

Fetal electrocardiography: feasibility of long-term fetal heart rate recordings

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The feasibility and accuracy of long-term transabdominal fetal electrocardiogram (fECG) recordings throughout pregnancy were studied using a portable fECG monitor. Fifteen-hour recordings of fetal heart rate (FHR) were performed in 150 pregnant women at 20–40 weeks of gestation and 1-hour recordings were performed in 22 women in labour and compared with simultaneous scalp electrode recordings. When $\geq 60\%$ of fECG signals was present, the recording was defined as good. Eighty-two percent (123/150) of antenatal recordings were of good quality. This percentage

increased to 90.7 (136/150 recordings) when only the night part (11 p.m.–7 a.m.) was considered. Transabdominal measurement of FHR and its variability correlated well with scalp electrode recordings ($r = 0.99$, $P < 0.01$; $r = 0.79$, $P < 0.01$, respectively). We demonstrated the feasibility and accuracy of long-term transabdominal fECG monitoring.

Keywords Antenatal monitoring, fetal electrocardiography, fetal heart rate.

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Introduction

Antepartum fetal surveillance constitutes an essential component of the standards of care in managing high-risk pregnancies, including maternal hypertensive disorders, intrauterine growth restriction, and other maternal and fetal pathophysiological conditions. Ultrasound examination (growth, Doppler flow velocimetry) and fetal heart rate (FHR) monitoring are the most commonly used antepartum fetal surveillance tests. In current obstetric practice, both techniques are used for short durations at regular intervals, although long-term monitoring could help improve clinical management in some women.¹ To date, this is only possible using ultrasound-based cardiotocography (CTG).¹ However, its use for a prolonged period both in the hospital and in the home environment remains cumbersome due to discomfort and poor signal quality in prolonged recordings.² Moreover, it exposes the fetus to prolonged ultrasound insonation. An alternative is the continuous monitoring of FHR through the measurement of the electrical signal of the fetal heart (fetal electrocardiogram, fECG). Originally hampered by technical difficulties,² the method seems now ready for clinical use. The primary aim of this study was to evaluate the quality of prolonged antenatal FHR recordings obtained with abdominal ECG electrodes

in the second half of gestation. In addition, the accuracy of transabdominal recordings was evaluated by comparing with scalp electrode measurements in a smaller set of intrapartum recordings.

Materials and methods

The antenatal group consisted of 150 pregnant women at 20–40 weeks of gestation. Exclusion criteria were multiple gestation and congenital malformations. Women were recruited for a single overnight recording either at home ($n = 110$) or during admission at the obstetrics ward ($n = 40$). Maternal mobility was not restricted while being attached to the monitor. Recordings were performed during 15 hours (5 p.m.–8 a.m.), mostly overnight, to minimise abdominal muscle activity that could result in distortion of the fECG signal.² Fetal presentation was determined by ultrasound examination before starting the recording. Table 1 summarises patient distribution according to gestational age periods, fetal presentation (cephalic, breech, and transverse), and fetal–maternal complications. The intrapartum group consisted of 22 women in labour at term recruited in the labour ward of our tertiary centre. Transabdominal and scalp electrode recordings were performed simultaneously for 1 hour in the

Table 1. Study population characteristics

	Antenatal recordings				
	20 ⁺⁰ –25 ⁺⁶ ; <i>n</i> = 20 (13.3%)	26 ⁺⁰ –31 ⁺⁶ ; <i>n</i> = 45 (30%)	32 ⁺⁰ –34 ⁺⁶ ; <i>n</i> = 30 (20%)	35 ⁺⁰ –37 ⁺⁶ ; <i>n</i> = 28 (18.7%)	≥38 ⁺⁰ ; <i>n</i> = 27 (18%)
Gestational age (weeks)					
Fetal presentation (%)					
Cephalic	10 (50)	28 (62.2)	27 (90)	28 (100)	26 (96.3)
Breech	4 (20)	7 (15.6)	2 (6.7)	0	1 (3.7)
Transverse	6 (30)	10 (22.2)	1 (3.3)	0	0
Fetal–maternal condition (%)					
None	14 (70)	18 (40)	18 (60)	17 (60.7)	24 (88.9)
Pre-eclampsia or pregnancy-induced hypertension	0	3 (6.7)	4 (13.3)	2 (7.1)	3 (11.1)
Intrauterine growth restriction	0	5 (11.1)	5 (16.7)	3 (10.7)	0
Preterm prelabour rupture of membranes	1 (5)	5 (11.1)	0	0	0
Preterm labour	1 (5)	4 (8.9)	0	0	0
Diabetes mellitus or gestational diabetes mellitus	2 (10)	3 (6.7)	0	2 (7.1)	0
Vaginal blood loss	0	5 (11.1)	1 (3.3)	0	0
Others*	2 (10)	2 (4.4)	2 (6.7)	4 (14.3)	0
Recording location (%)					
Home	18 (90)	23 (51.1)	23 (76.7)	22 (78.6)	24 (88.9)
Hospital	2 (10)	22 (48.9)	7 (23.3)	6 (21.4)	3 (11.1)
		Intrapartum recordings			
		Median		Range	
Gestational age (weeks)		40 ⁺¹		37 ⁺² –42 ⁺²	
BMI (kg/m²)		24.5		16.9–40.4	

*Others include fetal arrhythmias, antidepressants, polyhydramnios, and Morbus Graves.

first stage of labour. Medians of FHR and short-term variability (according to Dawes *et al.*³) were calculated as variables for accuracy. The median and ranges for gestational age and body mass index (BMI) of the women are summarised in Table 1.

Signal processing

The recordings were performed with the AN24 fetal ECG monitor (Monica Healthcare, Nottingham, UK). The electrophysiological signal, recorded using five disposable electrodes placed on the maternal abdomen, contains the maternal ECG (mECG), fECG, and noise. mECG and fECG complexes were used to calculate beat-to-beat (R–R) pulse intervals, which correspond to the maternal heart rates and FHRs, respectively. The methodology used for signal extraction and analysis has been described in detail by Pieri *et al.*⁴ The five disposable electrodes were placed on the maternal abdomen in a standardised manner, independent of fetal positioning; two electrodes along the midline (at the side of the uterine fundus and above the symphysis), one at each side of the uterus, and the ground electrode on the left flank. Skin impedance was reduced before placing the electrodes using abrading paper at the electrode placement site. Skin impedance was below 5 kΩ in all recordings. Data were analysed off line after computer download.

Quality assessment of fECG recordings

Signal loss was defined as the proportion of epochs (in %) during which no valid data were available (after data reduction over 3.75-second epochs).³ Instead of signal loss, we will use the term recording quality (RQ; 100%—signal loss), with RQ ≥ 60% to indicate a successful record based on Dawes *et al.*³

Statistics

SPSS for Windows (version 12.01; SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Results were summarised with the use of standard descriptives for nonparametric tests: medians and (interquartile) ranges. Groups were compared with the Kruskal–Wallis test with *post hoc* analysis where appropriate, and Spearman correlation was used to evaluate the effect of potential confounders.

Results

Antenatal group

Eighty-two percent (123/150) of the recordings were considered of sufficient quality (i.e. RQ ≥ 60%) when total recording time (5 p.m.–8 a.m.) was studied. There was a wide variation in RQ during the early evening probably due to maternal activity. From 9 p.m. onwards, the median RQ increased gradually to

a maximum of 100% from about 12 p.m. until 6 a.m. The proportion of recordings with sufficient quality reached 90.7% (136/150) during the night part (11 p.m.–7 a.m.), which will serve as the basis for the analyses presented further. RQ was high at 20–26 weeks of gestation, followed by lower values and wider variation at 26–34 weeks, with a gradual improvement thereafter (Figure 1). This trend was tested using Kruskal–Wallis test and was shown to be significant (H(4) statistic = 41.52, $P < 0.01$). RQ did not differ statistically between the home recordings (median RQ 95%, interquartile range 85.0–98.4%) and recordings made in the hospital (median 91.9%, interquartile range 77.9–97.8%, respectively, $P = 0.15$). RQ was not significantly affected by fetal positioning (median RQ 94.7, 89, and 92.2% for cephalic, breech, and transverse position, respectively) (H(2) statistic = 5.9, $P = 0.06$; Kruskal–Wallis test) or by the BMI (median 27.1; range 16.0–43.8, $R = 0.01$ Spearman's test, $P = 0.89$).

Intrapartum group

77.3% (17/22) of the recordings were of good quality (i.e. RQ $\geq 60\%$). The median FHR and median short term variability (STV) found in the 17 recordings using transabdominal fECG and scalp electrodes were as follows: FHR 140.6 beats per minute (range 127.9–155.4) versus 141.4 beats per minute (range 128.5–156.2), $r = 0.998$, $P < 0.01$, and STV 8.0 milliseconds (range 4.8–10.1) versus 8.1 milliseconds (range 4.5–9.0), $r = 0.79$, $P < 0.01$, respectively.

Adverse effects

After removal of the electrodes, 30 of the 150 women (20%) complained of skin irritation. In most women, irritation consisted of transient redness of the skin and itchiness on the site

where we had abraded the skin. Almost all these women were in late gestation and had no history of skin irritation. When asked whether they would like to use the monitor again, they replied not to mind in case there would be an indication for fetal monitoring. Overall, women did not experience any other discomfort while using the monitor.

Discussion

This study evaluated the feasibility and accuracy of an improved FHR monitoring technique using the external fECG signal. This technique is an alternative to ultrasound for long-term antenatal fetal monitoring. To date, all studies on long-term fetal monitoring are based on FHR data acquired in a hospital setting.^{1,5–7} They used either transabdominally placed needle electrodes,⁶ transabdominally placed 'sucking-cup' electrodes,⁷ or ultrasound heart rate monitors.^{1,5} Since the quality of Doppler CTG recordings is dependent on fetal movements, long-term monitoring requires frequent repositioning while the woman is restricted to a fixed position. The current method, being truly ambulatory, can perform long-term recordings also in the home environment. We showed that it can obtain approximately 8 hours of qualitatively good FHR records without the necessity of interference of any caregivers from 20 weeks of gestation onwards. There is a slight decrease in RQ between 26 and 34 weeks of gestation, but the signal quality remains acceptable. The 25th percentile of the night RQ remained far above the required minimum of 60% in this subgroup of gestational age. A subset analysis comparing pregnancies with fetal–maternal complications with healthy pregnancies found no significant difference in the magnitude of this effect. This is thus unlikely to be due to the occurrence of fetal–maternal complications at this stage of gestation and is probably related to the formation of the vernix caseosa at this gestational age as suggested by others.² Interestingly, the quality of fECG recordings was not influenced by maternal obesity as our results show no decline of RQ with increasing BMI.

The findings were validated in a smaller set of intrapartum recordings by comparing FHR and STV with measurements performed with the actual gold standard, the scalp electrode. Both methods were found to correlate well. The correlation was similar to the values reported in previous comparisons in the literature between noninvasive methods and scalp electrodes.^{8,9} Transabdominal fECG, therefore, seems to be a valid and accurate substitute for other noninvasive FHR monitoring techniques. The fECG technique has the advantages that its true ambulatory character enables long-term recordings, that the quality of its recording is not influenced by the women's BMI, which is becoming of increasing importance, and that the technique is purely noninvasive. Transabdominal fECG recording is, however, probably more than an adequate substitute for current methods, given its potential for true

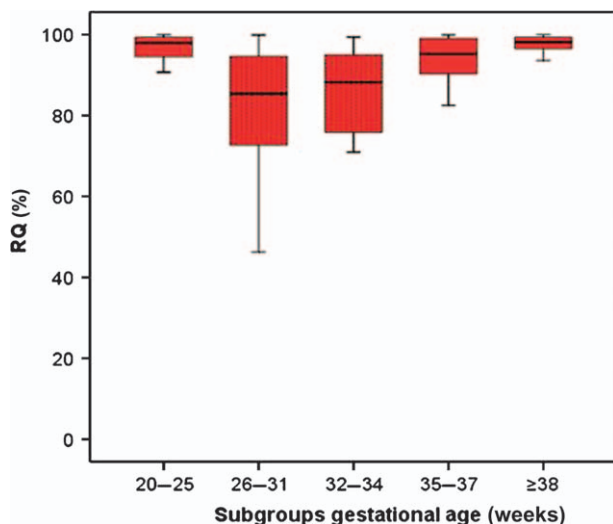


Figure 1. RQ (median; interquartile range, p2.3 and p97.7) in five distinct gestation periods (night recordings, $n = 150$). Marked boxes indicate $P < 0.05$ compared with the 20–25, 35–37, and ≥ 38 weeks subgroups.

beat-to-beat heart rate, variability, and ECG complex analysis. At this point, however, the technology available to the researchers did not allow for the computation of true beat-to-beat interval variability and fECG morphology. Following adult cardiology standards, an abdominal signal sample rate of 1000 Hz is required to calculate a true measure of beat-to-beat variability and follow changes in fECG morphology. The current version of this fECG monitor has a sample frequency of 300 Hz. This will be increased to 1000 Hz in subsequent research devices. It is worth noting that modern conventional fetal monitors only provide an accuracy of ± 1 beat per minute and update the FHR every 250 milliseconds (a sample of 4 Hz).

Conclusions

Our findings demonstrate the feasibility and accuracy of an improved fetal monitoring technique using the externally obtained fECG signal. Quality was optimal when the recording was performed overnight. fECG monitoring will be most applicable in high-risk pregnancies that require extended fetal monitoring.

Disclosure of interest

There are no known financial, personal, political, intellectual, or religious interests of any of the authors.

Contribution to authorship

G.H.A.V. was, besides the initiator, the supervisor of this study. E.J.H.M. was the leading force in the set up of the methodological layout. B.C.J. was involved in the revision of the manuscript. L.A.J.v.E. performed the 22 intrapartum recordings and performed the analysis on this data set. E.M.G. was a PhD student and research coordinator who informed and included all women, analysed the data, and wrote the manuscript.

Details of ethics approval

On 25 October 2005, the medical ethical committee (METC) of the University Medical Center Utrecht has approved the above described study titled 'Antenatal external fECG for heart rate monitoring: eval-

uation of an improved monitoring technique' (protocol number 05-256).

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Editor-in-Chief's Commentary

Continuous fetal heart rate monitoring was first developed using the fetal electrocardiogram (ECG) signal. The first person to demonstrate that electrical signals are generated by each heartbeat was Carlo Matteucci in 1838 (www.ecglibrary.com/ecghist.html), but it was not until 1906 that Cremer recorded the first fetal ECG from the abdominal surface of a pregnant woman (*Munch Med Wochenschr* 1906;53:811). In 1958, an analysis of the fetal heart rate pattern to assess its condition during labour was reported by Edward Hon in the USA (*Am J Obstet Gynecol* 1958;75:1215-30); he used the fetal ECG obtained through maternal abdominal electrodes (the maternal ECG was cancelled using separate electrodes). He then went on to devise the fetal scalp electrode (*Am J Obstet Gynecol* 1963;5;86:772-84), more practical for use in labour when the membranes are ruptured because it produces a much larger signal and avoids the electrical noise superimposed by contractions of maternal abdominal muscles. The use of Doppler ultrasound to detect fetal heart movement and derive the

fetal heart rate was described by EH Bishop (known more widely for his eponymous cervical score) in 1968 (*Clin Obstet Gynecol* 1968;11:1154–64). Doppler ultrasound is less invasive (its low power minimises its heating effects on the fetus), but initially the complex and variable nature of the ultrasound signal (which detects movement of the fetal heart, rather than its electrical activity) meant that the accuracy of fetal heart rate determination was much less than that derived from the ECG (the peak of the R wave can be determined to an accuracy of 0.2 milliseconds compared with no better than 30 milliseconds for a fetal heart movement pulse). Thus, ultrasound assessment of beat-to-beat changes was inaccurate, making the analysis of baseline variability unreliable (normal beat-to-beat heart rate change is usually less than 1 beat per minute; baseline variability is a complex sum of beat-to-beat changes, assessed over epochs of 30 seconds or more, with a normal range of 5–15 beats per minute). Improved accuracy of rate determination was achieved with electronic correlation analysis of the ultrasound signals, which allows adequate assessment of baseline variability, although it is still only an approximation of that derived from the ECG. For this reason, measurement of the fetal ECG remains the gold standard in assessing fetal heart rate. The system currently described by Graatsma *et al.* has an inadequate sampling frequency to determine true beat-to-beat variation because it only samples once every 3.3 milliseconds, and its main advantage over ultrasound is its ability to produce long-term recordings in a manner comfortable for the mother. Similar length recordings by ultrasound are difficult to achieve because movement of the fetus away from the ultrasound transducer interrupts recording. However, Graatsma *et al.* are planning to develop their system to measure to an accuracy of 1 millisecond, allowing true beat-to-beat measurement and more accurate assessment of fetal cardiovascular physiology. ■

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