pp. 1622-1628.
10. J.H. Nagel, 1984, "Progresses in Fetal Monitoring by Improved Data Acquisition," *IEEE Eng. Med. Biol. Mag.*, **3**, No. 9, pp. 9-13.
11. J. Pan and W.J. Tompkins, 1985, "A Real-Time QRS Detection Algorithm," *IEEE Trans. Biomed. Eng.*, **32**, pp. 230-235.
12. S. Azevedo and R.L. Longini, 1980, "Abdominal-Lead Fetal Electrocardiographic R-Wave Enhancement for Heart Rate Determination," *IEEE Trans. Biomed. Eng.*, **27**, pp. 255-260.

13. G.W. Lawson, R. Belcher, G.S. Dawes, C.W.G. Redman, 1983, "A Comparison of Ultrasound (With Autocorrelation) and Direct Electrocardiogram Fetal Heart Rate Detector Systems," *Am. J. Obstet. Gynecol.*, **147**, pp. 721-722.

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