NONINVASIVE DETERMINATION OF FETAL HEART RATE AND SHORT TERM HEART RATE VARIABILITY USING SOLELY DOPPLER ULTRASOUND WITH AUTOCORRELATION

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Abstract: Complications of pregnancy, labour and delivery represent the main risk for perinatal asphyxia [1]. The Confidential Enquiry into Stillbirths and Deaths in Infancy reported a mortality rate of 0.62 per 1000 births in England, Wales and Northern Ireland in 1999 [2]. In this work we compare the heart rate information that can be derived from the Doppler audio signal with that derived from the ECG from a scalp electrode, on a beat-to-beat basis. Challenges associated with using the Doppler audio signal include elimination of the noise arising from the movement of the foetal heart and valves and correct peak blood velocity identification. From this beat-to-beat analysis, we can explore the use of a quantitative measure of heart rate variability for the detection of foetal distress. Previously it has been found, in rats, that this measure of heart rate variability increases considerably when asphyxia occurs. Data has been collected from five mothers in the first stage of labour. Currently, the comparison of heart rate signals from the Doppler audio and ECG signals shows an excellent agreement on a beat-to-beat basis (rms error of less than 10 ms). In this pilot study the fetal heart rate variability has remained at a relatively constant low level, which is expected, as only 'normal' labours have been studied so far. Our results are very encouraging and show that there is potential for the use of this method of intrapartum monitoring and the technique could also be applied at antepartum, but this is a pilot study and many more results are needed before firm conclusions and recommendations can be made.

Keywords: fetal monitoring, noninvasive, Doppler ultrasound, heart rate variability, autocorrelation.

INTRODUCTION

Neonates asphyxiated at birth who develop hypoxic-ischaemic encephalopathy (HIE) have a very high risk of death (20-50%) and as many as 25 % of the survivors show signs of cerebral palsy with major motor-cognitive impairment [1,3,4]. While some deaths are unavoidable, it is thought that more can be done to reduce this level of mortality and early detection of signs of asphyxia can improve outcome by prompting appropriate medical intervention. Monitoring of labour and delivery is normally performed with cardiotocography (CTG) and assessment of fetal oxygen and acid-base status. Despite the continuous fall in the incidence of HIE [5], there is ongoing discussion about the effective contribution of CTG in uncomplicated pregnancies, due to its reduced sensitivity and specificity [1,3,4]. Fetal distress leads to well known decelerations in fetal heart rate (FHR), but difficulties in interpretation of FHR patterns, and lack of standardization, contribute to the poor specificity of CTG [6-8]. As a result, a large number of false-positives are subject to unnecessary intervention, such as caesarean delivery, thus contributing to increased costs and risk of complications. On the other hand, difficulties of interpretation and limitations in the sensitivity of FHR patterns contribute to inappropriate response times for staff to detect asphyxia and take action, which is normally in the range of 30-100 min [6]. Response times of this order are obviously inadequate since permanent brain damage can result from only 10 min of severe asphyxia. Therefore, improvements in the sensitivity and specificity of CTG could lead to earlier detection of intrapartum asphyxia, more immediate reaction and also a reduction in the false-positive rate leading to more appropriate use of resources and less iatrogeny. Recent advances in the analysis and interpretation of heart rate time series have the potential to improve the classical pattern analysis of FHR. In particular, autoregressive spectral analysis of pulse interval signals has been shown to reflect autonomic nervous system disturbances associated with stroke, brain death, diabetes, heart failure and myocardial infarction [9,10]. Application of these methods to perinatal asphyxia remains largely unexplored, but recently, in collaboration with Prof N. Thakor (Johns Hopkins School of Medicine, USA), we performed signal processing of ECG signals from anaesthetized rats, subjected to different lengths of asphyxia, and were able to detect its onset within 1 min., as well as to obtain an indication of its severity [11]. These preliminary results suggest that our technique might be more sensitive than classical interpretation of FHR patterns in response to asphyxia. Rather than assessing the classical decelerations in FHR associated with uterine contractions, our approach focuses on the more stable periods and could use the signal between contractions. This approach can also be potentiated by including newer techniques of non-linear dynamic analysis that can take into account the complete information available in the FHR tracing. Ideally, rather than using the scalp ECG as the source of the FHR signal, the use of Doppler ultrasound would reduce the risk of infection and allow wider automatic monitoring using

our approach (since most maternity units have an ultrasound monitor). A separate investigation would need to be completed to test whether its temporal resolution would be acceptable and also the reliability of recordings made during delivery. Following a study on the quality of ultrasound records [12], our preliminary results indicate this to be feasible [13]. In addition to umbilical cord or scalp pH, intrapartum pulse oximetry has been proposed, since the early 90's, as a more specific method to assess hypoxemia. The disadvantages of these techniques though are their cost, risk of complications, and technical difficulties [14-18]. If the hypothesis that spectral and non-linear analyses of FHR signals can yield parameters that correlate with scalp pH or pulse oximetry data this could represent a major breakthrough by leading to new technology that could considerably simplify and reduce the costs of monitoring high-risk labour/delivery.

MATERIALS AND METHODS

Data has been collected from five consenting mothers from the first stage of labour up to delivery. A HP8040A monitor was used, from which four signals were available and collected at 2000 samples per second: The scalp fetal electrocardiogram (FECG – figure 1) the uterine contractions (TOCO), the raw Doppler ultrasound signal and an approximation to the maximum Doppler frequency envelope extracted by the HP8040A monitor itself (figures 1 and 2).

The signal from uterine contractions (TOCO) was not used in this work. The FECG was used only in the final stage, for comparison of the detections and was not used to help improve detections. The raw signal is also being investigated, but the results are not shown here.

The individual heart beats were identified using solely the maximum frequency (velocity) envelope signal produced by the monitor.

The usual procedure for using Doppler signals is to start from the raw Doppler ultrasound signal (the audio signal resulting from the beating of the transmitted and the received ultrasound signals), splitting it into frames about 20 ms long each, performing spectral analysis of each frame and finding a 'maximum frequency envelope (corresponding to a maximum blood velocity above a 'noise' threshold), then repeating for the next frame. These frames can be overlapped to improve time resolution if antileakage windows are used prior to spectral estimation.

The maximum blood velocity signal resulting (by plotting the sequence of the maximum frequencies for all frames along time) needs to be further processed in an attempt to identify individual heart beats and then obtain average heart rate or, as we intend here, heart rate variability. This latter needs a very precise identification of fiducial points, which is no trivial matter given the quality of the maximum frequency envelope signals. In fact often it is a challenge to identify individual heart beats visually, let alone determine a fiducial point.

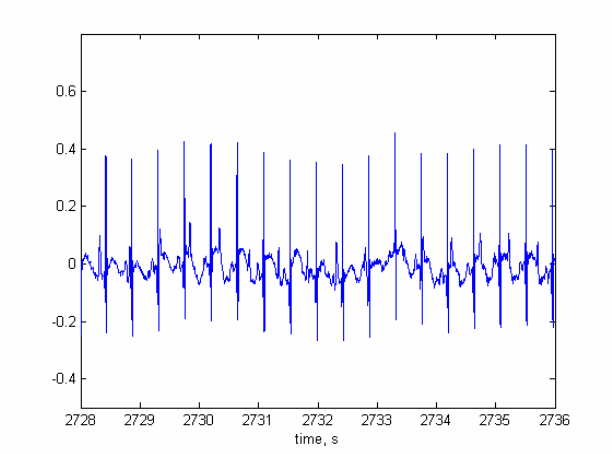

Fig. 1 The determination of fetal heart rate and short term HRV from the scalp FECG is straightforward.

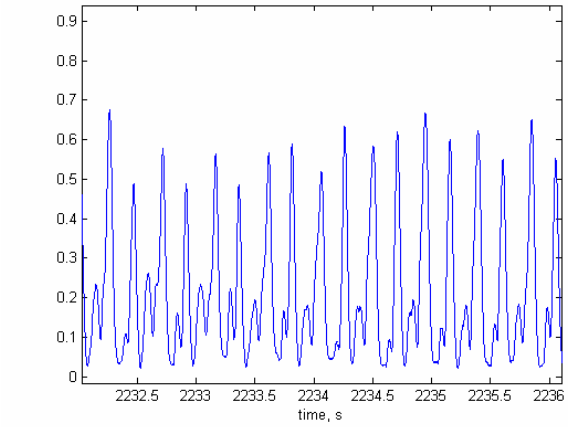

Fig. 2 The determination of fetal heart rate and short term HRV from a 'clean' Doppler ultrasound envelope is slightly harder because the peaks are 'rounder'.

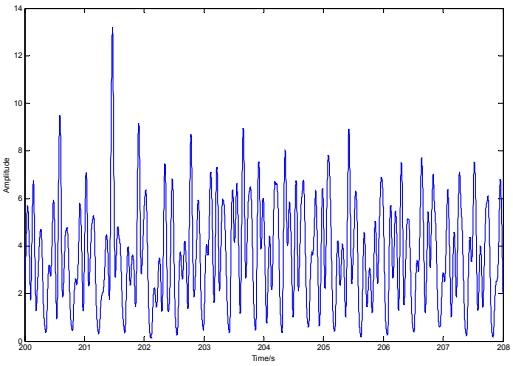

Fig. 3 The determination of fetal heart rate and short term HRV from a 'dirty' Doppler ultrasound envelope is much harder.

The LF maximum velocity envelope

The HP8040A monitor produces an approximation of the maximum frequency envelope which is obtained by using a clever analogue circuit: All Doppler ultrasound instruments used for blood flow measurement include a 'wall thump' high pass filter to remove the strong echoes from the slow moving vessel walls, cleaning the signal of interest (the Doppler shift caused by the red blood cells). The gain of the wall thump highpass filter is such that the power of the output signal is (roughly) proportional to its frequency for a certain frequency range. This fact is used to produce the approximation to the maximum frequency envelope. A low pass filter with cut-off frequency around the maximum frequency expected (300 Hz) follows the wall thump filter to produce what the Hewllett Packet HP8040A manual calls the 'LF signal'. This is the signal we have used (Figures 1 and 2).

As can be seen in Figure 3, it is sometimes rather difficult to identify individual heart beats and determine fiducial points from the Doppler ultrasound LF envelope. The solution we employed was to use a short term autocorrelation with a time window of 1.5s as an approximation to a matched filter.

Figure 4 shows the procedure: A short window (1.5s) of the LF envelope signal (Figure 4a) is autocorrelated to produce the signal shown in Figure 4b. There is a strong peak at lag=0, corresponding to the square of the signal and the signal is on top of a triangle since the DC level was not removed prior to the autocorrelation. The right-hand half of the signal shown in Figure 4b is then de-trended and the first 'strong' peak around the expected time (corresponding to a fetal heart rate between 100 and 200 bpm is marked as the fiducial point for the next heart beat (Figures 4b and arrow on Figure 4c). The threshold for determining the next beat (Figure 4c) is set initially at 20% of the peak at zero lag, but for certain signals where the quality of the data collected was very poor this had to lowered down to 10% for detection.

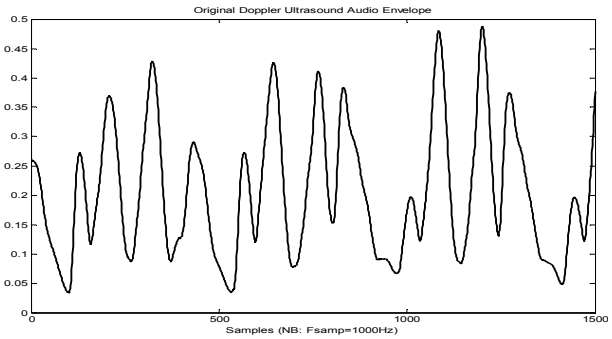

Fig. 4a The LF envelope signal.

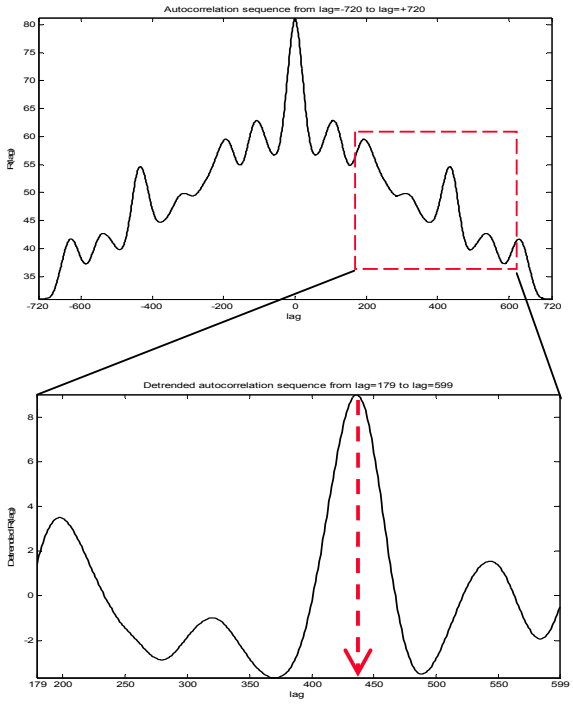

Fig. 4 (b and c) A short (1.5s frame of the LF envelope signal (4a) is autocorrelated (4b) and a 'strong' peak on the de-trended right hand half identifies the fiducial point of the next beat (4c).

RESULTS

For all the five signals collected it was possible to identify the individual heartbeats and determine the RR series from the Doppler ultrasound LF signal solely with great accuracy (compared to the FECG), as shown in Figures 5 and 6. The errors (defined as the difference in time between the RR interval from the FECG and the RR interval from the ultrasound) were measured and are typically less than 5 ms. These results are encouraging and allow us to measure the HRV (defined by the short-term standard deviation of RR intervals) solely from the ultrasound signal (figure 7). This is an important result since it is not possible to measure fetal ECG noninvasivaly in between 30 to 40% of the cases (personal communication).

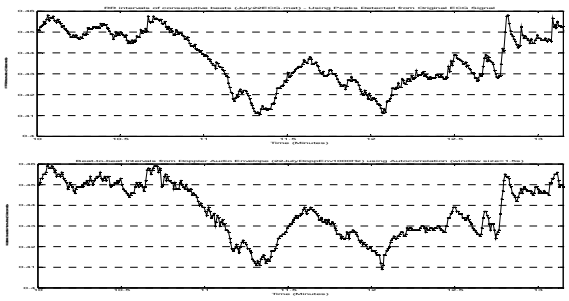

Fig. 5 The sequence of RR intervals determined from FECG (top) and from Doppler ultrasound (bottom) for an interval of about 13 minutes.

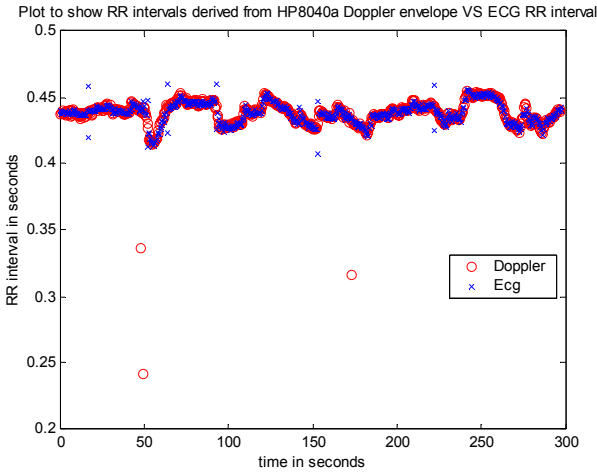

Fig. 6 The sequence of RR intervals determined from FECG (crosses) and from Doppler ultrasound (circles) for another patient.

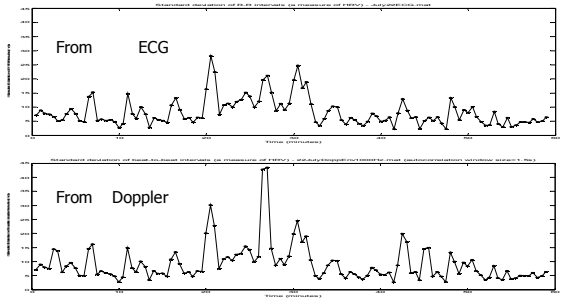

Fig. 7 The HRV signal determined from FECG (top) and from Doppler ultrasound (bottom) over a 1 hour interval.

CONCLUSION

The identification of individual heart beats and their precise localisation in time is possible by using the maximum frequency envelope of the Doppler ultrasound signal solely by using autocorrelation of short (1.5s) segments of the signal. Since the monitoring of fetal wellbeing during delivery relies mostly on ultrasound, this is an interesting alternative to performing the separation of fetal and maternal ECG using specialist equipment for signal collection followed by sophisticated signal processing.

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