ADVANCES IN DOPPLER ULTRASOUND SIGNAL PROCESSING FOR FETAL MONITORING

The fetal monitoring is based on a fetal heart rhythm analysis, and aimed at the detection of early symptoms of the intrauterine fetal hypoxia. The most often used method for acquisition of the fetal heart rate (FHR) during pregnancy is the Doppler ultrasound technique. When a penetrating beam is reflected from the moving parts, like valves of the fetal heart, its frequency is shifted according to the Doppler effect. The echoes received by transducer are demodulated to obtain differential frequencies describing the movements of objects within the ultrasound beam.

In earlier fetal monitors the continuous wave was applied and the measurements were carried out over the whole effective depth of the beam. The introduction of a pulsed wave enabled to analyse echo signals from a selected depth. Next improvement led to a dynamic focusing of ultrasound beam with respect to the depth and width of the acquisition window. In the first stage, the distance to a fetal heart was determined by gradual narrowing of the window. Then, relaying on the minimal window, the heart was followed up to compensate the fetal and maternal movements.

The useful components located in the acoustic band can be efficiently separated in the demodulated signal using the band-pass filtering, and then the signal envelope is determined using simple filtering or Hilbert transform. Each cardiac cycle is represented by a set of episodes related to the opening and closing of valves and to the movements of heart walls. The shape and the number of episodes being observed during a single cardiac cycle may vary. The precise heart beat occurrence in time cannot be explicitly defined and the measurement of beat-to-beat intervals defining the signal periodicity is a complex task.

In the first fetal monitors the measurement of FHR was based on peak detection algorithms applied to the envelope signal. In the next years the accuracy was significantly improved through analysis of the entire signal shape using the correlation technique with template matching, or the autocorrelation method. The matching relies on detection of the episodes which best correspond to the assumed signal template. Since the shape of signal envelope changes significantly between heartbeats, the template has to be frequently updated. The main drawback is the erroneous template in presence of artefacts in Doppler signal, causing long-lasting false periodicity measurements.

The application of autocorrelation function (AF) improves the noise immunity, although the obtained fetal heart rate signal shows a significant decrease of the beat-to-beat variability. This is caused by the fact that the periodicity value is calculated on the basis of all heart beats enclosed in the analysed AF window. The second issue is that the AF does not detect events (individual heart beats), which form the basis for evaluation of the instantaneous fetal heart rate variability.

As a standard in fetal monitors, the FHR measurements are provided with every 250 ms. It guarantees that even the shortest heart intervals are determined, but on the other hand the vast majority is measured multiple times. Hence, the problem of false FHR variability decreasing also remains open and the new algorithms are aimed at the reconstruction of the heart beats as time event series.

The resulting FHR signal can be visually interpreted by the clinicians, but very often it is automatically analysed (providing an objectivity and repeatability of assessment) to support the diagnosis. Analysis of the FHR signal consists in detection of clinically important patterns like bradycardia or tachycardia, accelerations and decelerations, as well as quantification of instantaneous variability of the fetal heart rate. Automated pattern recognition methods are based on estimation of a so-called FHR baseline, and the baseline estimation algorithm determines the efficiency of the quantitative

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signal analysis as a whole. Although these algorithms have been continuously improved for many years, there are still classes of FHR signals, for which the known methods fail.

Historically, the first method of baseline determination was based on an autoregressive low-pass filter, and the bidirectional approach was used to obtain the zero-phase shift. More efficient algorithms were based on nonlinear filtering, where the filter settings were adaptively changed according to some statistical measures of the input signal. Further improvements was achieved using an iterative filtering, when after each step of filtering the output signal was modified to restore the primary samples in these parts where the differences between the signal and the baseline were less than the established thresholds.

One of the latest methods is based on the weighted myriad filtering. The myriad filters, belonging to a wide class of robust filters, have been originally applied to suppress impulsive noise in electrocardiographic signals. However, the filters can be adjusted to the patterns observed in the FHR signal. In relation to currently proposed baseline estimation algorithms the robust filters are easy to optimized, and there is no need for preliminary interpolation of signal loss segments, which is necessary for classical methods. Hypothetical nature of the FHR baseline makes impossible to create any experimental procedure which enables its validation. Only the reference baseline provided by clinical experts can be used to evaluate a given algorithm. It was found that even small inaccuracy in the baseline estimation may distort detection of the accelerations and decelerations, and cause a false recognizing of the fetal wellbeing. Therefore, different algorithms are evaluated as regards their influence on identification of those clinically important patterns.

The latest investigations indicate that the highest diagnostic value is attributed to quantitative parameters describing the instantaneous FHR signal variability. These measures have been originated from the fetal electrocardiogram recorded during a labour via a direct electrode. Hence the importance of evaluation of their sensitivity to periodicity measurement inaccuracy, especially to the averaging effect of the ultrasound technique.

The research attention is also paid to the nonlinear measures of complexity and irregularity of the FHR signal: point correlation dimension and approximate entropy. It was confirmed that the irregularity of FHR signal increases with gestational age (with a development of the autonomous nervous system) and is significantly reduced in case of fetal distress. The nonlinear measures can be used for fetal state assessment, however their usefulness has not yet been finally proven.

All the presented investigations lead to a considerable increase of diagnostic value of the electronic fetal monitoring. However, the leading research centers continue the works to develop more efficient methods for the automated classification of the fetal heart rate signals. An increasing attention is paid to the computational intelligence as a tool for reasoning. Different procedures of qualitative assessment of signals were proposed, but the methods based on fuzzy inference, non-linear classification using artificial neural networks and neuro-fuzzy systems are of the special interest. The performance of the methods is objectively verified by retrospective evaluation based on neonatal outcome attributes. It is expected that in the near future the new methods will enable the development of a new generation of reasoning systems for early detection of the fetal distress, improving the probability of survival of the newborns with symptoms of intrauterine hypoxia during pregnancy.