*Quality of Life through Quality of Information*
*J. Mantas et al. (Eds.)*
*IOS Press, 2012*


*doi:10.3233/978-1-61499-101-4-123*

# An Application of Symbolic Dynamics for FHRV assessment

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

**Abstract.** Fetal heart rate variability is surely one of the most important parameters to monitor fetal wellbeing. Linear studies, widely employed to study fetal heart variability and its correlations with the development of the autonomous nervous system, 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. Techniques investigating nonlinear dynamics have been already successfully employed in adults, to analyze different physiological and pathological states. Concerning fetal monitoring, instead, a smaller number of papers is available in the literature; even if symbolic dynamics was recently employed to quantify fetal heart rate regularity, demonstrating that the use of this technique may lead to a better and more differentiated understanding of normal fetal physiological development. In this work, we applied the symbolic dynamics to analyze fetal heart rate variability in healthy fetuses at the end of a physiological pregnancy. Our results confirmed the potentiality of the technique to highlight differences between signals characterized by more or less variability.

**Keywords.** Fetal heart rate variability, Symbolic dynamics, Cardiotocography, Nonlinear dynamics

## Introduction

Cardiotocography, which simultaneously records FHR and uterine contractions, is the routine test to ascertain fetal health (mainly at the end of pregnancy). Among characteristics of FHR signals, FHR variability (FHRV) is one of the most important, considered an essential marker for fetal wellbeing. It is generally assumed that FHRV modifications during pregnancy reflect prenatal development of the autonomic nervous system (ANS), with the growing influence of the vagal system. In normal fetuses, development of ANS, as well as the development of input mechanisms (baroreceptors, chemoreceptors, etc.), can also explains the increase in complexity of FHR [1].

Studies in the time domain and in the frequency domain have shown some limitations in highlight dynamics potentially relevant in clinical environment [2]; therefore, during the last decades, increasing efforts were made to analyze the chaotic nature of cardiac activity by applying analysis methods from nonlinear systems theory.

Techniques analyzing nonlinear dynamics have been already successfully employed in adults [1]; even if, the development of these techniques can be surely

[1] Corresponding Author. Mario Cesarelli email: cesarell@unina.it

considered still in progress. Among nonlinear techniques, we can mention symbolic dynamics (SD), approximate entropy (ApEn), Lyapunov exponents, fractal dimension (FD), etc. They were used to analyze different physiological and pathological states and to investigate and improve, for example, risk stratification [2, 3, 4].

In fetal monitoring, a smaller number of works about nonlinear techniques is available in the literature. However, the use of SD, which allows a simple description of a system's dynamics with a limited amount of symbols [2], and appropriate classification schemes, was recently employed to quantify FHR regularity, demonstrating that the use of this technique may lead to a better and more differentiated understanding of normal fetal physiological development [1].

Aim of this work was to apply the SD to analyze FHRV in healthy fetuses at the end of a physiological pregnancy.

## 1. Methods

### *1.1 Data collection*

We recorded FHR signals by means of commercially available cardiotocographs (HP-135x or Sonicaid). Patients involved in this study were healthy pregnant women (physiological singleton pregnancies), close to delivery (36-42 gestation weeks). In line with clinical practice, cardiotocographic signals (CTG) lasting less than 20 min or excessively noisy signals (which showed evident artifacts or prolonged loss signal) were excluded from our database. Finally we analyzed more than 300 CTG recordings.

### *1.2 Preprocessing*

Both kind of devices used for this study provide a three-level signal which indicates the 'quality' of the received Doppler signal (optimal, acceptable or insufficient); but they employ different strategies to store FHR samples. HP-135x cardiotocographs use a zero-order interpolation in order to provide in output an evenly sampled series. In order to eliminate possible modifications of results due to zero order interpolation, and, more generally, to recover the true (unevenly spaced) FHR series from CTG data, CTG recordings were pre-processed by means of an algorithm previously developed, and already employed by the authors, which, in addition, provides a segmentation of FHR signals in reliable tracts by eliminating artifacts related to the Doppler technique [5, 6]. Sonicaid cardiotocographs, on the contrary, store FHR signals in the original uneven format. Hence, in this case, the preprocessing is limited to delete outliers and to fragment FHR signals in tracts of good quality.

### *1.3 Symbolic Dynamics Analysis*

The core of the technique is an adaptation to the fetal case of a previously published analysis method [7]. Since the cited analysis method was applied to the RR series (series of inter-beat interval durations), firstly, we obtained the RR series by using the formula: $\mathrm{RR} = \frac{60}{\mathrm{FHR}}$ (1)

Then, we computed the series ΔRR calculating the difference between consecutive RR values. Finally, the time series of ΔRR was transformed into symbol sequence from a given alphabet (for each ΔRR value, one symbol is assigned). By comparing different kinds of transformations, we found that the use of five symbols is adequate. In particular, we chose the following symbols: V (vagal activation), D (deceleration of the

heart rate), O (absence of significant variability), A (acceleration of the heart rate), S (sympathetic activation).

The symbol of our alphabet that had to be associated with a ΔRR sample was chosen comparing the ΔRR value with set thresholds. In analogues analysis on adult subjects, the thresholds were set to ± 10 ms e ± 50 ms, considering, respectively, the sampling frequency of HR signal and the statistical parameter pNN50. Peak to peak amplitude of variability in FHR signals is very reduced respect to that of HR signals, most values are confined between -5 ms and 5 ms, hence we had set different thresholds.

The primary threshold (PT) was chosen considering that its value must be such that below it, there have to be only samples of the signal FHR that are not due to the physiological variability of the cardiac rhythm. Therefore, it was set in order to confine between its positive and negative value samples due to noise (related to the uncertainty of the measurement). In particular, recording devices provide FHR values with a resolution of 0.25 bpm, the corresponding uncertainty in RR values depends on FHR value (see equation 1), so we decided to choose the PT value according to the FHR mean value of the FHR signal under analysis. About secondary threshold (ST), it was heuristically set to 3 ms. At this point, we performed the encoding reported in the following table 1.

**Table 1**. Encoding used for transforming the series DRR into symbols sequence. In the first column rules adopted in comparing DRR with the set thresholds, in the second column symbols of our alphabet and in the third column the meaning assigned to the chosen symbol.

| 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 |

Established the encoding, a sliding window of length (L) is shifted along the codified ΔRR series with an overlap of 99%, transforming it in a sequence of patterns of L samples (words). The length L of the words was chosen equal to 7, according to physiological considerations, in order to cover both a vagal response (almost immediate) and a sympathetic response (delayed of about 3 s) [8, 9].

*1.4 Dominance criterion*

By using words of 7 symbols, with 5 possible symbols (N), $N^L$ (78125) words can be obtained. Even considering the number of combinations with repetitions, 330 different words could be obtained. Of course, it could be quiet difficult to manage and interpret such an amount of data, so we have grouped the words in different classes by the occurrence of the same symbol within them, using the criterion described in Table 2.

## 2. Results

For each analyzed ΔRR, we evaluated, simply by means of bar charts, the percentage of occurrence of different symbols and the percentage of occurrence of classes of words. However, in the figures we reported only the histogram of the classes of words, on which we focused our attention, and the corresponding FHR signals, in order to highlight its variability.

**Table 2**. Criterion adopted in order to group the words by the occurrence of the same symbol within them. In the first two columns examples of words that we grouped and their description, in the third column the meaning assigned to each kind of words and in the last column the symbol used to label the class of words.

| Description | Example | Meaning | Code |
|---|---|---|---|
| At least 4 symbols “S” anywhere in the word | SSSSXXX | high sympathetic activation | S |
| At least 3 symbols "S" and 1 symbol “A” anywhere in the word | SSSAXXX | | |
| At least 4 symbols “A” anywhere in the word | AAAAXXX | sympathetic activation | A |
| At least 3 symbols “A” and 1 symbol “S” anywhere in the word | AAASXXX | | |
| At least 4 symbols “O” anywhere in the word | OOOOXXX | absence of variability | O |
| At least 3 symbols “D” and 1 symbol “V” anywhere in the word | DDDVXXX | vagal activation | D |
| At least 4 symbols “D” anywhere in the word | DDDDXXX | | |
| At least 3 symbols “V” and 1 symbol “D” anywhere in the word | VVVDXXX | high vagal activation | V |
| At least 4 symbols “V” anywhere in the word | VVVVXXX | | |
| All other cases | | random | R |

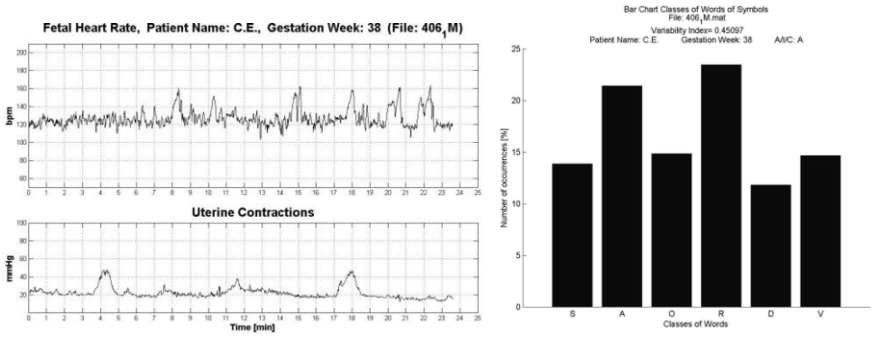


**Figure 1**. On the left, CTG recording # 406_1 (internal numbering of our database); on the right, histogram of the classes of words recognized for the ΔRR series computed from this signal.

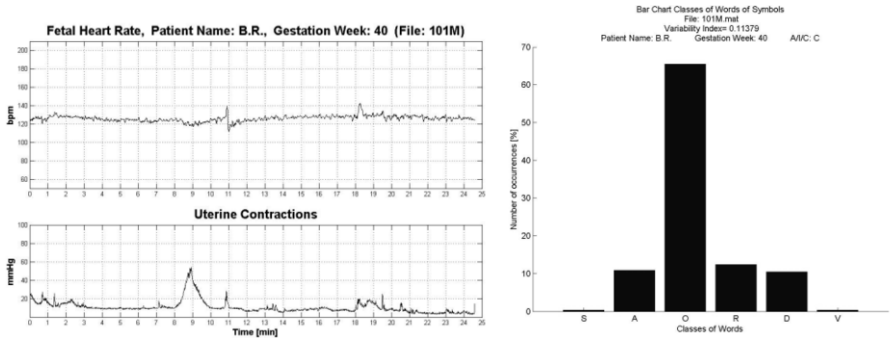


**Figure 2**. On the left, CTG recording # 101 (internal numbering of our database); on the right, histogram of the classes of words recognized for the ΔRR series computed from this signal.

As it can be observed in the examples shown in the figures 1 and 2, the distributions of classes of words of analyzed FHR signals were very different. They, in fact, having very dissimilar aspects magnify the existent differences in FHRV. In the CTG recording #406 (figure 1) a good reactivity in response to the contractions can be observed and in fact only 15% of classes of words are found within the class “O”. Vice versa, in CTG recording #101 (figure 2), there is a substantial absence of physiological

variability (trace defined as silent in clinical environment) and in fact about the 65% of classes was defined as "O". We observed this behavior for all the analyzed CTG recordings.

## 3. Discussion

It is known that FHRV is an important parameter in monitoring fetal well-being and that classical linear analysis methods are not able to investigate all the complex systems which interact in heart rate controlling. Nonlinear techniques have gained a great interest in the recent years since they can be a useful tool to highlight, quantify and better understand these mechanisms. In adult subjects, different nonlinear analysis have already proven their powerful in discriminating between physiological and pathological situations and classifying different kinds of diseases [10].

In fetuses, analysis of FHR irregularity has been seen, for example, like expression of ANS development. However, research work is less than adults and, in particular, at the best of our knowledge, very few applications of SD are available.

In this work, we described in detail a procedure to evaluate variability of FHR signals by means of SD. The results, about the distributions of words of length 7 by an alphabet of 5 symbols, of healthy fetuses near to term, showed clear and interesting differences between signals characterized by more or less variability.

Of course, further investigations are necessary, these results in fact have to be quantified, for example introducing concise indexes, and extended to different case studies. Besides, we would to examine the possibility of distinguishing between vagal and sympathetic activation times. However, results presented in this work confirm that SD can be a helpful approach to classify FHRV.

## References

[1] 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

[2] 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

[3] van Leeuwen P, Bettermann H. The status of nonlinear dynamics in the analysis of heart rate variability. Herzschrittmachertherapie und Elektrophysiologie, 1999;10 (3):127-130

[4] Yeragami VK, Nadella R, Hinze B, Yeragani S, Jampala VC. Nonlinear measures of heart period variability: decreased measures of symbolic dynamics in patients with panic disorder. Depress and anxiety. 2000; 12: 67-77

[5] Cesarelli M, Romano M, Bifulco P, Fedele F, Bracale M. An algorithm for the recovery of fetal heart rate series from CTG data. Comput Biol Med. 2007; 37 (5): 663-669

[6] 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

[7] 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. Comp Cardiology 2005; 32: 575-578.

[8] Martin CB. Physiology and clinical use of fetal heart rate variability. Clin Perinatol.1982;9(2):339-352

[9] Zhuravlev YE, Rassi D, Mishin AA, Emery SJ. Dynamic analysis of beat-to-beat fetal heart rate variability recorded by squid magnetometer: quantification of sympatho-vagal balance. Early Hum Dev. 2002; 66: 1-10

[10] van Leeuwen P, Lange S, Bettermann H, Gronemeyer D, Hatzmann W. Fetal heart rate variability and complexity in the course of pregnancy. Early Hum Dev. 1999; 54: 259–269