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Magnetocardiography in the diagnosis of fetal arrhythmia

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Objective To examine the possible use of magnetocardiography in the diagnosis of fetal arrhythmias.

Design Investigation of routinely examined pregnant women, as well as women referred because of arrhythmias or other reasons.

Participants Sixty-three women between the 13th and 42nd week of pregnancy.

Methods Recording of 189 fetal magnetocardiograms, of which 173 traces (92%) demonstrated sufficient fetal signal strength to permit evaluation. After digital subtraction of the maternal artefact, all fetal complexes were identified and the recording was examined for arrhythmic events.

Results Short bradycardic episodes, not associated with any pathological condition, were found in 26% of all recordings, usually in mid-pregnancy. In 12 cases, isolated extrasystoles of no clinical importance could be identified. There were nine traces which revealed multiple arrhythmias including ventricular and supraventricular ectopic beats, bigeminy and trigeminy, sino-atrial block and atrio-ventricular conduction disturbances. Furthermore, two cases with tachycardia were found.

Conclusion Magnetocardiography offers a simple noninvasive method for examination of the fetal cardiac electrophysiological signal. It may thus be useful in the identification and classification of clinically relevant arrhythmia and aid in decisions concerning treatment.

INTRODUCTION

Deviations in the normal sinus rhythm of the fetal heart can occur throughout pregnancy. The identification and classification of such deviations is of diagnostic importance as some forms may compromise the fetus and require treatment. In particular, long sustained fetal tachycardia and bradycardia may lead to heart failure, hydrops, intrauterine growth retardation and death.

Conventional techniques in the diagnosis of fetal arrhythmia include cardiotocography, electrocardiography and echocardiography. The cardiotocograph detects the fetal heart beat on the basis of the Doppler-shift of an ultrasound signal and delivers a tachogram based on the consistent repetition of these signals. Irregular beats are generally not registered and the presence of arrhythmia is indicated solely by the absence of a regular rhythm, thereby not allowing the discrimination of haemodynamically relevant forms[1]. Fetal electrocardiography, on the other hand, allows the analysis of the waveform of the electric signal. However recording of the electrocardiogram has never attained clinical significance because its signal-to-noise ratio is low, thereby precluding the demonstration of atrial activity. Furthermore, its recording is severely restricted between the 26th and 32nd week due to the presence of the vernix caseosa[2]. The current method of choice is M-mode Doppler echocardiography, which assesses the type of arrhythmia on the basis of contractile and flow behaviour in the atria and ventricles. This method is limited because it is dependent on the investigator's experience and is restricted by fetal movement and position[3]. Furthermore, as analysis of the signal morphology is not possible, differential diagnosis of an arrhythmic event may be difficult.

Fetal magnetocardiography is an alternative to these methods. It measures, in a non-invasive way, the magnetic field produced by electrical currents in the fetal heart[4,5] and generates recordings with a good signal-to-noise ratio and with high temporal resolution (Fig. 1). Magnetocardiography allows the examination of the morphology of the fetal cardiac signal as early as the

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Fig. 1. Fetal magnetocardiogram in the 29th week of gestation. Two selected channels, one with a strong and one with a weak maternal artefact, before (a) and after (b) digital subtraction of the maternal signal (m = maternal R wave, f = fetal R wave).

second trimester of pregnancy[6]. The purpose of this study was to acquire examples of various types of arrhythmia found in fetuses recorded by magnetocardiography and consider their physiological and clinical significance, in order to demonstrate the potential of the method in the diagnosis of clinically important fetal arrhythmias.

METHODS

We investigated 63 pregnant women with a mean age of 31 years (SD 4, range 22–41), all of whom gave their informed consent. Thirty-seven women had normal healthy singleton pregnancies, eight were referred because of suspected fetal arrhythmia and 18 were referred for other reasons, such as twin pregnancy, growth retardation, pre-eclampsia, previous HELLP syndrome, and methadone use. One hundred and eighty-nine fetal magnetocardiograms were recorded in 65 fetuses between the 13th and 42nd week of gestation. The mean number of recordings per fetus was 3·1 (SD 2·4, range 1–11). In 16 cases, all before the 20th week, signal strength was too weak to permit evaluation, making 173 recordings available for this study. The study was approved by the regional ethics committee.

One hundred and fifty-five recordings (82%) were performed using a 37-channel biomagnetometer (Siemens Krenikon, Erlangen, Germany), consisting of first order gradiometers with a baseline of 7 cm with a probe diameter of 19 cm. System noise was < 30 fT/Hz^{-1} for frequencies > 2 Hz and 10 fT/Hz^{-1} for frequencies > 10 Hz (fT: femtotesla). Thirty-four measurements (18%) were performed with a 67-channel biomagnetometer (BTi 1300C, San Diego, California, USA), consisting of magnetometer sensing coils arranged concentrically on a curved surface with a diameter of 33 cm and including a configuration of 11 reference coils used to detect ambient noise. Intrinsic system noise was less than 10 fT/Hz^{-1} for frequencies > 5 Hz. Each sensing coil noninvasively detects the magnetic field produced by the electrical currents in the fetal heart, the signals produced by other, more distant sources being eliminated or reduced by the compensation or reference coils[6]. To further attenuate the influence of electromagnetic artefacts, the measurements were performed in a shielded room (Vakuumschmelze AK3b, Hanau, Germany). The multichannel probe was positioned over the maternal abdomen such that the amplitude of the fetal signal was as large as possible. The probes were not in contact with the abdomen, and the technique is noninvasive and without any risk to mother and child. The data were recorded usually for five minutes, with a bandpass of 1–200 Hz at a sampling rate of 1 kHz.

The maternal cardiac signal was generally present in those channels closer to the maternal heart. In order to examine fetal activity uncorrupted by the maternal cardiac signal, all maternal beats were automatically identified by correlation to a maternal QRS signal template. An average maternal PQRST signal was calculated and digitally subtracted in all channels (Fig. 1). The remaining signal (Fig. 1 b) was subsequently examined for fetal arrhythmic events: the fetal QRS complexes were identified by referring to a fetal QRS signal template. Generally the majority of the QRS complexes could be found and complexes not automatically recognised were visually identified and added manually; similarly, artefacts were removed manually. Time series of the RR interval were reconstructed by determining the duration between consecutive QRS complexes to an accuracy of 1 ms.

RESULTS

Different types of abnormal rate and rhythm (supraventricular and ventricular ectopic beats as well as brady- and tachycardias) were present in about half of the magnetocardiograms (Table 1). Defining bradycardia as nonextrasystolic beats with a heart rate below 100 beats per minutes (RR interval ≥ 600 ms), we found 26 recordings in which at least one beat fulfilled this condition. Most of these were found in earlier pregnancy. They occurred typically in recordings with a constant heart rate in the normal range (140–160 bpm) with minimal beat to beat variability, which was then interrupted by a sudden lengthening of the RR interval in a single beat, the following 10–25 beats shortening in duration until the basal rate was again achieved. As Fig. 2 shows, this phenomenon was also initiated by beats with RR intervals < 600 ms. These episodes were observed in approximately one-third of the recordings and occurred in almost all the pregnancies in this study. They were present most commonly in the second trimester, becoming less frequent as term approached. In no case could they be linked to acute or chronic disturbances in the fetus.

In 12 traces, isolated extrasystolic beats both of ventricular and supraventricular origin could be observed (Fig. 3). None of these arrhythmias were of clinical relevance. In addition, some recordings were especially interesting, some of which are presented below. None of these fetuses had cardiac structural anomalies diagnosed during pregnancy.

1. One recording in the 31st week of pregnancy showed persistent trigeminy due to multiple supraventricular extrasystoles (Fig. 4). The premature beat is followed by two beats of normal duration, the RR interval of the first being consistently shorter than the second. This was due to the atrioventricular delay of the extrasystolic beat, leading to a relative shortening of the corresponding RR interval. There was no evidence of arrhythmia in the postnatal period.
2. Figure 5 shows a recording from a fetus in the 42nd week of gestation with numerous supraventricular extrasystoles with compensatory pauses, as well as supraventricular extrasystoles with atrio-ventricular block, with a delay in the following sino-atrial depolarisation, possibly due to a first degree sinoatrial block or a form of 'overdrive suppression' of the sinus node. Postpartum an atrial septal defect with a right-left shunt was diagnosed, with a moderate volume overload of the right ventricle. The electrocardiogram revealed a shortened PQ duration and a wide QRS complex possibly due to an accessory pathway. Seven months after birth, atrioventricular junctional tachycardia has not been observed.
3. Figure 6 is a recording from a fetus in the 35th week of gestation with two types of extrasystole: one supraventricular and the other probably originating from the bundle of His. In the latter the QRS complexes were of varying duration; in addition, the coupling interval of the premature beats with wide complexes was shorter. This suggests that the origin of the extra-systole was in the neighbourhood of the bundle of His with varying bundle branch block, depending on the coupling interval. In some cases these premature beats were followed by a prolonged pause (Fig. 6 c, d). As there was no evidence

Table 1. Number of fetal magnetocardiogram recordings examined at different times during pregnancy and the frequency of deviations from normal rhythm in these recordings. SA = sino-atrial; ES = extrasystole; SVES = supraventricular extrasystole; VES = ventricular extrasystole.

Week of gestation	Recordings examined	Slow beats*		Recordings with		
		< 100 bpm	> 100 bpm	SA block	ES (SVES/VES)	Tachycardia
16–23	32	9	16	–	2 (2/0)	–
24–31	60	11	18	–	6 (3/3)	–
32–42	81	6	6	3	13 (11/3)	2
TOTAL	173	26	40	3	21 (16/6)	2

*Single beats or short episodes with an RR interval duration of around 600 ms (see Results section).

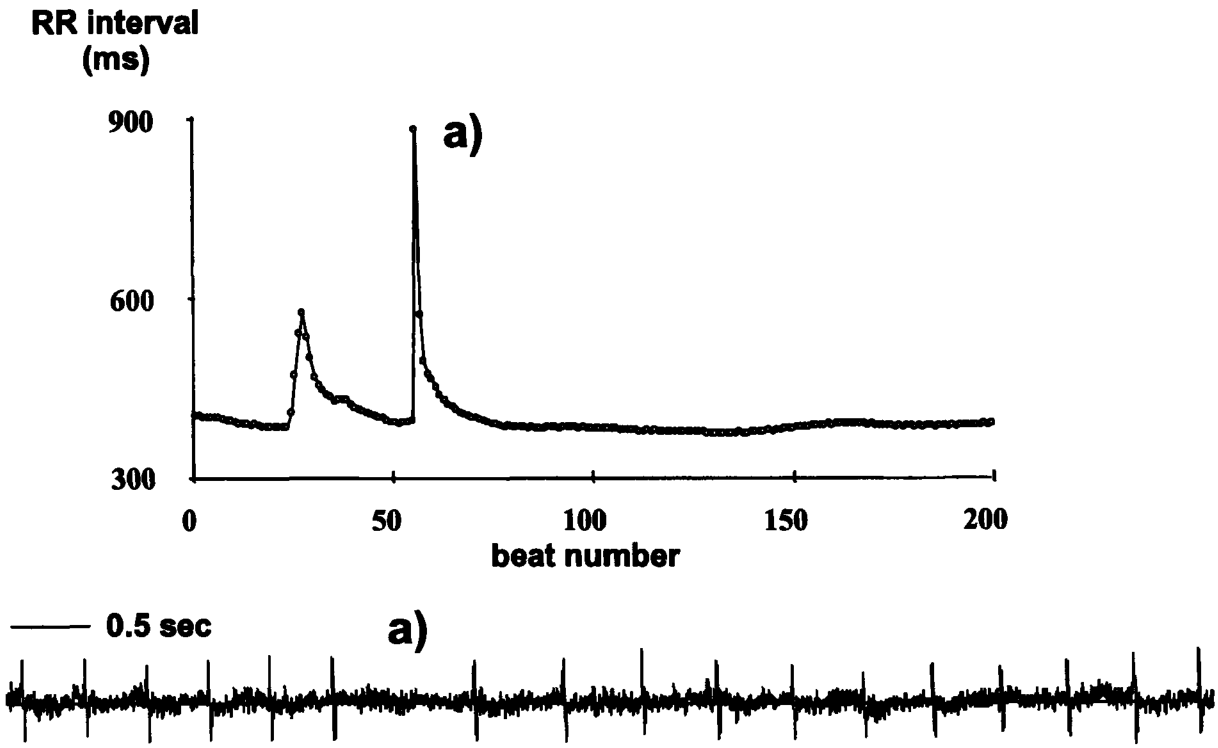

Fig. 2. Episode of fetal bradycardia in the 20th week of gestation: a sudden lengthening of the RR interval to 881 ms (a) is shown in the time series of the RR intervals and in the signal trace.

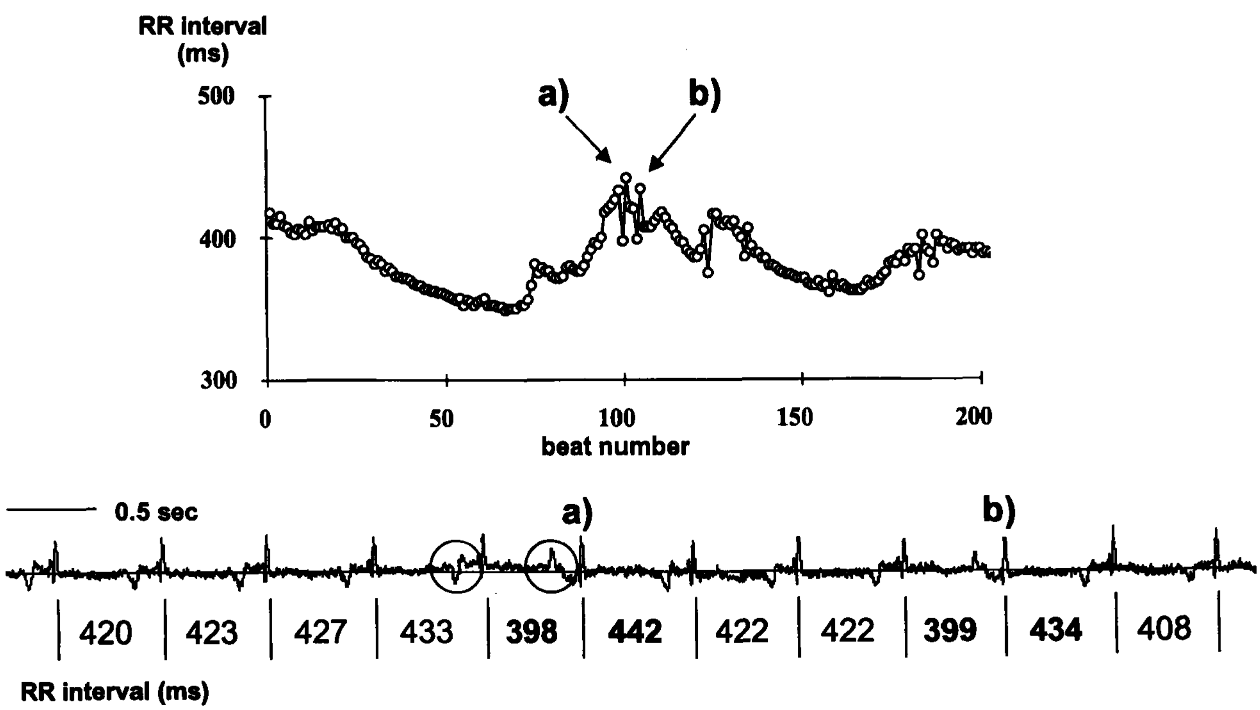

Fig. 3. Time series and signal trace of a fetus in the 36th week of gestation: a) and b) indicate supraventricular extrasystoles. Note the changes in P wave morphology in the signal trace (circled).

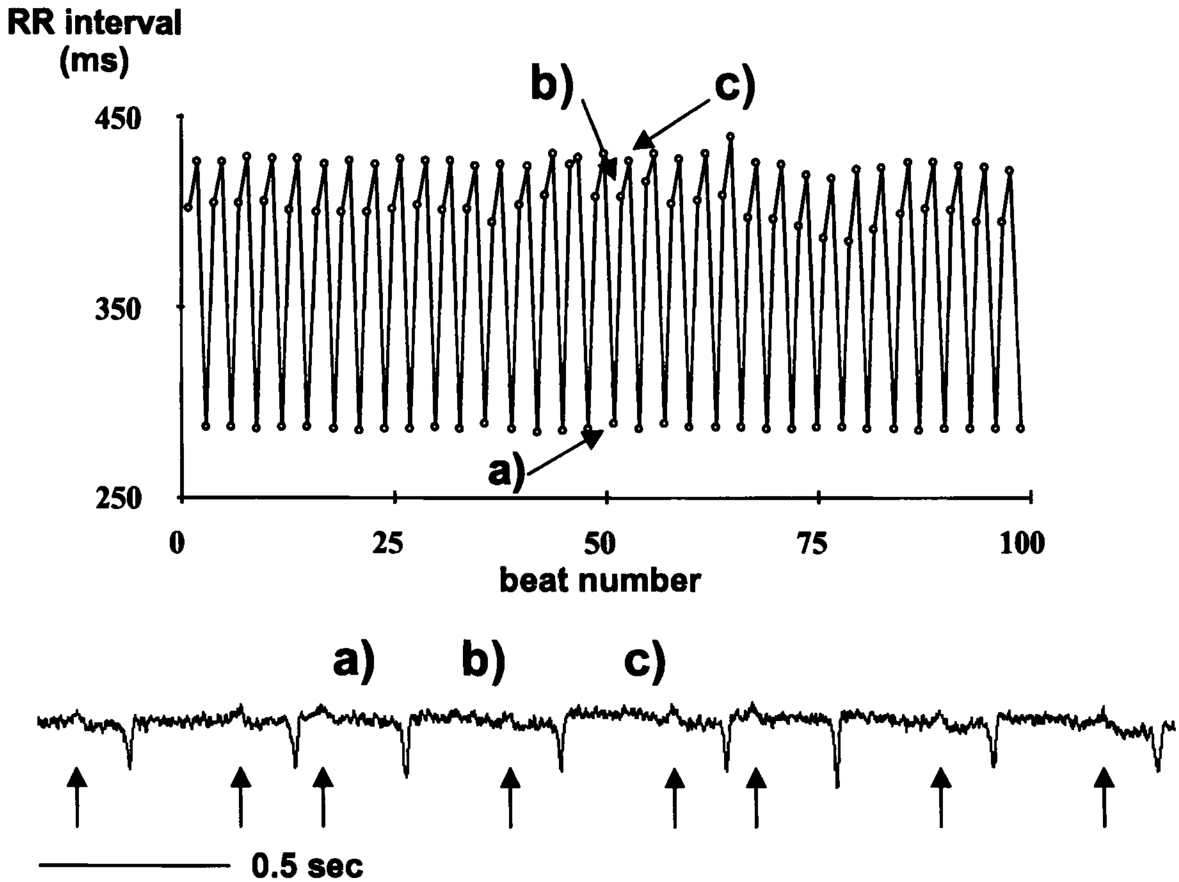

Fig. 4. Time series and signal trace of a fetus in the 31st week of gestation: a) extrasystolic beat followed by two beats, b) and c), of normal duration. Note the timing of the P waves (↑).

of a P wave, depression of the sino-atrial node or sino-atrial conduction may have occurred. Although the mother had acquired chicken pox in early pregnancy, this was not associated with embryopathy. After birth episodes of bradycardia with heart rates about 70 bpm occurred. In the absence of structural disease no treatment was given.

4. Figure 7 shows a trace obtained in the 34th week of gestation which included frequent ventricular premature beats, episodes of bigeminy and period doubling. The extra-systolic beats in the bigeminy included wide and narrow complexes, suggesting ventricular as well as supraventricular origins. Digital averaging of the beats demonstrating a period doubling allowed the clear identification of a P wave prior only to the QRS complexes, implying that the pause was caused by a second degree sino-atrial block. The child was born by caesarean section in the 39th week (oligohydramnios, late decelerations) and no further evidence of arrhythmia was found in the first postnatal year.
5. We documented one case with tachycardia in the 37th week of gestation. During a 10 minute recording a normal heart rate of 150–170 bpm was interrupted by a premature beat which led to a 10 s episode at a heart rate of ca. 270 bpm (Fig. 8). It began with an RR interval of 212 ms which gradually increased to 241 ms when the tachycardia terminated and the heart rate returned to normal. Examination of the digitally-averaged sinus rhythm beats allowed the identification of a P wave, whereas the averaged tachycardia beats showed no evidence of atrial depolarisation. However, subtracting the QRS complex of the sinus beat from the QRS complex of the tachycardia beat showed P waves embedded in the QRS complexes (Fig. 8 c, d). The differential diagnosis includes an atrial tachycardia with a long atrio-ventricular delay or a tachycardia associated with atrio-ventricular nodal re-entry. Atrio-ventricular junctional tachycardia seems unlikely due to the short RP interval. The mother was subsequently treated with digitalis and, although fetal supraventricular extrasystoles were observed in a follow up magnetocardiogram, further episodes of tachycardia were not observed. The baby was born in the 38th week

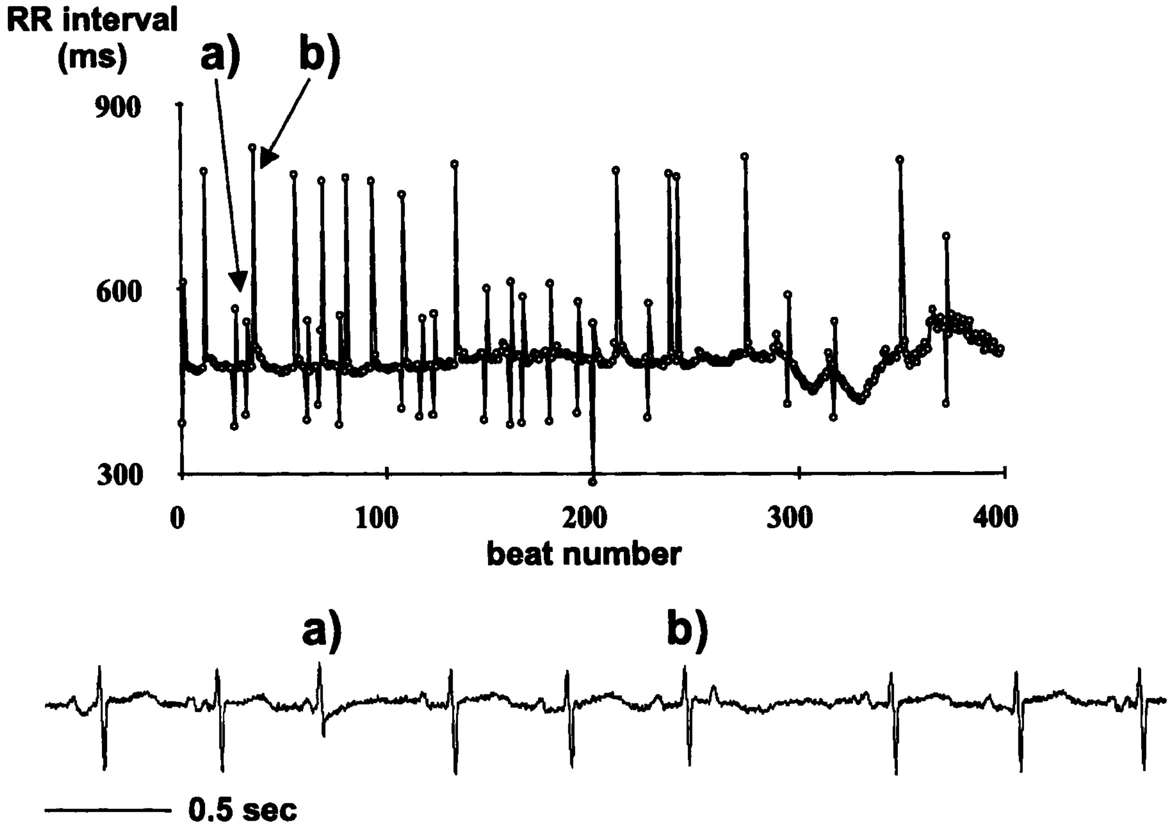

Fig. 5. Time series and signal trace of a fetus in the 42nd week of gestation: the trace shows a) the sinus rhythm interrupted first by a supraventricular extrasystole and shortly thereafter b) by a supraventricular extrasystole with atrio-ventricular block (note the P wave directly following the QRS complex).

and atrial tachycardia with 4:3 conduction was diagnosed. There was no evidence of an accessory pathway. The newborn was treated with digitalis until the age of one year when no further episodes of atrial tachycardia occurred.

DISCUSSION

Fetal arrhythmias may be identified and differentiated using M-mode echocardiography, two dimensional imaging, pulsed Doppler and colour flow Doppler by examining the movement of cardiac structures and blood flow patterns[7–9]. As a complement to these methods, the present study demonstrates the possible usefulness of magnetocardiography in the recording and diagnosis of fetal arrhythmias. As in electrocardiography, it allows the examination of the electrical impulses of the heart whereby the waveform is generated by the magnetic component of fetal cardiac activity. In contrast to fetal electrocardiography, the good signal-to-noise ratio of the magnetocardiogram allows clear identification of deviations from a normal rhythm as well as the classification of conduction abnormalities on the basis of the morphology of the magnetic waveform. Various forms of arrhythmia have been described using magnetocardiography, from the mid-trimester onwards[6,10–12].

In this study brief episodes of bradycardia, which have been reported by others[1,2], could be identified in a substantial number of magnetocardiographic recordings. They were typically initiated by a single beat with a prolonged RR interval, in episodes with low heart rate variability. As they usually occur in mid-pregnancy when signal quality does not allow the unambiguous identification of the P wave their origin is unclear, although we may presume that they result from a sinus-exit, sino-atrial or atrio-ventricular block. They seem to be of no clinical significance as they have not been associated with fetal pathology[2] and are not to be confused with important bradycardia, defined as heart rates < 100 beats per minutes for > 10 s[9]. Their cessation in later pregnancy probably reflects the development of the fetal conduction system with maturation of the vagal innervation of the fetal heart[13]. Magnetocardiography offers the possibility of investigating this phenomenon in more detail, since it permits a simple, non-invasive recording of

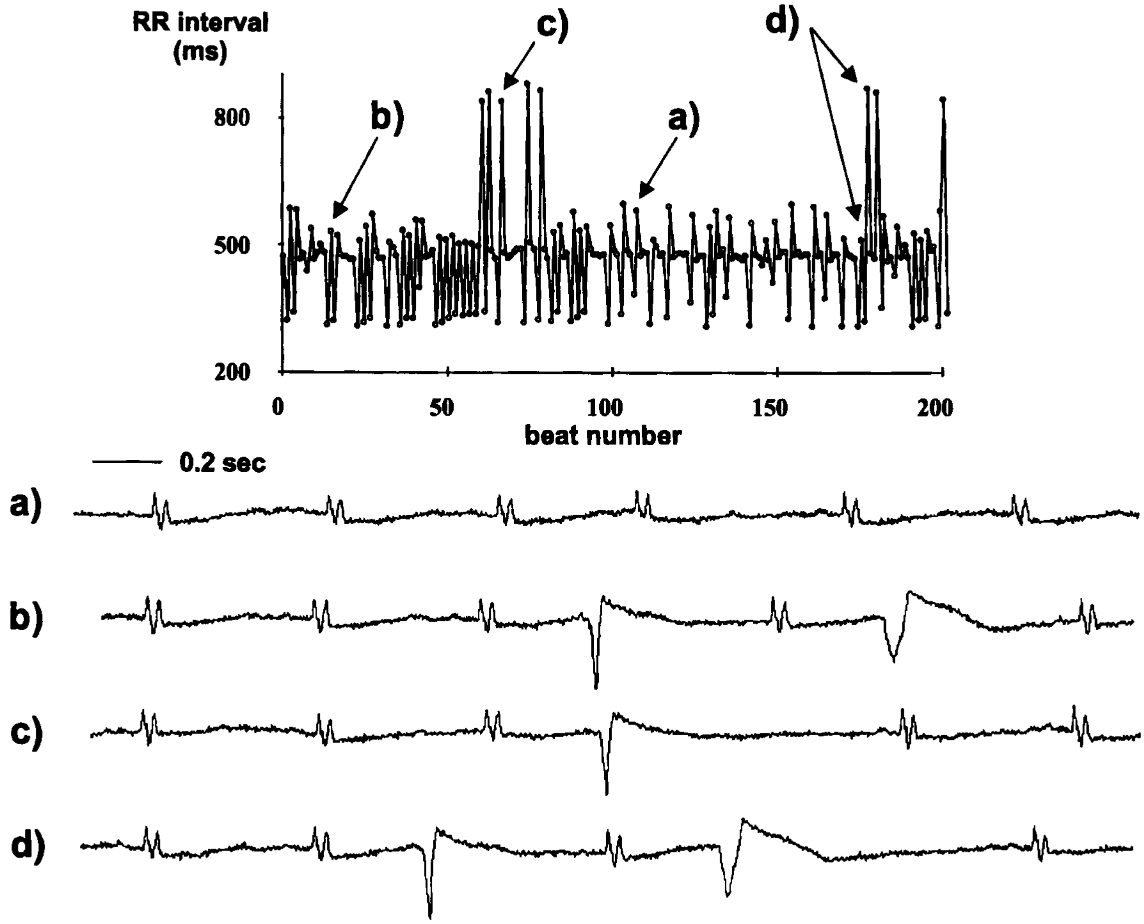

Fig. 6. Time series and signal trace of a fetus in the 35th week of gestation. The signal traces show premature beats a) with QRS morphology similar to normal complexes (supraventricular extrasystoles), b) with differing QRS morphology, c) and d) with a prolonged pause.

fetal cardiac activity in digitised form. Other methods of investigating fetal cardiac activity are unable to detect such subtle changes in development. Further analysis of fetal heart rate behaviour by magnetocardiography will be necessary before a final interpretation of these variations in rhythm will be possible.

Isolated premature (supraventricular and ventricular) beats are relatively common, have been observed throughout pregnancy and generally resolve in the perinatal period[1,2,7]. In general they are considered benign, possibly due to an imbalance between the sympathetic and parasympathetic innervation[14]. It has also been suggested that they result from gastrointestinal stimuli leading to increased vagal activity[15] or from a rise in maternal levels of adrenaline[16,17]. They are of clinical importance in that they may in some cases induce tachycardia, as shown in Fig. 8. Premature beats with atrioventricular block may lead to an ambiguous cardiotocogram, suggesting bradycardia which may be interpreted as resulting from heart block or fetal distress[3]. The case shown in Fig. 6 was referred because of a suspected diagnosis of bradycardia.

The identification of the origin of arrhythmia is made easier by magnetocardiography, as the P wave is often visible in the signal trace (Figs 3–5). If the signal trace is ambiguous then more information is obtained by signal averaging of similar beats, as shown in Fig. 7 and 8. As these examples demonstrate, conduction delays and atrio-ventricular block can be identified and classified by consideration of the relation between the P and R waves as well as their morphology. Of particular interest is the case with tachycardia (Fig. 8) in which digital signal processing allowed a detailed examination of the underlying electrophysiological activity where standard analysis and analysis of the averaged signals did not reveal the underlying arrhythmic mechanism. The subtraction of the QRS complex, revealing the embedded P wave, demonstrates the advantage of digitally acquired signals and their processing.

CONCLUSION

Fetal magnetocardiography is a new test for the

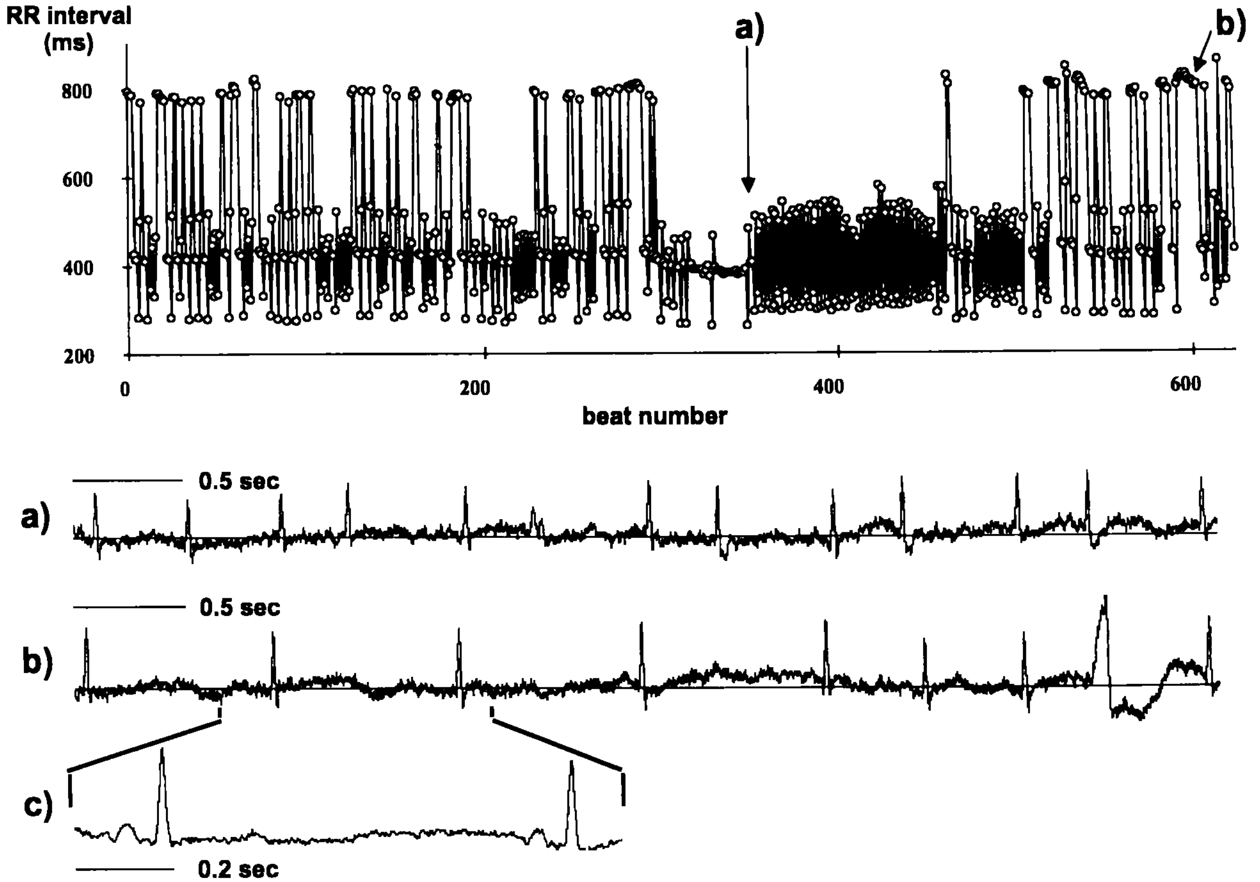

Fig. 7. Time series and signal trace of a fetus in the 34th week of gestation with complex arrhythmias. Traces show a) transition from sinus rhythm to bigeminy with narrow and wide QRS complexes, b) several beats with period doubling followed by a return to sinus rhythm interrupted by an ectopic beat, and c) averaged signal of the bradycardia beats showing lack of a P wave suggesting a sino-atrial block (see text).

identification and classification of fetal arrhythmias and may aid in decisions concerning treatment in pregnancy and childbirth. In this study, there was general agreement of the magnetocardiograms and the cardiac findings in the newborns. Fetal magnetocardiography may therefore be useful in assessing cases with suspected or unclear arrhythmia as well as in the classification of more complex conduction abnormalities. In cases of paroxysmal supraventricular tachycardia, it may help to determine the best time to begin drug treatment. It may also be useful with echocardiography as a screening test in pregnancies at high risk of fetal arrhythmia, such as those with structural cardiac defects, maternal congenital heart disease or systemic lupus erythematosus. Magnetocardiography is noninvasive, fast and easy to perform, the recordings showing high temporal and spatial resolution. It is possible from mid-trimester onwards and is not affected by vernix caseosa. Its general application is hindered by high purchasing and maintenance costs; however, improvements in design and further technological innovation may offset these disadvantages.

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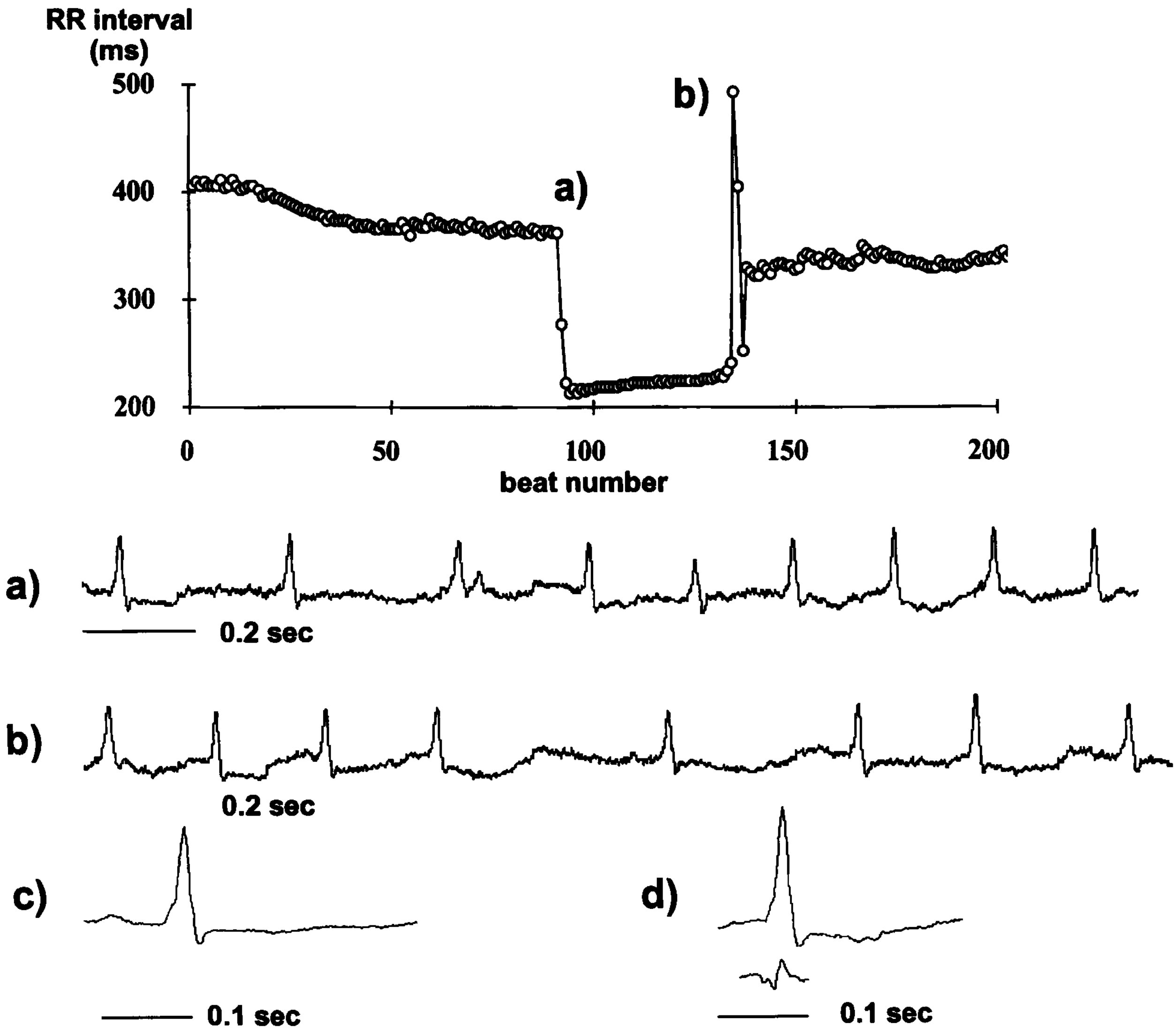

Fig. 8. Time series and signal trace of a fetus in the 37th week of gestation with an episode of tachycardia. The signal traces show a) the beginning and b) the termination of the episode; c) is the signal-averaged normal sinus beat showing the P wave and d) is the signal averaged tachycardia beat showing the embedded P wave (see text).

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