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Self-similarity behavior characterization of Fetal Heart Rate signal in healthy and Intrauterine Grow Retardated fetuses

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***Abstract*—In this paper we deal with the problem of the interpretation of the fetal heart rate (FHR) signal. From literature is known that FHR contains both linear and non linear components. Starting from this consideration we analyzed FHR as a fractal time series and we evaluated its self similarity behavior using the Hurst's coefficient (H). We first evaluated the stationarity of FHR time series and then we estimated H with Detrend fluctuation analysis (DFA) method.**

We calculated Hurst's coefficient for healthy fetuses and for fetuses affected by Intrauterine grow retardation (IUGR). Results provided H = 0,350 ± 0,064 (avg ± std) for healthy patients and H = 0,461 ± 0,059 for IUGR. It is also shown that IUGR patients exhibit a "less non-stationary" and longer-memory behavior than normals with a reduced information content of FHR signal.

We propose for this phenomenon a physiological explanation connected with the abnormal autonomic nervous system development of IUGR patients.

***Key words*: FHR, Hurst's coefficient, DFA, Periodogram, IUGR**

I. INTRODUCTION

CARDIOTOCOGRAPHY (CTG) is a nowadays standard diagnostic tool for prenatal obstetrics. It consists of the monitoring of the fetal heart rate signal (FHR), simultaneously with the registration of intrauterine pressure. This non invasive method gives information on the general health status of the fetus and particularly on its developmental stage.

Nowadays the typical approach to the interpretation of the CTG trace is made starting from a morphological signal processing based on the analysis of accelerations and decelerations in FHR signal [1] [2]

Nevertheless, according to the guidelines of the International Federation of Gynecology and Obstetrics (FIGO), at present the CTG exam shows a low predictive ability for gestational risks and a poor significativity for the recognition of prenatal pathologies [3]. Even life-threating diseases, like Intrauterine grown restriction (IUGR), are often not properly recognized.

Starting from the literature [4] [5] [6], where it is demonstrated that the FHR signal shows both linear and non linear features, we decided to face the problem of CTG interpretation using non-linear analysis methods. Thus we analyzed the long memory behavior of the FHR signal looking for differences between Healthy and IUGR FHR signals in terms of Hurst's coefficient (H).

The importance of the analysis of cardiac signal regularity, furthermore, derives from the clinical observation that a pathologic system, because of the deterioration of neural control systems, aims to be isolated from the rest of the system and its output (FHR in this case) can show an increased regularity.

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II. MATERIALS AND METHODS

A. The dataset

The analyzed FHR series have been acquired from a fetal CTG monitor Hewlett Packard M1351A. The US burst frequency was 998,4kHz, repeated at a frequency of 3,2kHz. The FHR was obtained thanks to a peak-detection software applied on the Autocorrelation function (ACF) of the US cardiac signal. The ACF was also useful for a classification of the quality of FHR. If a series contained more than 5 consecutive "low quality points" (according to the machine ACF classification algorithm), it wasn't considered for the analysis. An expert physician classified FHRs and acted as gold standard [7].

The FHR signals derive from the CTG registrations of 27 fetuses, 14 normal and 13 IUGR, between the 33rd and the 38th gestational weeks, producing 53 good-quality healthy FHR series and 46 good-quality IUGR series. Each recording is more than 60 minutes long and contains at least one transition from quiet to activity behavior.

The dataset was provided by the Obstetrics Clinic of the University of Rome "Tor Vergata".

B. Methods

In a previous work we investigated the effectiveness of the most up-to-date methods for the estimation of Hurst's coefficient (H) in time series. In particular we evaluated a blind method for the estimation of H, without any *a priori* knowledge on the time series [8]. In that work the analysis of the performance was made for different kinds of synthetic time

series (fBm, fGn, 1/f and FARIMA) [9] [10], for each value of H in the range $0.1 \leq H \leq 0.9$ with step 0.1, for eight different methods [10]: Aggregate Variance [11], Modulus of the Aggregate series [11], Higuchi [12], Dispersional Analysis (DA) [13], Detrended Fluctuation Analysis (DFA) [14], Periodogram [11] [15], Allan factor and Fano factor [16]. From the results of these simulations, we proposed a procedure able to estimate the Hurst's coefficient without any knowledge about the series in exam. This procedure [8] is made up of two steps (see figure 1):

First step. Estimation of the decay rate α of the average variance of the fractal time series [17]. This estimation is made with Periodogram for "discontinue jumping" time series (e.g. Lévy Flight processes [18]) by calculating the spectral slope in a bi-logarithmic scale-estimator chart, close to the zero-frequency axis, or with DFA for a "non-jumping" time series evaluating α_{DFA}, with $\alpha = 2*\alpha_{DFA} + 1$. From α value, it's possible to estimate the stationarity of the series. We have decided to distinguish three different "stationarity zones" in α range. "High stationarity" for $\alpha<0.5$, "High non-stationarity" for $\alpha>1.5$ and a transition zone for $0.5\leq \alpha\leq 1.5$.

Second step. Considering sub-series without "jump points", estimate H as follows: for High stationary time series the best estimations are assured by DA or Periodogram; for High non-stationary series we proposed Modulus of the Aggregate series, Higuchi or DFA and for intermediate behaviors the value of H obtained from DFA of the previous step.

It is well-known that the FHR signal presents an high number of "jump-discontinuity" points in concomitance with the changes of fetal activity: a transition low-high of the heart rate corresponds to an alteration quiet status – active status of the fetus, and *vice versa*.

Starting from this consideration we began the analysis by applying the Periodogram method for a first estimation of H.

III. RESULTS

We first applied Periodogram and we found an α value approximately equal to 1.6 for both populations (α = 1,653 ± 0,241 (avg ± std) for healthy and α = 1,613 ± 0,223 for IUGR). This value is a border line case staying between "transition zone" and "non-stationarity zone" (H ≈ 0,3). The obtained values are consistent with previous results [19] [7]. We then applied DFA to the time series of both groups, according to the "Second step".

As can be seen in figure 2, all the same, an analysis made up with the Periodogram method is less precise than DFA. In this case, nevertheless, DFA is not applicable to the whole FHR series, because of the presence of "jump points".

As can be seen from figure 2, however, Periodogram tends to overestimate H, and consequently, it underestimates the non-stationarity of the time series.

This consideration allowed us to use DFA for the "Second step" without worry about the "First step": even if, from the first processing stage, we would obtain an H value higher than the real one, this result justified, however, the use of DFA.

According to the "Second step", we adopted the DFA method for both groups in the sub-series without punctual changes in the "fetal activity" ("jumps") and without low-quality points (low quality points, marked from the CTG system with a zero in the FHR signal, introduce a relevant frequency artifact; Periodogram method, used in the first step, is insensitive to them). By considering subsets without changes in the "fetal activity", in fact, FHR is assimilable to an fBm process.

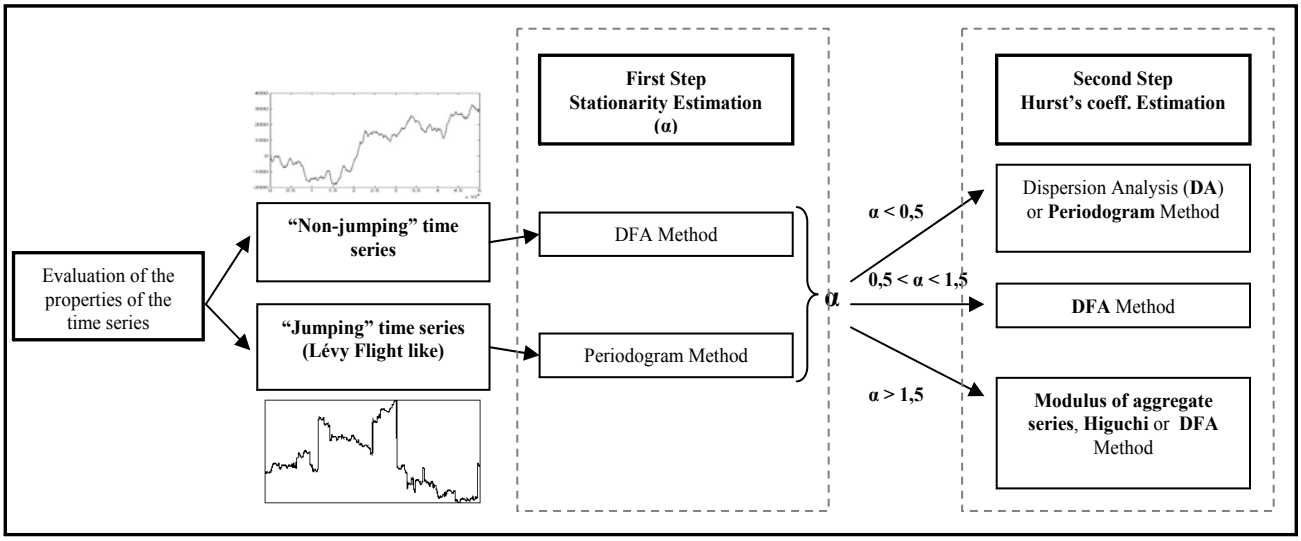

Fig. 1: Graphic representation of the H estimation algorithm (see Methods)

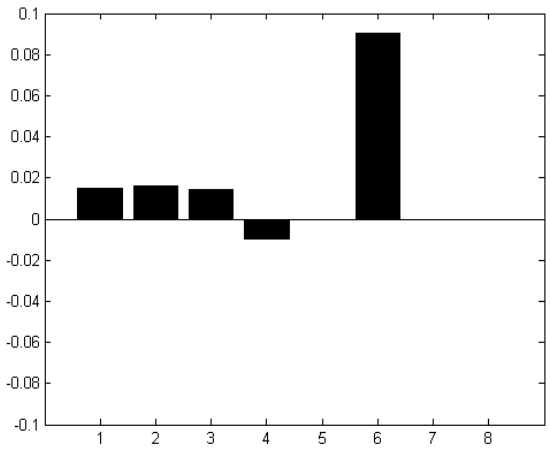

Fig. 2: Graph representing the deviation of the real estimation from the expected estimation value, made by each of the 8 method considered in [8] *for H=0,3 in fBm. 1=Aggregate Variance, 2=Modulus, 3=Higuchi, 4=DFA, 5=DA (not shown), 6=Periodogram, 7=Fano (not shown), 8=Allan (not shown). Methods 5, 7 and 8 are not applicable with an fBm time series.*

From this more refined analysis we obtained that the coefficient H is able to distinguish the two population of healthy and IUGR patients (figure 3).
In particular we found a mean H value of 0,350 ± 0,064 (avg ± std) for healthy patients and H = 0,461 ± 0,059 for IUGR. The two series are clearly distinguishable and marginally overlapped. For IUGR patients an higher value of HRV Hurst's coefficient is easily identifiable.

IV. DISCUSSION

From a physiological point of view it is reasonable to ascertain the general anti-persistence of the FHR series (H ≤ 0,5): the heart rate, in fact, is the result of the coexistence of different kinds of antagonist *stimuli*.

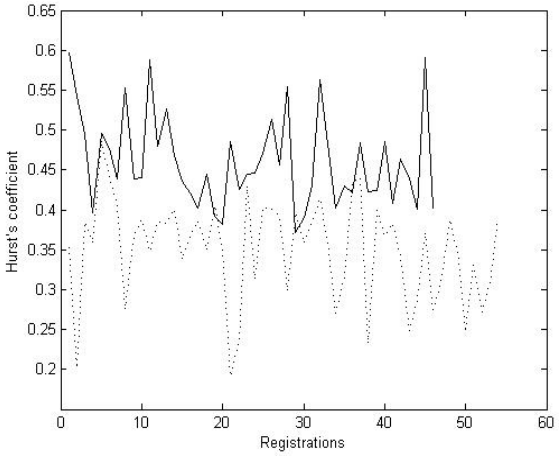

Fig. 3: H values estimated for IUGR patients (solid line) and healthy patients (dotted line) for each registration (46 IUGR and 53 normal).

The creation of a drift in the baseline of the heart rate, as a result of a persistent series (α > 2), would be incompatible with life.
The results show that the healthy FHR series is more non-stationary than IUGR FHR series. From the literature it is well known that an imbalance in intrauterine growth stages (e.g. in IUGR) is seldom correlated with an imbalance in the autonomic control system of the fetus [20] [7]. From the analysis of data it is remarkable that healthy fetuses exhibit a short-memory [17] anti-cooperative behavior. This anti-cooperative behavior probably derives from the coexistence of antagonist heart rate control systems: e.g. the baroreflex control, the response to the maternal respiration rate, etc…. In the healthy case, moreover, responses are very fast and generate a short-memory system.
An IUGR fetus, on the contrary, because of the control system retardation, tends to show trends in the FHR, i.e. a more cooperative system, and slow responses (long-memory process). Besides these, because of the signal shows a Hurst exponent near to 0,5, that is the H value typical of Brownian motion, it seems to be greatly emptied of information content.
From these considerations it seems that in IUGR fetuses the control on heart rate mainly occurs at a central level, with long times, and in a discontinuous way: the regulation system, in other words, intervenes just when the heart rate is too high or too low with respect to the actual fetus needs. The normal beat-to-beat control, produced by autonomic responses, seems to be lost in IUGR. Other recent works also underline the possibility to identify fetal distress with Entropy-based regularity estimators [21].
Our results are consistent with other autonomic control researches. For example, studies in literature on the Hurst's coefficient of heart rate variability (HRV) of cardiovascular disease patients before and after the cardiac transplant [19] show a variation in the value of α consistent with our results. The transplanted heart is lacking of the autonomic innervation: the Hurst's coefficient in this case is higher than the healthy one.
The consonance of these results supports our physiologic interpretation.

V. CONCLUSION

We measured the Hurst's coefficient (H) of the heart rate variability signal of healthy and IUGR fetuses. For a systematic approach to the problem we applied an H-estimation blind algorithm that we proposed in [8] [10]. Starting from this algorithm we evaluated the Hurst's coefficient in two steps: we first estimated the stationarity of the time series with the periodogram method; next we calculated H with selected sub-series of the original series.
From the analysis we obtained that the two series are clearly distinguishable and marginally overlapped.

From these results we argued that such different behavior is due to the retardation in autonomic nervous system development, typical in IUGR patients. This lets up systemic controls and made the sum of central and peripheral heart rate controls more predictable.

Further developments: for a deep understanding of the physiological working of this phenomenon, a further analysis should be done at a multi-fractal level, in order to recognize the different contributions of FHR. If the proposed physiological interpretation is correct, in IUGR fetus a multi-fractal dimension reduction should be identified. In this case, moreover, the preeminent dimension should be that one associated to the central control.

The results of this paper suggest to include the evaluation of the Hurst's coefficient among the methods used for the multivariate analysis of FHR often proposed in literature (e.g. [2]).

Finally an application of this method to other fetal diseases ascribable to autonomic activity alterations, like maternal diabetes or fetal macrosomy, could produce interesting results.

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