Application of fuzzy inference systems for classification of fetal heart rate tracings in relation to neonatal outcome

Zastosowanie rozmytych reguł wnioskowania do automatycznej klasyfikacji zapisów częstości uderzeń serca płodu w odniesieniu do stanu urodzeniowego

Czabański Robert[1], Jeżewski Janusz[2], Wróbel Janusz[2], Sikora Jerzy[3], Jeżewski Michał[1]

[1] Zakład Elektroniki Biomedycznej, Instytut Elektroniki, Politechnika Śląska, Gliwice, Polska
[2] Instytut Techniki i Aparatury Medycznej, Zabrze, Polska
[3] Klinika Położnictwa i Ginekologii ŚLAM, Katowice, Polska

Abstract

Objectives: *Fetal monitoring based on the analysis of the fetal heart rate (FHR) signal is the most common method of biophysical assessment of fetal condition during pregnancy and labor. Visual analysis of FHR signals presents a challenge due to a complex shape of the waveforms. Therefore, computer-aided fetal monitoring systems provide a number of parameters that are the result of the quantitative analysis of the registered signals. These parameters are the basis for a qualitative assessment of the fetal condition. The guidelines for the interpretation of FHR provided by FIGO are commonly used in clinical practice. On their basis a weighted fuzzy scoring system was constructed to assess the FHR tracings using the same criteria as those applied by expert clinicians. The effectiveness of the automated classification was evaluated in relation to the fetal outcome assessed by Apgar score.*

Material and methods: *The proposed automated system for fuzzy classification is an extension of the scoring systems used for qualitative evaluation of the FHR tracings. A single fuzzy rule of the system corresponds to a single evaluation principle of a signal parameter derived from the FIGO guidelines. The inputs of the fuzzy system are the values of quantitative parameters of the FHR signal, whereas the system output, which is calculated in the process of fuzzy inference, defines the interpretation of the FHR tracing. The fuzzy evaluation process is a kind of diagnostic test, giving a negative or a positive result that can be compared with the fetal outcome assessment. The present retrospective study included a set of 2124 one-hour antenatal FHR tracings derived from 333 patients, recorded between 24 and 44 weeks of gestation (mean gestational age: 36 weeks). Various approaches for the research data analysis, depending on the method of interpretation of the individual patient-tracing relation, were used in the investigation. The quality of the fuzzy analysis was defined by the number of correct classifications (CC) and the additional index QI – the geometric mean of the sensitivity and specificity values.*

Corresponding author:
Robert Czabański
Zakład Elektroniki Biomedycznej, Instytut Elektroniki
Politechnika Śląska, ul. Akademicka 16, 44-100 Gliwice
e-mail: robert.czabanski@polsl.pll

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Results: *The effectiveness of the fetal assessment varied, depending on the assumed relation between a patient and a set of her tracings. The approach, based on a common assessment of the whole set of tracings recorded for a single patient, provided the highest quality of automated classification. The best results (CC = 70.9% and QI = 84.0%) confirmed the possibility of predicting the neonatal outcome using the proposed fuzzy system based on the FIGO guidelines.*

Conclusions: *It is possible to enhance the process of the fetal condition assessment with classification of the FHR records through the implementation of the heuristic rules of inference in the fuzzy signal processing algorithms.*

Keywords: **fetal monitoring** / **fetal heart rate** / **fuzzy logic** /

Streszczenie

Cel pracy: *Monitorowanie płodu na podstawie analizy sygnału czynności serca płodu (FHR) jest najczęściej stosowaną metodą biofizycznej oceny stanu płodu w czasie ciąży i porodu. Wzrokowa analiza krzywej FHR jest trudna z uwagi na jej złożony kształt. Z tego względu, komputerowo-wspomagane systemy monitorowania stanu płodu dostarczają szeregu parametrów będących rezultatem ilościowej analizy rejestrowanego sygnału. Parametry te są podstawą dla jakościowej oceny stanu płodu. Do najczęściej stosowanych wytycznych, określających sposób interpretacji sygnału FHR należą kryteria określone przez FIGO. Na ich podstawie skonstruowano ważony rozmyty system punktowy, którego zadaniem jest określenie stanu płodu na podstawie kryteriów oceny, jakimi posługuje się ekspert kliniczny. W pracy przedstawiono badania nad zgodnością rozmytej klasyfikacji z oceną stanu płodu wyznaczaną na podstawie punktacji Apgar.*

Materiał i metody: *Proponowany system do automatycznej, rozmytej klasyfikacji stanowi rozwinięcie idei skal punktowych wykorzystywanych do jakościowej oceny zapisów czynności serca płodu. Za pomocą jednej reguły rozmytej modelowana jest zasada oceny pojedynczego parametru opisu ilościowego sygnału FHR zgodnie z wytycznymi FIGO. Wejściami systemu rozmytego są wartości parametrów ilościowych sygnału FHR, a stan wyjścia, wyznaczany w procesie wnioskowania rozmytego, definiuje interpretację zapisu. Proces rozmytej oceny sygnału jest rodzajem testu diagnostycznego, którego wynik, negatywny lub pozytywny, można porównać z oceną stanu urodzeniowego noworodka. Badaniem retrospektywnym objęto zbiór 2124 godzinnych zapisów ciążowych pochodzących od 333 pacjentek, zarejestrowanych pomiędzy 24 a 44 tygodniem ciąży (średni wiek ciążowy to 36 tygodni). W eksperymentach zastosowano różne konstrukcje zbiorów danych, w zależności od przyjętego sposobu interpretacji zbioru sygnałów zarejestrowanych dla pojedynczej pacjentki. Jakość rozmytej analizy automatycznej oceniano na podstawie liczby poprawnych klasyfikacji CC oraz wskaźnika QI będącego średnią geometryczną czułości oraz swoistości.*

Wyniki: *W zależności od przyjętej metody analizy zbioru danych otrzymano różną skuteczność oceny stanu płodu. Podejście, w którym określano jedną wspólną ocenę dla całego zbioru zapisów zarejestrowanych dla pojedynczej pacjentki, pozwoliło na uzyskanie najwyższej jakości automatycznej klasyfikacji. Najlepsze z uzyskanych wyników (CC = 70.9% i QI = 84.0%) potwierdzają możliwość predykcji stanu urodzeniowego płodu na podstawie rozmytego wnioskowania opartego na wytycznych FIGO.*

Wnioski: *Istnieje możliwość wspomagania procesu diagnostyki stanu płodu przez zastosowanie systemu rozmytej klasyfikacji sygnałów FHR, opartego o heurystyczne reguły wnioskowania właściwe doświadczonemu klinicyście.*

Słowa kluczowe: **monitorowanie płodu** / **częstość uderzeń serca płodu** / / **logika rozmyta** /

Introduction

Cardiotocography is one of the most important methods used in modern obstetrics, where the correct analysis of the fetal heart rate (FHR) signal is crucial for the evaluation of fetal well-being. Automated interpretation of tracings allows a precise and accurate quantitative description of the characteristic patterns [1]. Despite newer and more sophisticated techniques of quantitative analysis, the qualitative assessment of fetal condition that could effectively support the process of the decision-making of a physician, remains to be the goal of many studies [2, 3]. The way the clinical expert interprets the recordings, as well as lack of normal limits for signal parameters indicating an uncompromised fetal condition, are prerequisites for the application of fuzzy logic and the fuzzy set theory [4]. One of the first reports on this subject presented possible modifications of the classical expert scoring system using fuzzy inference [5]. Various fuzzy inference algorithms were examined for the FHR evaluation in the intrauterine growth restriction and diabetes in pregnancy [6, 7]. As an extension of these studies, a fuzzy inference system that allows to predict fetal distress on the basis of the analysis of cardiotocographic signals was proposed [8].

More complex algorithms of the FHR evaluation, based on the artificial neural networks, neuro-fuzzy systems, and support vector machines (SVM) were all investigated as well [9, 10, 11, 12, 13, 14, 15]. Currently, the SVM method is recognized as one of the most suitable classification algorithms for the assessment of fetal condition. The combination of the SVM procedure with empirical mode decomposition provided a highly accurate method in comparison with the interpretation of the FHR signals performed by a clinician [16]. Effective procedures for predicting the risk of neonatal acidemia based on the combination of SVM with fuzzy inference procedures were reported [17, 18]. Among them, the Weighted Fuzzy Scoring System arouses particular interest. This system was developed on the basis of the guidelines for electronic fetal monitoring from the Fédération Internationale de Gynécologie et d'Obstétrique (FIGO) [19].

Objectives

Very often, the accuracy of automated assessment of the FHR tracings is verified by comparing the results with the interpretation of experienced clinicians. Another approach to evaluating the effectiveness of fetal assessment is based on a retrospective analysis involving the assumption that neonatal outcome corresponds to the fetal condition at the time of monitoring. The paper presents a new method of fuzzy classification of the FHR signals, whose effectiveness was evaluated using the results of fetal outcome assessed by Apgar score [20].

Materials and methods

Quantitative assessment of the fetal heart rate signal

The visual analysis of signal patterns describing the FHR variability is challenging due to the complexity of a waveform shape. To increase the assessment objectivity, the computer-aided fetal monitoring systems provide an automated quantitative analysis of tracings, and calculate a set of quantitative parameters that are crucial for the evaluation of fetal condition [21]. To improve the quality of the interpretation, the FIGO guidelines for electronic fetal monitoring were proposed [19]. They established a set of parameters that are crucial for the quantitative description of the signal, along with their dedicated ranges defining the fetal condition.

According to these criteria, the tracing interpretation involves the analysis of the basal fetal heart rate (BFHR), the acceleration and deceleration patterns, as well as instantaneous FHR variability [22].

In this paper, the typical reference ranges for the number of accelerations/decelerations were replaced with a mean number of accelerations (ACC) and decelerations (DEC) detected per one hour of recording.

The descriptive assessment of decelerations expressed by criteria defining the amplitude and duration resulted in three types: DECA (> 15 bpm, > 10 s), DECB (> 10 bpm, > 25 s) and DECC (> 15 bpm, > 10 s, but related to the uterine contraction). We considered two types of instantaneous FHR variability: short-term (STV) defining changes of intervals between two consecutive heart beats, and long-term, with periodical changes of short-term variability leading to oscillations (OSC) [23]. Depending on the OSC value, four types of oscillation were distinguished according to Hammacher [24]: OSC0 - silent oscillation, with the amplitude less than 5 bpm, OSCI - narrow undulatory oscillation, with the amplitude from 5 to 10 bpm, OSCII – undulatory oscillation, with the amplitude from 10 to 25 bpm, and OSCIII – saltatory oscillation, with the amplitude exceeding 25 bpm. The FHR tracing can be classified as describing a normal, suspicious or abnormal fetal condition. The proposed criteria of classification, according to the FIGO guidelines, are presented in Table I.

There is no other noninvasive diagnostic method that would provide more precise information about fetal condition at the time of monitoring. The actual fetal condition can be revealed after the delivery only. Assuming that the fetal condition cannot change rapidly during pregnancy, the neonatal outcome attributes can be used as the reference values. In our approach, we selected the 10-min Apgar score for the verification process of our classification algorithms. The score of 5 points was assumed as a cut-off value that defines uncompromised fetal well-being.

Table I. Criteria for classification of antenatal FHR tracings according to the FIGO guidelines.

Fetal condition	Quantitative parameters describing FHR tracings				
	BFHR [bpm]	ACC [1/h]	DEC [1/h]	STV [ms]	OSC [%]
Normal	[110, 150]	$>12^{**)}_{(15)}$	$DEC_A \in [0,^{0}1.5)$ and $DEC_B=0$ and $DEC_C=0$	$[6_{(10.5)}, 14]$	$OSC_0=0$ and $OSC_I \in [0,^{0}40)$ and $OSC_{III} = 0$
Suspicious	[100, 110)*) or (150, 170]	$(1.5_{(5)}, 12_{(15)}]$	$DEC_A \geq 1.5$ or $DEC_B \in (0,^{0}1.5)$ or $DEC_C \in (0,^{0}1.5)$	> 14	$OSC_0 \in [0,^{0}40_{(6)})$ and $OSC_I \geq 40$
Abnormal	[0,100) or >170	$[0, 1.5_{(5)}]$	$DEC_B \geq 1.5$ or $DEC_C \geq 1.5$	$[0, 6_{(10.5)})$	$OSC_0 \geq 40_{(6)}$

*) [- closed range,) – open range,
**) a value derived directly from the criteria of FIGO, whereas () contains the modified value, being the result of statistical analysis of the research material

Fuzzy Classification

The fuzzy classification system, which was described in details as Weighted Fuzzy Scoring System, is the extension of scoring systems used for qualitative evaluation of the FHR tracings [17, 18, 24, 25]. The application of a scoring system involves assigning a given score to a relevant range of values for each analyzed signal feature. The sum of scores assigned to all tracing parameters indicates a qualitative assessment of the fetus. A single fuzzy rule of our system corresponds to a single evaluation principle of a signal parameter that was defined in the FIGO guidelines. The inputs are the values of quantitative parameters of the FHR signal, whereas the sign of the system output value, calculated in the process of fuzzy inference, defines the interpretation of the FHR tracing. A positive sign or a zero value indicates a pathology, while a negative sign represents fetal well-being.

Research material

The research material included the results of analysis of recordings randomly selected from the archive of the computerized fetal monitoring system MONAKO [26]. The data consisted of parameters of quantitative description of the FHR signals and corresponding values of the Apgar score derived from the newborn forms. We analyzed a set of 2124 one-hour antenatal FHR tracings from 333 patients, recorded between 24 and 44 weeks of gestation (mean gestational age: 36 weeks). According to the Apgar score classification, 27 tracings were considered as abnormal. The number of tracings per single patient varied, and the mean value was six per patient. This fact was the reason why three different methods of research data analysis were used:

- one patient – one tracing (OT), when only one single tracing from each patient was analyzed,
- one patient – many tracings (MT), when the tracings of all patients were analyzed independently,
- one patient – a set of tracings (ST), when the assessment of the fetal condition was a result of analysis of the whole set of tracings recorded from a given patient.

Additionally, we distinguished three various principles during the ST analysis:

- the optimistic approach (O) – fetal condition was considered as normal if at least one tracing was normal,
- the pessimistic approach (P) – fetal condition was considered as abnormal if at least one tracing was classified as abnormal,
- the majority approach (M) – fetal condition was considered as normal if most of the tracings were classified as normal.

In the OT approach, the earliest tracing was chosen for each patient. However, gestational age at the time of the recording should not exceed the 37th week of gestation. Consequently, a set of 113 tracings was distinguished, including five corresponding to the abnormal fetal outcome.

Performance measures

To evaluate the effectiveness of fuzzy classification system, we compared its results with the fetal outcome assessed by Apgar score. In addition to the correct classification (CC) index, defined as the number of correctly classified cases expressed as the percentage of the dataset, we calculated also the sensitivity (SE) and specificity (SP) indices. Due to the fact that an increase of SE frequently results in a decrease of SP (and vice versa), we also introduced the integrated classification quality index:

$$QI = \sqrt{SE \cdot SP}.$$

Results

The parameter values of membership functions of fuzzy sets were obtained on the basis of statistical analysis of the available research material [17, 18]. In order to find a scoring that leads to the best classification results, the number of points assigned to the "suspicious" values of quantitative parameters of FHR signal varied from –0.5 to +0.5 with a step 0.25.

The first step of our investigation was to calculate the weights of the fuzzy system, which represent the degree of certainty of the FHR tracing assessment based on the evaluation of a single quantitative parameter. Their values were defined as the normalized areas under the receiver operating characteristics (ROC) curves. The higher the area under the ROC curve, the higher the certainty of the fetal outcome prediction. The results (Table II) show that the highest predictive capability is ensured by the number of acceleration patterns ACC and saltatory oscillation OSCIII. The mean value of the normalized area above 0.60 was also obtained for the short-term variability index STV and the basal fetal heart rate BFHR. The low diagnostic value of the number of decelerations was rather unexpected. However, our previous studies showed that its predictive value increases considerably when evaluating the FHR tracings recorded during labor [27]. For both datasets, the mean area values calculated for all quantitative parameters were the same and equal to 0.62.

In the first group of experiments, we calculated the membership function of fuzzy sets using the parameter ranges specified according to the FIGO guidelines (Table I). The results are shown in Table III.

For the MT approach, the fuzzy analysis based on the original FIGO ranges did not provide satisfactory results. The accuracy of the fetal assessment did not exceed 60%, while the quality described by QI was equal to 66.3%. A significant effectiveness improvement was noticed when analyzing single tracings. The application of OT approach resulted in an increase of both accuracy and classification quality (CC = 88.7%, QI = 73.4%). The ST approach using the pessimistic (P) principle, as well as the majority (M) approach, did not improve the results. However, with the optimistic principle (O), a significant improvement in the classification accuracy and quality was noted (CC = 93.6%, QI = 81.3%). Nevertheless, the number of false negative results remained high, because in the group of 27 abnormal tracings eight were classified as normal.

In order to improve the classification, we modified the ranges of ACC, STV and OSC0, previously established according to the FIGO guidelines. New boundaries are shown in Table I in brackets as the indices of the original values. This modification allowed us to increase the sensitivity of the classification due to the strengthening of the assessment criteria (Table IV).

After modifying the class ranges, we achieved no false-positives cases, which improved the classification quality using OT, as well as the optimistic principle with ST approach (CC = 70.9%, QI = 84.0%).

Table II. The summary of area values under the ROC curve for particular parameters of quantitative FHR tracings description.

Data analysis methods	Quantitative parameters of FHR tracing								
	BFHR	STV	ACC	DEC_A	DEC_B	DEC_C	OSC_0	OSC_I	OSC_{III}
MT	0.55	0.66	0.70	0.57	0.60	0.56	0.62	0.62	0.67
OT	0.65	0.56	0.79	0.55	0.59	0.59	0.65	0.52	0.65

Table III. The results of the FHR tracing classification for different methods of data analysis.

Prognostic index	Data analysis methods				
	OT	MT	ST		
			O	P	M
SE	60.0	59.4	70.4	77.8	51.8
SP	89.9	74.1	93.9	13.5	60.7
CC	88.7	59.6	93.6	14.3	60.6
QI	73.4	66.3	81.3	32.4	56.1

Table IV. The results of fuzzy classification after modifying the class ranges for particular FHR tracing features.

Prognostic index		Data analysis methods									
		OT		MT		ST					
						O		P		M	
TP[1)]	FP[2)]	5	45	25	1253	27	618	22	2022	22	1468
FN[3)]	TN[4)]	0	74	2	844	0	1479	5	75	5	629
CC		63.7		40.9		70.9		4.57		30.6	
QI		78.9		61.0		84.0		17.1		49.4	

[1)] TP – true positive, [2)] FP –false positive, [3)] FN –false negative, [4)] TN –true negative

Discussion

The objective of the proposed fuzzy scoring system is to evaluate fetal condition on the basis of the analysis of the quantitative FHR parameters in a manner that emulates the interpretation criteria used by expert clinicians. These criteria were the basis of conditional rules, defining the fuzzy inference. Direct application of class ranges for particular FHR parameters (derived from the FIGO criteria) did not give satisfactory results due to the relatively low sensitivity. A significant improvement of the classification quality was noticed after modifying the ranges of ACC, STV and OSC_0.

The new limits may seem excessive from the perspective of the FIGO criteria, however the analyzed tracing features are represented by mean values for the entire recording, not the instantaneous ones calculated for a selected fragment of the tracing. Reducing the possibility to classify the tracing as "normal" increased the probability of detection of pathology but also increased the risk of false alarms. Nevertheless, the assessment of a single tracing and the optimistic ST approach significantly improved the final classification quality. As the higher classification effectiveness was obtained when analyzing the earliest tracings, it seemed reasonable to include gestational age in the fetal assessment criteria. Although the evaluation of tracing sets (ST), combined with the optimistic approach, is questionable in terms of medical application, it provides the best effectiveness of fetal assessment. It is also consistent with the characteristics of FHR monitoring, since the reassuring signal features in about 95% cases are confirmed by a normal fetal outcome. In cases when the parameters of the FHR quantitative description are beyond the normal ranges, other diagnostic procedures are recommended to confirm the risk of abnormal fetal condition.

Conclusions

In the presented work we investigated the possibility of assessing fetal condition on the basis of the FHR tracing evaluation using a fuzzy inference system. We analyzed a set of parameters of quantitative FHR description included in the FIGO guidelines. These criteria were also the basis for the development of the rule base of the weighted fuzzy scoring system. The verification of the classification effectiveness was performed using the results of the retrospective analysis in relation to fetal outcome assessed by Apgar score. Various methods of data analysis were applied in our experiments. The approach based on a common assessment of the whole set of tracings recorded for a single patient resulted in the highest effectiveness of fuzzy analysis. The results proved the possibility to support the process of fetal assessment with FHR through the implementation of the heuristic rules of inference in the fuzzy signal processing algorithms.

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