Data and Knowledge for Medical Decision Support
B. Blobel et al. (Eds.)
IOS Press, 2013

doi:10.3233/978-1-61499-240-0-140

Prognostic Decision Support Using Symbolic Dynamics in CTG Monitoring

Mario CESARELLI[a,1], Maria ROMANO[a], Paolo BIFULCO[a], Giovanni IMPROTA[a] and Giovanni D'ADDIO[b]
[a] *DIBET, University of Naples "Federico II", Naples, Italy*
[b] *S. Maugeri Foundation, Rehabilitation Institute of Telese, Telese Terme, Italy*

Abstract. Foetal heart rate variability is one of the most important parameters to monitor foetal wellbeing. Linear parameters, widely employed to study foetal heart variability, have shown some limitations in highlight dynamics potentially relevant. During the last decades, therefore, nonlinear analysis methods have gained a growing interest to analyze the chaotic nature of cardiac activity. Parameters derived by techniques investigating nonlinear can be included in computerised systems of cardiotocographic monitoring. In this work, we described an application of symbolic dynamics to analyze foetal heart rate variability in healthy foetuses and a concise index, introduced for its classification in antepartum CTG monitoring. The introduced index demonstrated to be capable to highlight differences in heart rate variability and resulted correlated with the Apgar score at birth, in particular, higher variability indexes values are associated to early greater vitality at birth. These preliminary results confirm that SD can be a helpful tool in CTG monitoring, supporting medical decisions in order to assure the maximum well-being of newborns.

Keywords. Foetal health monitoring, Symbolic dynamics, Computerised cardiotocography, Foetal health prognostic decision support.

Introduction

Monitoring foetal wellbeing by means of electronic recording of foetal heart rate (FHR) always aimed at preventing serious complications due to acute hypoxic events. While the negative predictive value of cardiotocography (CTG) is very good, positively diagnosed foetuses not always manifest cardiotocographic changes [1], however. Moreover, the CTG interpretation is still very often entrusted to the obstetrician's experience, who has to formulate the diagnosis of foetal wellbeing. Nevertheless, the CTG is currently the routine procedure for assessing the foetal state in late pregnancy. For this reason, many researchers attempt to make it more reliable and reproducible, introducing the computerized analysis. This kind of analysis has the advantage of making quantitative, and then more objective, the evaluation of some parameters historically and habitually used by clinicians for the diagnosis. Besides, the computerised CTG allows the introduction of new parameters that can serve to assess aspects of the FHR signal that are not normally considered [2, 3, 4]. The possibility to consider these new parameters should support gynaecologists and obstetricians in the formulation of a more reliable diagnosis and, consequently, in a more adequate management of pregnancy and labour.

[1] Corresponding Author. Mario Cesarelli, DIBET, University of Naples "Federico II", Via Claudio 21, 80125 Naples, Italy; Email: cesarell@unina.it

FHR variability (FHRV) is doubtless one of the most important parameters of FHR signal. Nevertheless, processing in the time domain and in the frequency domain has shown some limitations in highlight dynamics potentially relevant in clinical environment [5]; therefore, increasing efforts were made to analyze the chaotic nature of cardiac activity by applying analysis methods from nonlinear systems theory. The symbolic dynamic (SD) analysis, which allows a simple description of a system's dynamics by means of a limited amount of symbols [5, 6] and appropriate classification schemes, was recently employed to quantify FHR regularity [7]. Aim of this work was to describe a novel index quantifying SD analysis of FHRV in antepartum CTG monitoring, assessing its prognostic value related to a greater vitality at birth.

1. Methods

1.1. Data collection and software for CTG monitoring

CTG recordings were collected in clinical environments, using commercially available cardiotocographs, by healthy patients. Sixty antepartum recordings made at 38th±1 week gestation, in absence of uterine contractions (UC) and lasting at least 20 minutes were selected. Signals database has been completed by a medical follow-up recording of patients and newborns clinical information, particularly including the Apgar score, used to assess newborns' health at 1 and 5 minutes after birth (respectively APG1, APG5). CTG signals were analysed by a software previously developed by the authors and elsewhere described [8-10]. For each analysed CTG signal, the developed software provides in output a set of parameters for its characterisation. The main estimated parameters can be grouped in three classes [3, 8, 10, 11]: a) Technical characteristics (percentage of lost and interpolated signal, ...), b) "Classical" parameters (FHR mean, accelerations, decelerations, ...), c) Less traditional parameters (short term variability, symbolic dynamics indexes, …). Classical parameters are computed following criteria based on Mantel indications and/or FIGO guidelines [8]. Other parameters were elsewhere described [3, 10, 12].

1.2. Symbolic dynamics analysis

Additionally to classical parameters used to describe FHR features, the amount of variability in FHR has been assessed by a novel index of symbolic dynamic analysis. Firstly, RR time series (series of inter-beat interval durations) has been derived from FHR signals, then the ΔRR series of the difference between consecutive RR values has been calculated and transformed into a symbol sequence from a given alphabet of five symbols (Table 1). The decision rule adopted to associate each ΔRR sample with one symbol of our alphabet was the comparison between the ΔRR value with values of a primary threshold (PT) and a secondary threshold (ST) (Table 1).

Table 1. Encoding used for transforming the series DRR into symbols sequence.

ΔRR value	Symbol	Meaning
ΔRR > + ST	V	range of values corresponding to a high vagal activation
PT < ΔRR < + ST	D	range of values corresponding to a vagal activation
- SP < ΔRR < + SP	O	range of values corresponding to absence of variability, i.e. to noise
- ST < ΔRR < - SP	A	range of values corresponding to a sympathetic activation
ΔRR < - 3ms	S	range of values corresponding to a high sympathetic activation

Then, a sliding window of length L=7 has been shifted along the codified ΔRR series with an overlap of L-1 points obtaining a patterns sequence of L symbols (words). The seven length words of five symbols have been then grouped in different classes by the within-word symbol occurrence, using the criterion described in Table 2. Further technical details have been previously described elsewhere by the authors [11].

Table 2. Criterion adopted to group the words by the occurrence of a symbol in any position within them.

Description	Meaning	Code
At least 4 symbols "S"	high sympathetic activation	S
At least 3 symbols "S" and 1 symbol "A"		
At least 4 symbols "A"	sympathetic activation	A
At least 3 symbols "A" and 1 symbol "S"		
At least 4 symbols "O"	absence of variability	O
At least 3 symbols "D" and 1 symbol "V"	vagal activation	D
At least 4 symbols "D"		
At least 3 symbols "V" and 1 symbol "D"	high vagal activation	V
At least 4 symbols "V"		
All other cases	random	R

Finally, in order to put in evidence the amount of physiological variability of the signal, a novel variability index (V.I.), derived from occurrence values of the corresponding words classes (p_S, p_A, p_O, p_R, p_D and p_V), has been derived as

$$V.I. = \frac{p_S}{100} * 1 + \frac{p_A}{100} * 0.5 + \frac{p_O}{100} * 0 + \frac{p_R}{100} * 0 \frac{p_D}{100} * 0.5 + \frac{p_V}{100} * 1 \quad (1)$$

where at the p_S and p_V occurrences (variability due to high sympathetic or vagal activations) was assigned the maximum weight, while at the p_O and p_R occurrences (variability null or absent) was assigned zero weight. As last step, analyzing the most histograms of word classes, randomly chosen from our database, three ranges of values were experimentally set for V.I.: V.I. < 0.20 – low variability, 0.20 ≤ V.I. ≤ 0.28 – medium variability, V.I. > 0.28 – high variability.

1.3. Statistical analysis

The association between V.I. and APG1 and APG5 has been assessed splitting data in three groups, regarding both Apgar score's values at birth. Normality distribution of V.I. index for all groups has been assessed by D'Agostino & Pearson omnibus normality test (alpha=0.05) and difference between groups has been assessed by an unpaired one-way analysis of variance followed by Tukey's multiple comparison post-test between each groups' couples.

2. Results

Examples of analyzed CTG signals and related V.I. are shown in figure 1. In the CTG recording # 486 a reassuring variability and a good reactivity of the foetus to the contraction can be observed and in fact a V.I. value of 0.29 (high variability) was obtained. Vice versa, in CTG recording # 382, despite to the presence of little accelerations in correspondence to foetal movements (little spikes and variations in toco signal), there is not a considerable variability as results by a V.I. value of 0.1 (low variability).

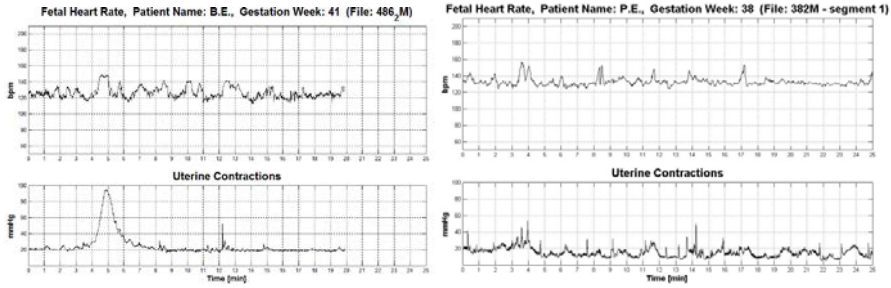

Figure 1. On the left, CTG recording # 486 (internal numbering of our database), VI = 0.29; on the right, CTG recording # 382, VI = 0.10. For each CTG; FHR on the upper part, and UC on the lower.

The following Table 3 describes results of the statistical analysis. V.I. values, for all the groups, resulted normally distributed according to the D'Agostino & Pearson test (alpha=0.05). Apgar values ranged from 7 to 9 for APG1 and from 8 to 10 for APG5. Most of CTG recordings corresponded to an APG1 score value of 8, improving to 10 for the APG5 score value. V.I. showed a gaussian distribution in all groups ($p>0.05$) and a significant p value ($p<0.005$) of ANOVA between all the three studied groups for both APG1 and APG5. Higher V.I. values of antepartum CTG recordings are associated to early greater vitality at birth quantified by APG1 score. Particularly, Tukey's post-tests for APG1 revealed a significantly different mean V.I. values discriminating antepartum CTG recordings corresponding to APG1=7 vs. 9 and APG1=8 vs. 9 (Table 3 and figure 2). This behaviour is confirmed by the recovery at five minute after birth. Higher V.I. values of antepartum CTG recordings are associated to late greater vitality and vital primary functions' efficiency at birth quantified by APG5 index. Particularly, Tukey's post-tests for APG5 revealed a significantly different mean V.I. values discriminating antepartum CTG recordings corresponding to APG5=8 vs. 10 (Table 3 and figure 2).

Table 3. Association between APG and VI (* for $p<0.05$; ** for $p<0.005$; ns for not significant)

	APG1			APG5		
APG value	7	8	9	8	9	10
# CTG recordings	8	44	8	8	16	36
VI index (mean±std)	0.19±0.07	0.20±0.05	0.27±0.02	0.22±0.08	0.25±0.05	0.29±0.07
D'Agostino norm. test	0.33	0.12	0.76	0.53	0.96	0.18
ANOVA		p=0.0028**			p=0.0072**	
Tukey's post-test	7 vs 8 (ns)	7 vs 9*	8 vs 9**	8 vs 9 (ns)	8 vs 10*	9 vs 10 (ns)

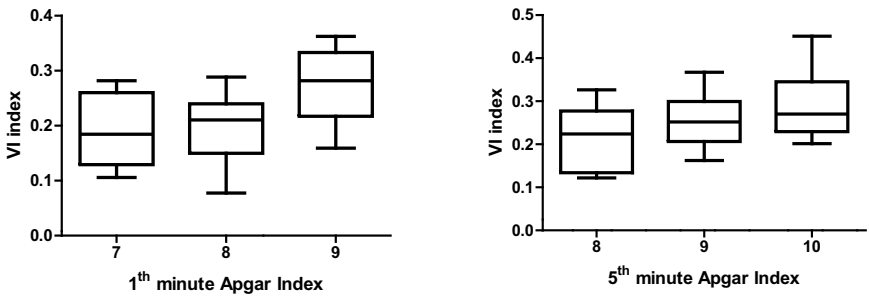

Figure 2. Box-and-whisker plots of V.I. for each Apgar score at 1st (on the left) and 5th (on the right) minute after birth.

3. Discussion

The paper describes a novel application of symbolic dynamic analysis of foetal heart rate variability in computerised CTG monitoring

The capability of the V.I., here introduced to classify FHR signals, is demonstrated for healthy foetuses near to term, using words of length 7 and an alphabet of 5 symbols. In fact, V.I. computed emphasized differences between signals characterized by more or less variability, even if these differences were not so evident by a visual analysis of the printed CTG.

Preliminary results on our data clearly showed that higher foetal heart rate variability, quantified on antepartum CTG monitoring by means of V.I. of symbolic dynamic analysis, is significantly associated to greater newborns' vitality at birth.

This association suggests a prognostic value of V.I., suggesting that this index can be a helpful decision support tool addressing the medical decision about the delivery time acceleration or caesarean section vs spontaneous delivering option, in order to assure the maximum well-being of newborns.

Further studies will be addressed in testing the prognostic power of the proposed technique, also using a swarm intelligence algorithm [13], in wider ranges of Apgar score values related to antepartum CTG recordings database.

References

[1] Royal College of Obstetricians and Gynaaecologists (RCOG). The use of electronic fetal monitoring. The use and interpretation of cardiotocography in intrapartum fetal surveillance. Royal College of Obstet. and Gynaecol. 2001. Evidence-based Clinical Guideline Number 8.

[2] Pardey J, Moulden M, Redman CWG. A computer system for the numerical analysis of nonstress tests. Am J Obstet Gynecol 2002 May; 186(5):1095-1103.

[3] Cesarelli M, Romano M, Bifulco P. Comparison of short term variability indexes in cardiotocographic foetal monitoring. Computers in Biology and Medicine 2009; 39(2):106-118.

[4] Signorini MG, Magenes G, Cerutti S, Arduini D. Linear and nonlinear parameters for the analysis of fetal heart rate signal from cardiotocographic recordings. IEEE Trans Biomed Eng 2003 Mar; 50(3):365-75.

[5] Voss A, Schulz S, Schroeder R, Baumert M, Caminal P. Methods derived from nonlinear dynamics for analysing heart rate variability. Phil Trans R Soc A 2009; 367:277-296.

[6] Porta A, D'Addio G, Pinna G, Maestri R, Gnecchi Ruscone T, Montano N, Furlan R, Guzzetti S, Malliani A. Symbolic analysis of 24h Holter heart period variability series: comparison between normal and heart failure patients. IEEE Computer Society Press, Computers in Cardiology 2005; 32:575-578.

[7] van Leeuwen P, Cysarz D, Lange S, Geue D, Groenemeyer D. Quantification of fetal heart rate regularity using symbolic dynamics. Chaos 2007; 17 (015119): 1-9

[8] Improta G, Romano M, Amato F, Sansone M, Cesarelli M. Development of a software for automatic analysis of CTG recordings. GNB2012, June 26th-29th 2012, Rome, Italy

[9] Cesarelli M, Romano M, Bifulco P, Fedele F, Bracale M. An algorithm for the recovery of fetal heart rate series from CTG data. Computers in Biology and Medicine 2007; 37(5):663-669.

[10] Romano M, Cesarelli M, Bifulco P, Ruffo M, Fratini A, Pasquariello G. Time-frequency analysis of CTG signals. Current Development in Theory and Applications of Wavelets 2009; 3(2):169-192

[11] Cesarelli M, Romano M, Bifulco P, Improta G, D'Addio G. An Application of Symbolic Dynamics for FHRV assessment. Stud Health Technol Inform 2012; 180:123-7

[12] Cesarelli M, Romano M, D'Addio G, Ruffo M, Bifulco P, Pasquariello G, Fratini A. Floatingline estimation in FHR signal analysis. 5th European IFMBE Conference, 14-18 September 2011, Budapest, Hungary. IFMBE Proceedings 2011; 37:179–182.

[13] Arpaia P, Manna C, Montenero, D'Addio G. In-Time Prognosis Based on Swarm Intelligence for Home-Care Monitoring: A Case Study on Pulmonary Disease. IEEE Sensors Journal 2012 March; 12(3):692-698.