fetal monitoring,
fetal electrocardiography,
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COMPARISON OF INSTANTANEOUS FETAL HEART RATE EXTRACTED FROM ABDOMINAL AND DIRECT FETAL ELECTROCARDIOGRAMS

This work is an attempt to assess the reliability of indirect abdominal electrocardiography as an alternative technique of fetal monitoring. As a reference signal we used the simultaneously acquired direct fetal electrocardiogram. Each recording consisted of four signals acquired from maternal abdomen and the reference signal acquired directly from fetal head. The first stage of our study concerned the signal loss episodes. In order to reduce the influence of incorrectly detected R-waves, some certain validation rules were applied. In the second stage, the corresponding intervals determined on basis of both acquisition methods were matched and the accuracy of fetal heart rate measurement was evaluated. Although the accuracy of abdominal electrocardiography turned out to be slightly lower than reported for ultrasound method, it still has some unique features deciding of its prevalence in a certain circumstances.

1. INTRODUCTION

The heart activity signal measurements rely on detection of successive heart beats and determination of time intervals T_{RR} between them. However, in clinical practice the more often used is the fetal heart rate (FHR, expressed in beats per minute), calculated according to the formula: FHR [bpm] = 60000/T_{RR} [ms]. One of the most commonly used techniques of fetal heart rate measurement is a pulsed Doppler ultrasound method which detects heart beats from movements of the fetal heart. However, Doppler ultrasound monitors provide the FHR which is not a true beat-to-beat heart rate but represents an average over neighbouring beats [9].In fact, the exact cardiac cycle can be measured only on a basis of electrical activity signal – the fetal electrocardiogram (FECG). Recording of FECG can be accomplished by two methods: the direct one – possible only during labour, where the spiral electrode is directly attached to the fetal head, and the indirect one – where measuring electrodes are placed on maternal abdomen. The direct method provides the reference signal – where the low frequency interferences can be easily filtered out. However, the most promising from the clinical point of view is the indirect method, which has two fundamental advantages over the direct one: it is non-invasive and can be applied during pregnancy. Of course, the main problem of its practical implementation is the maternal electrocardiogram (MECG), many times exceeding the useful signal. Additionally, during labour the second source of unwanted component is the uterine contractile activity [2].

So far, there has been no comprehensive study evaluating the accuracy of fetal heart rate measurement in abdominal FECG signal, on a beat-to-beat basis. In some papers the work is limited just to an assessment of success rate of deriving the FHR measurements from the raw abdominal data [5, 11, 18] or the accuracy assessment is based on Doppler ultrasound technique [6, 19]. The major shortcoming of using a direct FECG technique is its invasiveness. However, some reports have compared abdominal and direct FECG recordings. Graatsma et al. [4] analyzed 22 intrapartum recordings of one-hour duration and compared beat-to-beat FHR values but the recording system had sampling frequency equal to 300Hz, which is inadequate to determine true beat-to-beat variation. The intrapartum recordings of better quality (32 channels at 1 kHz) were acquired by Clifford et al. [1]. However, since the main aim of their work was to prove that abdominal FECG signal can be extracted without distorting the ST-segment, the beat-to-beat accuracy of FHR measurement was not evaluated.

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The aim of this study was to look at the feasibility of the abdominal electrocardiography as a reliable technique for fetal monitoring. The accuracy of derived T_{RR} intervals was evaluated in reference to the direct electrocardiography, which remains the "gold standard". The acquisition of direct FECG was possible only during labour, that strongly affects the quality of abdominal records, due to a considerable muscular activity of the uterus. Therefore, the reliable evaluation of method accuracy required a detailed analysis of signal loss periods.

2. METHODOLOGY

We have developed a computer-aided instrumentation for simultaneous recording and analysis of FECG signals from the maternal abdomen and directly from a fetal head. The recorder is equipped with four differential abdominal channels and one for connecting a spiral electrode attached to the fetal head [7]. The electrodes were placed as shown in Figure 1: four around the navel, a reference electrode above the pubic symphysis and a common mode reference electrode (with active-ground signal) on the left leg. Both direct and abdominal signals were acquired simultaneously and their processing was carried out in on-line mode. The comparison process itself was accomplished off-line.

Suppression of the dominant component in abdominal signals – the maternal electrocardiogram – is the decisive step in the abdominal fetal electrocardiography [18]. The MECG amplitude is much higher than the FECG one and the overlapping of the frequency contents of the maternal and fetal QRS complexes makes the suppression of MECG by the simple filtering impossible [11, 14]. The applied method of MECG suppression consists of the following steps: determination of the precise locations of maternal QRS complexes, PQRST pattern calculation of the weighted averaging method [16, 17] and its subtraction from abdominal signal around these complexes [13].

Then, the resulting signal is provided to the fetal QRS-complex detector, consisting of two main blocks: the fetal QRS enhancement block (based on digital filter cascade with frequency response magnitude adjusted to the spectrum of fetal complexes) and the heart beat determination block, whose task is to detect the peaks and to decide whether the peak represents the R-wave or not. This online detector was described in details in [12, 15].

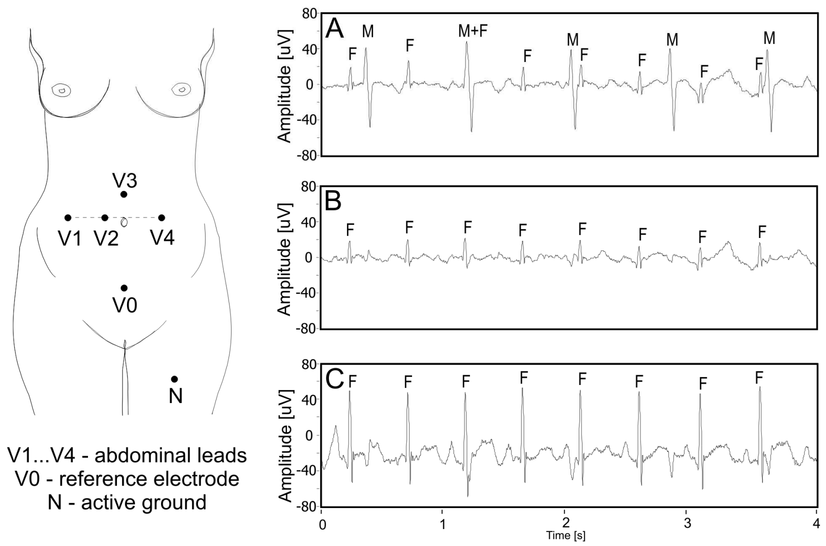

Fig. 1. A typical configuration of the abdominal electrodes and selected fragment of high quality FECG signals. A – abdominal signal after preliminary filtering, B – abdominal signal after MECG component suppression,
C – direct FECG signal simultaneously recorded from fetal head
(M – maternal QRS complexes, F – fetal QRS complexes).

The time interval between two consecutive R-waves defines the duration of cardiac cycle T_{RR}. Before the accuracy of T_{RR} intervals can be assessed, the detected complexes must undergo the validation. The applied procedure is based on a set of decision rules, complying with the physiological range of possible changes of successive fetal heart beat durations. The validation starts from basal rule [3]. In the first step those peaks are accepted for which the calculated T_{RR} period fulfills the formula:

$$T_{RR}(i-1)-0.43\cdot\Delta(i-1)<T_{RR}(i)<T_{RR}(i-1)+\Delta(i-1) \tag{1}$$

where:

$$\Delta(i-1)=\begin{cases}T_{RR}(i-1)-300ms & dla \quad T_{RR}(i-1)\geq 320ms\\ 20ms & dla \quad T_{RR}(i-1)<320ms\end{cases}$$

The range of acceptable T_{RR} changes is based on two premises: the acceptable change between two successive intervals proportionally depends on the value of these intervals, and the wider range of changes is permitted if the interval is extending (i.e. during deceleration pattern of the FHR). The final acceptance is granted to those peaks that belong to the group of three consecutive peaks fulfilling the (1). To assure correct interpretation of heart beats within the slopes of acceleration or deceleration patterns, a wide range of instantaneous changes of FHR is accepted. However, it leads to incorrect detections of QRS complexes during ‘flat’ segments of FHR signal, so that in many cases the obtained T_{RR} values are in fact erroneous. Commonly the peak provided by QRS complex detector is slightly shifted in time in relation to the actual QRS complex. The incorrectly determined R-wave position affects two successive beats, resulting in lengthening of one and shortening of the other. Since the differences are rather small, according to (1) the obtained interval values are accepted, distorting the analysis of beat-to-beat variability. Therefore, we proposed an additional rule for validation of detected R-wave positions, which is based on analysis of monotonicity of beat-to-beat changes. A given T_{RR} interval is assumed to be incorrect if its first derivative changes the sign for this interval and a product of differences between a given T_{RR} interval and the neighboring ones exceeds 25 [10].

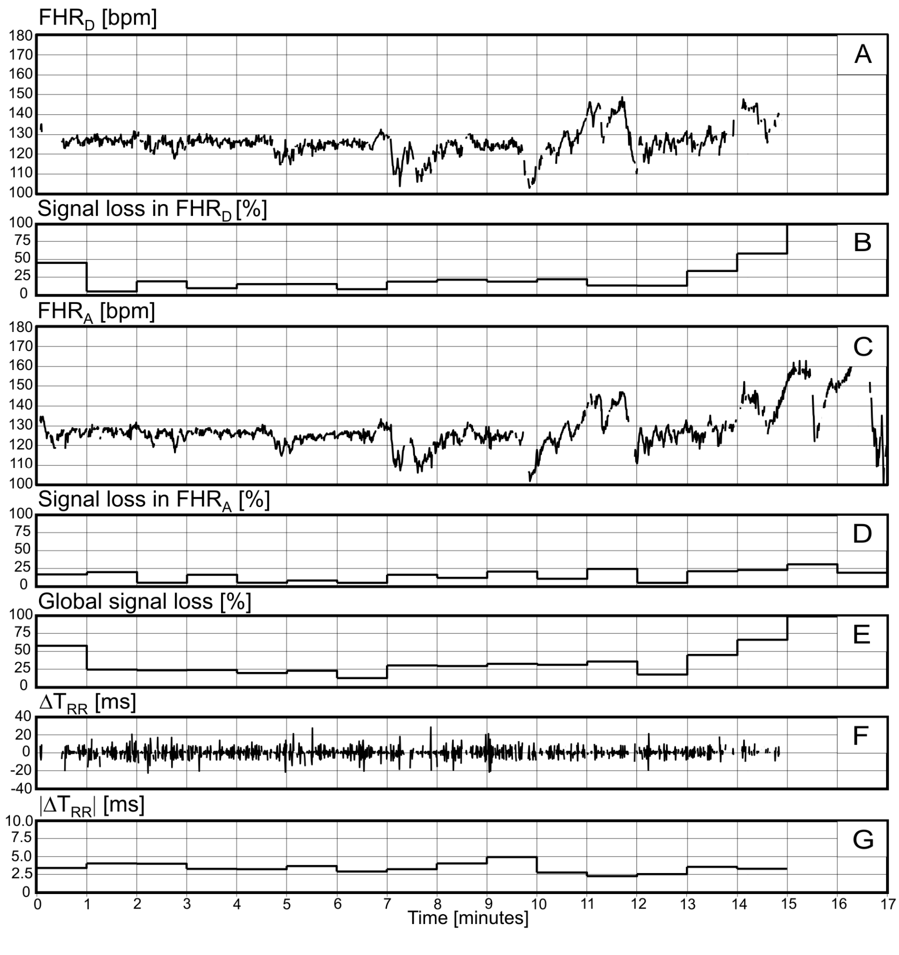

Fig. 2. Illustration of successive steps of T_{RR} accuracy evaluation procedure for abdominal electrocardiography in relation to the reference intervals obtained by direct approach. Part A is a FHR_D signal obtained from direct electrocardiography whereas the C is the simultaneously acquired fragment derived from the abdominal method. The plots B and D respectively let us evaluate a percentage of signal loss in particular one-minute segments for each method, while the E shows the global signal loss as an OR function of both. Waveform F presents interval measurement errors determined as differences between the corresponding intervals. The mean interval measurement errors calculated over one-minute segments are presented by plot G.

Finally, two signals describing the electrical activity of fetal heart, calculated on a basis of abdominal information (A) and from direct electrode (D), are obtained. In Figure 2 there is an example recording with the signal loss marked as discontinuity in FHR_D and FHR_A waveforms. Also a percentage of signal loss in the successive one–minute fragments was calculated for each recording. Then FHR_D and FHR_A signals were directly compared to determine differences between corresponding beat durations and to calculate the absolute error of interval measurement. However, to assure reliable measurement of accuracy of the abdominal method it was necessary to remove from both signals all those fragments where at least one method was unable to provide correct measurements. A global signal loss parameter was defined (Fig.2E) to indicate which fragments of both signals would undergo detailed comparison. The differences between corresponding intervals ($\Delta T_{RR} = T_{RR}^{A} - T_{RR}^{D}$) are graphically presented in Fig. 2F, whereas Fig. 2G depicts the mean absolute ΔT_{RR} calculated in one–minute fragments.

3. RESULTS

Our comparative study was based on four recordings comprising signals acquired from maternal abdomen and the reference FECG signal acquired directly from fetal head (Fig. 1). In all cases the scalp electrode was placed for a clinical indication. Ethics committee approved all procedures and informed consent was obtained from every woman. Signals were recorded in the Department of Obstetrics at the Medical University of Silesia. The patient age was between 21 and 25. The recordings were made during established labours from 38 to 41 weeks of gestation. Total monitoring time was 265 minutes. A total number of 36325 "possible T_{RR} intervals" were determined in all transabdominally acquired fetal electrocardiograms, while the direct FECG signals contained 36695. After application of validation rules a total number of 22939 correct T_{RR} intervals (63.1%) remained in FHR_A signal, and 27024 (73.6%) in FHR_D signal. We can notice that the signal loss ratio was much lower in FHR_D signals. Only the shortest Rec. 1 is an exception from this rule, as the total signal loss in FHR_D signal was twice higher (334 seconds compared to 170 seconds in FHR_A). After the validation process, the signals are characterized by different number and duration of signal loss segments. Therefore, in order to compare them, we additionally rejected all those T_{RR} intervals which had been previously classified as a signal loss in at least one of the FHR signals. Table 1 presents a detailed data describing the correct T_{RR} intervals that were qualified to the final comparative signal analysis.

Table 1. Detailed data describing the acquired signals, validation results as well as the number and duration of correct T_{RR} intervals qualified to the comparative analysis.

		Rec. 1	Rec. 2	Rec. 3	Rec. 4	Σ
Duration [s]		1058	7668	2206	4988	15920
Detected intervals [n]	D*	2355	17208	5225	11907	36695
	A#	2244	17101	5134	11846	36325
Accepted by validation rules [n]	D	1514	13677	2944	8889	27024
	A	1897	11786	1483	7773	22939
Signal loss[s]	D	334	1407	891	1141	3773
	A	170	2353	1555	1697	5775
Compared T_{RR} pairs [n]		1335	9654	1123	5828	17940
Resulting signal	[s]	637	4388	485	2466	7976
	[%]	60.21	57.22	21.99	49.44	50.10
Pearson corr. (r)		0.98	0.97	0.99	0.99	0.98

*in direct FECG; #in abdominal FECG

Finally, 17940 pairs of T_{RR} intervals obtained from both methods were used for direct comparison (with total length above 132 min). Analyzing the average values of T_{RR} intervals for different recordings we did not notice any statistically significant difference (t-Student test, $p>0.05$). Moreover, for corresponding T_{RR} intervals we noticed high value of Pearson correlation coefficient ($r=0.98$, $p<0.01$).

The detailed values of descriptive statistics, concerning the differences between the corresponding T_{RR} intervals, represented in a form of time event series (beat-to-beat) is presented in Table 2.

Table 2. The descriptive statistics concerning the differences between corresponding T_{RR} intervals, derived from direct and abdominal methods.

Term		Rec.1	Rec.2	Rec.3	Rec.4	Σ
Mean value of interval differences	ms	-0.04	0.03	-0.07	-0.07	-0.01
	bpm	0.01	-0.01	0.02	0.02	0.00
Standard deviation	ms	5.07	6.97	5.67	5.09	6.13
	bpm	1.32	2.05	1.76	1.79	1.89
Double standard deviation	ms	10.14	13.94	11.34	10.18	12.26
	bpm	2.64	4.10	3.52	3.58	3.78
Mean value of absolute interval differences	ms	3.30	4.96	3.56	3.42	4.25
	bpm	0.87	1.45	1.14	1.19	1.30
Median value of absolute interval differences	ms	2.00	3.00	2.00	2.00	2.00
	bpm	0.51	0.99	0.74	0.78	0.87

It can be seen that the mean value of interval differences is close to zero. It proves that the T_{RR} values derived from abdominal signals are not affected by a systematic error. The standard deviation of differences is very similar for particular recordings, ranging between 5.07 and 6.97 ms (1.32 – 2.05 bpm). Considering standard deviation we can notice that 68% of differences do not exceed 6.13 ms, whereas only 5% are higher than 12.26 ms. Compared to a typical T_{RR} interval length in our research material (usually between 400 and 500 ms), these values seem to be rather low. Additionally, two different error measures are calculated for the time event series representation: mean absolute error equal to 4.25 ms (1.30 bpm) and median of absolute error equal to 2.00 ms (0.87 bpm).

4. DISCUSSION

The main aim of our work was to assess the reliability of indirect abdominal electrocardiography as an alternative technique of fetal monitoring. As a reference method we used the direct FECG, being the gold standard for the instantaneous FHR values determination. The signals acquired from scalp electrode were distorted by low frequency interferences connected with movements of the patient. Additionally the electrode very often was losing contact with fetal head, causing temporary signal loss. The power line interferences were rather absent, however, the interferences of maternal muscle and heart activity were visible. The labour conditions also affected the quality of abdominal FECG signals. In this case the main source of interferences was strong bioelectrical activity of uterus during labour contractions. Closer analysis of distribution of the FHR signal loss episodes showed that almost all of them (for both FHR_A and FHR_D) were not longer than 10 s (most of them were shorter than 2 s). However, in all FHR_D signals longer episodes of signal loss (up to 100 s) occurred. They were caused by cyclic palpation examination routinely performed by the obstetrician during labor (which had almost no influence on quality of FHR_A signal).

Finally, only those intervals were accepted for the comparison, which were successfully measured using both acquisition methods. In effect, due to the low quality of signal derived from at least one of the acquisition techniques, a half of the recording (50.1% of the total signal length) was removed from the process of T_{RR} accuracy assessment. Pieri et al. [18] analyzed large dataset of abdominal recordings and obtained success rate of around 65% (the success rate was defined as the percentage of the total recording time during which valid FHR data, averaged over 2 s, could be produced). This value was very similar to the results obtained in our study (36% signal loss rate for abdominal signals), nevertheless, our analysis was performed on a beat-to-beat basis. Better results were noted by Guerrero et al. [5], who reported sensitivity of QRS detector equal to 89%, which means that only 11% of QRS complexes were not recognized. However, the R-wave location error (with reference to R-waves manually marked) was as high as 11.96 ms, with standard deviation 9.56 ms.

The remaining verified pairs of T_{RR} values were a basis for the main analysis of quality of abdominally acquired FHR signals. However, the most often used accuracy measure is the mean absolute difference between corresponding T_{RR} intervals. This parameter was equal to 4.25 ms (1.30 bpm) on average. The mean absolute errors as well as standard deviations were very similar for all recordings, except for recording 2, where obtained error values were considerably higher. Most likely it was caused by variability of signal shape related to biphasic QRS complexes being observed in abdominal FECG signal. The inaccuracy of R-wave localization resulted in noticeably higher errors while comparing the T_{RR} values derived from both methods.

The obtained error value of 1.30 bpm indicates that the accuracy of indirect FECG is similar to the Doppler ultrasound acquisition method evaluated in [9], where the mean absolute error of interval measurement was equal to 0.89 bpm. It confirms that even at current stage of its development, the abdominal electrocardiography offers accuracy equivalent to Doppler ultrasound method [8]. What is more, the indirect electrocardiography has a number of advantages over the ultrasound technique. The Doppler fetal monitor is unsuitable for long-term ambulatory use and the transducer has to be continually repositioned to ensure that the fetal heart is within the ultrasound beam. Abdominal FECG technique is completely passive and uses standard electrodes, which means that it can be used for long-term recording without the presence of trained operators. Additionally, an analysis of morphology of FECG (for example the ST segment changes) may result in a completely new quality of diagnostic information, enabling up-to-date verification of fetal distress, especially in case of abnormal or suspicious signal patterns [20].

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