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THE INFLUENCE OF WINDOW SIZE OF AUTOCORRELATION FUNCTION ON FETAL HEART RATE VARIABILITY MEASUREMENT USING THE DOPPLER ULTRASOUND SIGNAL

Commonly used noninvasive fetal monitoring is based on fetal heart rate (FHR) variability analysis of the Doppler ultrasound signal coming from the mechanical activity of the fetal heart. Estimation of periodicity of acquired signals using the autocorrelation technique is very important. The determination of cardiac intervals using the Doppler signal is more difficult than in electrocardiography, where the R-waves are evident. We investigated the influence of the autocorrelation window size on the FHR variability analysis. The indices describing the FHR variability calculated for signals obtained using two different autocorrelation techniques with various window lengths were compared with the reference ones obtained from fetal electrocardiogram. The optimal window was a compromise between artifacts resistance and the averaging level of instantaneous variability.

1. INTORDUCTION

Evaluation of instantaneous variability of fetal heart rhythm is considered as a valuable predictor of the fetal state. In automated analysis of the fetal heart rate (FHR) signal two main components of instantaneous variability (short- and long-term) are evaluated quantitatively using various numerical indices. The most widely used method of FHR acquisition is based on the Doppler ultrasound (US). Long-term FHR variability indices derived from this method are obtained with rather a good precision. However, depending on the calculation procedure, the short-term variability indices may be considerably decreased while using autocorrelation technique to process the Doppler ultrasound wave.

The highest possible accuracy of the fetal cardiac interval measurement is ensured by the direct fetal electrocardiography (FECG), when during labour an electrode is directly attached to fetal head [4]. In the Doppler ultrasound technique the fetal heart beats are detected from the envelope of the ultrasound signal containing information on valves and walls movement (Fig.1). It is impossible to detect an evident point (the equivalent of the R-wave from FECG) using simple peak or threshold detection methods. Therefore, the FHR values are determined usually by the use of autocorrelation or cross-correlation techniques. The cross-correlation method is based on comparing the incoming signal with the changeable template. In the autocorrelation technique the adaptive window width selection is the most important and this problem is the subject of this paper.

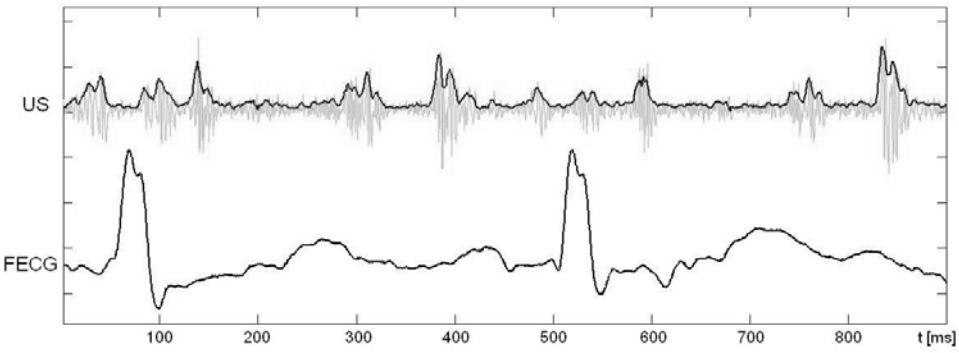

Fig.1 The fetal direct electrocardiogram (FECG) from the fetal head and simultaneously recorded the Doppler ultrasound signal (US) from the ultrasound transducer

In autocorrelation technique a function of similarity between the input ultrasound signal and its time-shifted version is analyzed [3]. Determination of the autocorrelation function and the position of its dominant peak enable the determination of the cardiac cycle duration T_i. Values of T_i intervals are transformed into instantaneous fetal heart rate (FHR) expressed in beats per minute (bpm) accordingly to the equation: FHR_i [bpm] = 60000 / T_i [ms]. In this paper we simultaneously use the FHR_i term in reference to the instantaneous periodicity as well as to the interval duration T_i. Simple approach to FHR signal

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determination relies on a preliminary segmentation of the US envelope in relation to particular heart beats. Then, for each segment the autocorrelation function is calculated within the window of the established length. Position of the function maximum estimates the FHR value in the given interval. More often the calculation of an autocorrelation function is repeated many times for a given cardiac cycle. This provides a new interval value with every autocorrelation function repetition. Therefore, the instantaneous FHR is represented by a set of evenly spaced values [2]. In the next phase the signal has to be divided into segments corresponding to cardiac cycles and the final FHR values should be calculated from the measurement series. The ultrasound method provides lower measurement accuracy of the fetal cardiac cycle durations than the fetal electrocardiography does. This is particularly visible while comparing the indices describing the short-term FHR variability [3]. In this paper we discussed the influence of fetal heart rate estimation method on the results of FHR variability analysis. The descriptive parameters obtained via ultrasound are evaluated with the reference values from the direct fetal electrocardiography.

2. METHODOLOGY

The research material is based on two signals simultaneously recorded during labour: electrocardiogram captured directly from the fetal head as the reference signal and the signal from mechanical activity of fetal heart acquired using the US method. Both signals were sampled with 2 kHz. Three traces of the total length of 28 minutes (3630 intervals) were chosen for analysis. The cross-correlation function was used to find QRS complexes in FECG signal by comparing the signal with a template. Since the R-wave is the dominating component of the QRS complex, the cross-correlation peak corresponds to matching of the R-waves in two complexes being compared. Therefore, a distance between two consecutive peaks is the reference T_i interval.

In order to evaluate the influence of the window length on FHR variability assessment, two different approaches were applied to determine the cardiac intervals from the Doppler ultrasound signal. Determination was carried out in two stages. In the first one, the characteristic points were preliminary found, which defined segments corresponding to consecutive heart beats [4]. For this task, the Doppler envelope underwent low-pass filtering with the cut-off frequency of 2 Hz. Then, the local maximums were recognized in the obtained low frequency signal and established as the characteristic points (Fig. 2b). In the second stage precise T_i intervals were calculated using two different algorithms.

Algorithm A: The characteristic point (after taking into account the signal time shift caused by the filtering process) defines a location of center of the window comprising the original Doppler envelope, where the autocorrelation function is calculated (Fig. 2c). The autocorrelation function (and thus the instantaneous FHR value) is calculated only once for each heart cycle, which significantly reduces a computational time, and it is the main advantage of this method.

Algorithm B: This algorithm is based on multiple cyclic calculation of autocorrelation function describing values of cardiac cycles. The algorithm determines the autocorrelation function within a window of assumed width and shifted with every 40 samples. This results in 50 calculations of instantaneous FHR per second for the sampling frequency of 2 kHz. Since each heart interval is measured many times, the obtained FHR signal provides several slightly different values of heart beat periodicity between two consecutive characteristic points (Fig.2d). In each segment the incorrect samples are excluded, and the mean value from the rest is the FHR value which describes the heart beat being analyzed (Fig. 2e). Incorrect samples was recognized with a help of criteria for T_i interval validation. [5].

Because of the wide physiological range of the FHR values the window length in both algorithms can not be set as a constant value. Thus, adapting of window length adjustment was involved. When the current FHR value is obtained, the new length T_{win} (expressed in milliseconds) is recalculated according to the formula: $T_{win} = T_i \cdot C$, where T_i is the length of the last interval, and C is the window scaling factor. For the whole analyzed trace the scaling factor was constant. Analysis of trace was repeated with the factor being modified from 2 to 5 and additionally for C = 1.75 with a step of 0.5.

Direct comparison of corresponding intervals, simultaneously obtained from the ultrasound signal and fetal electrocardiogram was accomplished using the mean value and standard deviation of the absolute error of T_i interval determination: $\Delta T = | T_{US} - T_{REF} |$ [ms]. The analysis of instantaneous FHR variability was carried out basing on two indices: STI index for short-term and LTI index for long-term variability [1]. For each record the ultrasound and reference STI (LTI) indices were computed over one-minute segments, and the relative error δSTI was calculated as: $\delta STI = (STI_{US} - STI_{REF}) / STI_{REF}$ [%] and δLTI respectively.

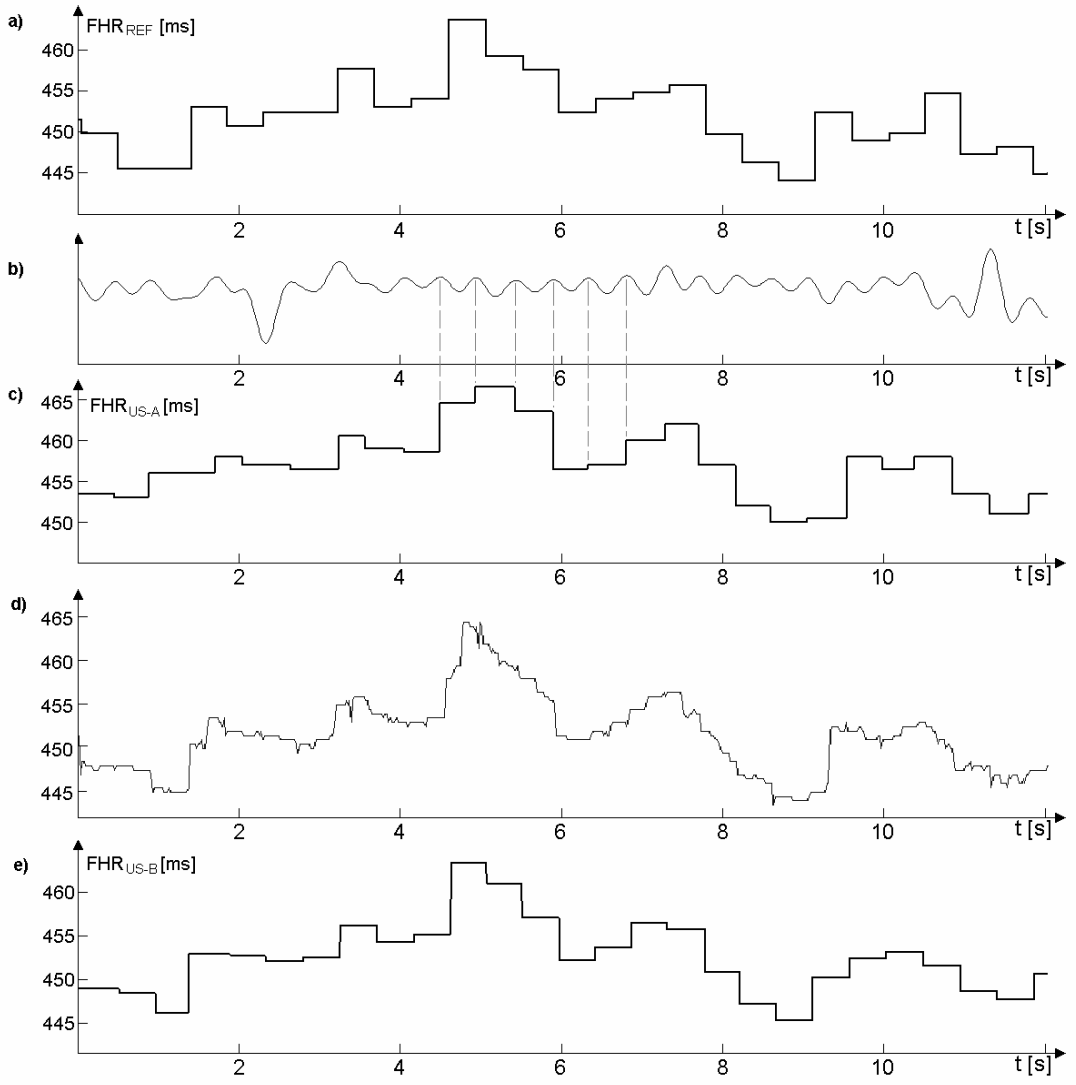

Fig.2 Determination of the instantaneous values of the fetal heart rate as time event series. a) Reference FHR_{REF} signal from the fetal electrocardiogram. b) Slow-varying signal obtained by low-pass filtering of Doppler ultrasound envelope with cut-off frequency of 2 Hz. Peak detection appoints estimated locations of the heart cycles. c) FHR_{US-A} signal obtained from the ultrasound using algorithm A. d) Signal obtained from ultrasound, containing evenly spaced redundant values of heart beat periodicity within each heart cycle. e) FHR_{US-B} signal obtained from the ultrasound using algorithm B.

3. RESULTS

Generally, regardless the autocorrelation window length applied the better results were obtained using the method B. The lowest value of the interval error was 1.4 ms for C = 2, whereas for the algorithm A the lowest value of 1.8 ms was noted for the window with C = 2.5 (Fig. 3). For both algorithms, we noticed that for the autocorrelation windows with $C \geq 2.5$, as the window scaling factor increases by one the ΔT increases by 0.5 ms. It is caused by the fact, that longer window comprises several intervals and the output value represents their mean value. In this range of C value, the difference between corresponding ΔT for both methods is practically constant and equal to about 0.15 ms. This difference takes significantly larger value of about 0.5 ms for window with C = 1.75 and C = 2. It is because for shorter autocorrelation widows for the algorithm A, where a given interval is determined only once, influence of window positioning in Doppler signal increases. In the algorithm B, where a given interval is measured several times, this influence is quite low. This algorithm for window with $C \leq 2$ is more stable, that is confirmed by the SD value presented in Fig. 3. This is important considering that value of the interval calculated in short window does not include the error component resulting from averaging characteristics of the autocorrelation and allows for more precise determination of the FHR variability indices.

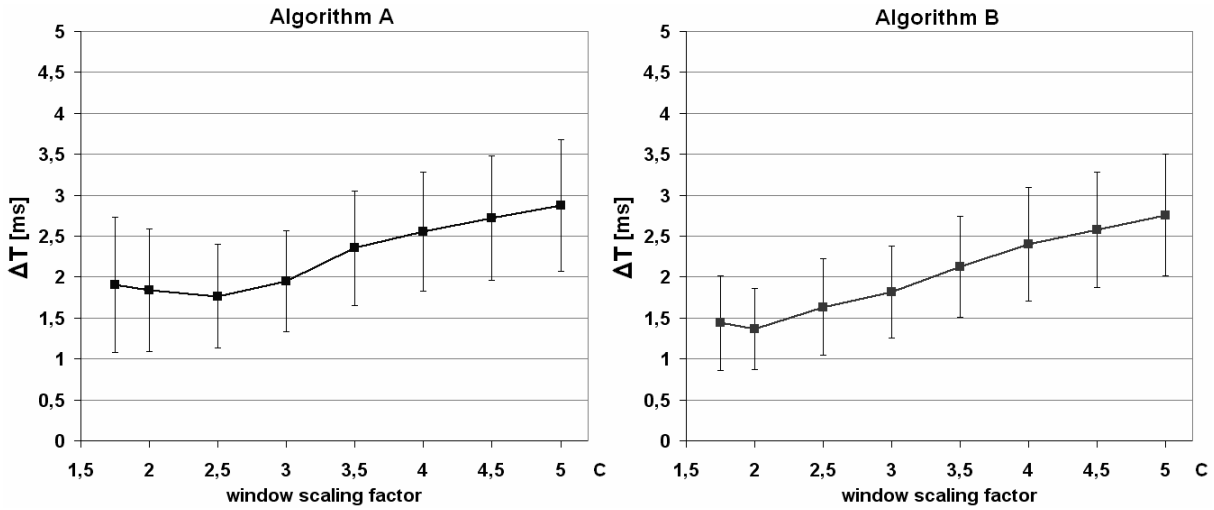

Fig.3 Relationship between absolute ΔT error (mean and SD) and the corresponding autocorrelation window scaling factor C, for two different FHR calculation algorithms A and B.

Mean values of the relative error of STI index determination obtained using both algorithms for the established length of the autocorrelation window are shown in Fig. 4. For the windows with C ≥ 2.5 (for algorithm A) and with C ≥ 2 (for algorithm B) the mean error of the STI index calculated using FHR signal obtained from algorithm A and B takes negative value. For such window length the measured interval is distorted by averaging error, thus the FHR short-term variability is decreased in relation to the values obtained from the reference method. For the windows with C ≥ 3 this error has very similar value for both algorithms and it increases by 15% as the window scaling factor increases by 1. Like in the analysis of ΔT error, the largest differences in results were obtained for windows C = 1.75 and C = 2. Difference of δSTI value between the algorithm A and B was about 17%. But the very important is the different error characteristic obtained for the algorithm A. The error changes from negative to positive values, and thus the index value is decreased. Such tendency of the index change is very dangerous because in perinatology a large STI index value is related to a good fetal state, and thus situation when the fetal condition is deteriorated may be missed. The change of δSTI error for the algorithm A is caused by (as it has been mentioned during analysis of ΔT) incorrect positioning of the autocorrelation window, which directly results in larger random error of measurements of the consecutive interval values.

The mean value and standard deviation of the relative error δLTI as a function of window length are presented in Fig. 5. Unlike δSTI, there are no significant differences of δLTI values observed for FHR signals calculated using the algorithm A or B. Additionally, regardless the autocorrelation window length the error δLTI fluctuates between zero value and -5%.

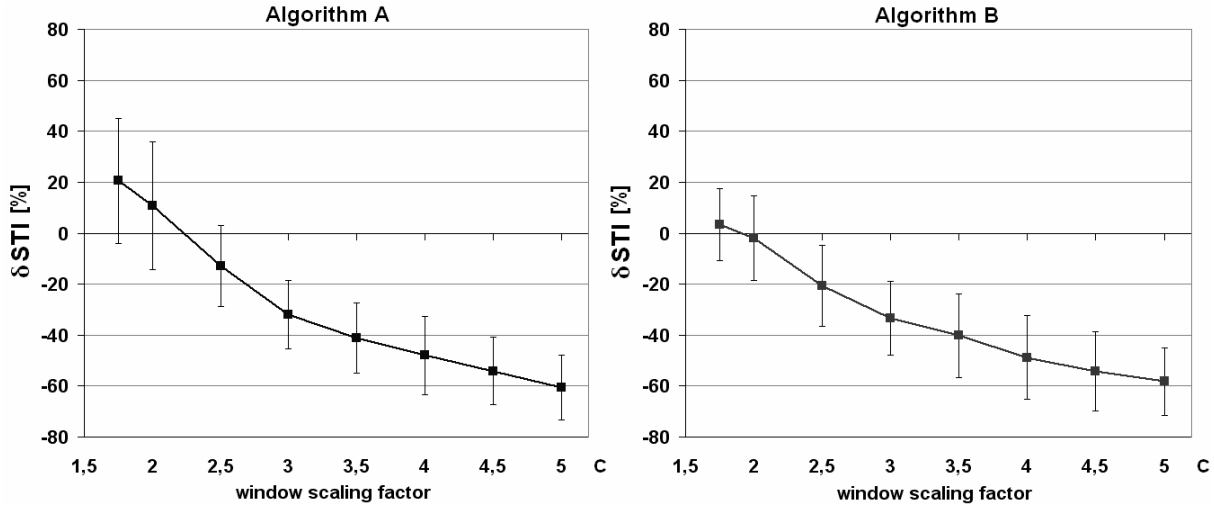

Fig.4 Change of the relative error δSTI for determination of the short-term variability index for algorithms A and B in relation to the established scaling factor of autocorrelation window.

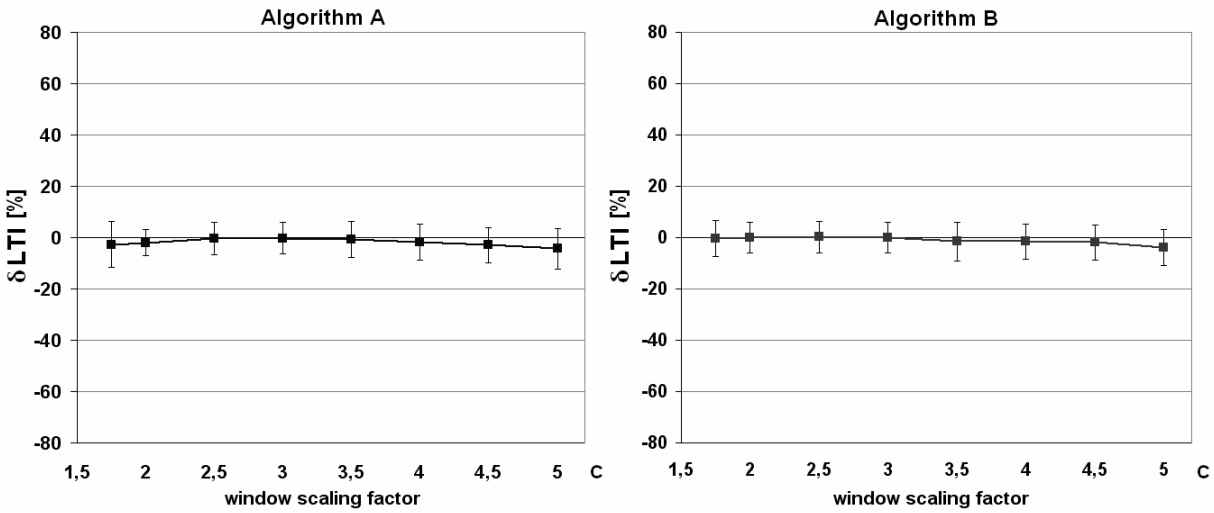

Fig.5 Change of the relative error δLTI for determination of the long-term variability index for algorithms A and B in relation to the established scaling factor of autocorrelation window.

Additionally, it was tested how the ΔT and δSTI change depending on the shape of the FHR signal. The one-minute mean values of ΔT, δSTI and δLTI are plotted together with the FHR trace in Fig. 6. Lack of correlation between the index determination error δSTI and measurement interval error ΔT can be seen. The measurement interval error ΔT is considerably higher in FHR fragments of higher variability (starting from the sixteenth minute). In this fragment for the third minute the index error δSTI takes positive value. It is connected with significant signal loss occurring in the signal slopes for the second trace and leading to the index value increase during these minutes. The δLTI error fluctuates around zero value and similarly to δSTI it is not correlated with the interval error ΔT.

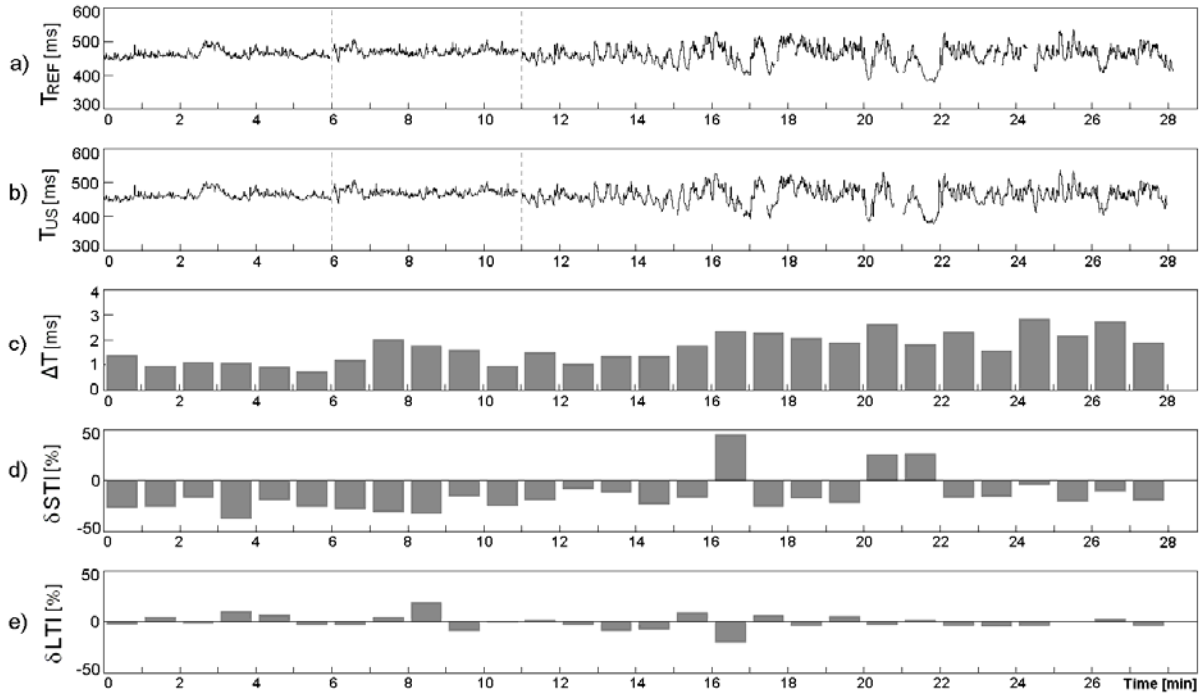

Fig.6 Overall presentation of the signals used: T values for the reference signal (a) and for the US method with the algorithm A and window with C = 2.5 (b). Below, one-minute mean values of: ΔT (c) as well as the relative errors of the indices δSTI (d) and δLTI (e).

4. CONCLUSIONS

Two algorithm were proposed to determine beat-to-beat heart intervals in Doppler ultrasounds signals provided by the fetal monitor. Both of them utilize the autocorrelation function with adaptive window length adjustment as a function of previously measured FHR values. Their influence on the interval determination and on the instantaneous fetal heart rate

variability was tested in relation to the reference electrocardiogram. Regardless the window length, the better results were obtained using the algorithm B, where the final interval value was determined from a set of values being a result multiple calculation of autocorrelation function for the given interval. Its advantage over the algorithm A, where the interval value was obtained from autocorrelation function calculated only once for each heart cycle, is significant for short windows applied. It is important, since shorter autocorrelation window ensures more precise determination of beat-to-beat intervals because an averaging of autocorrelation function is reduced. Consequently, accuracy of the short-term FHR variability is higher for shorter window lengths. Considering the long-term variability we noticed a lack of influence for both algorithms, as it could be expected.

The best approach for processing of the Doppler ultrasound signal to obtain the fetal heart rate values is to apply the autocorrelation with a moving window of the length equal to a doubled interval value. Multiple measurement of a given interval allows for additional verification, which leads to correct determination of the final interval value, and as a consequence, to correct estimation of the FHR variability. What is very important the proposed algorithm does not cause unjustified increase of the short-term fetal heart rate variability, which could lead to false negative fetal state assessment. Decrease of the FHR variability usually caused by the Doppler ultrasound method provides more pessimistic FHR trace interpretation, and thus it is less dangerous than the possible increase.

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