Characterization of Fetal Heart Rate Using Approximate Entropy

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Abstract

Approximate entropy (ApEn) is an interesting measure for assessing the irregularity of time series and in particular for characterizing heart rate variability. In the present paper we apply ApEn to the characterization of three patterns of fetal heart rate (FHR): calm sleep; calm vigilance; pathological flat-sinusoidal condition. We conclude that ApEn can perfectly discriminate the pathological FS pattern from the normal A and C patterns and is far better for FHR pattern discrimination than classic time-domain variability indexes used in clinical practice.

1. Introduction

Fetal heart rate (FHR) variability has been characterized by several methods. The most popular method, in clinical practice, is a time-domain method, the so-called variability indices: heart rate amplitude range in consecutive windows of one minute (LTV: long-term variability) or one second (STV: short-term variability) duration. Spectral and fractal methods have also been proposed. Several authors have found evidence that heart rate either in the adult or in the fetus be well modeled by temporal fractals. In our previous work [1] we were able to classify fetal heart rate patterns based on fractal features.

An interesting measure - inspired on measures for chaotic systems - to assess the degree of randomness of sequences of numbers was proposed by Steve Pincus [2] and called approximate entropy (ApEn) given its similarity with entropy measures. The good properties of this measure in characterizing the degree of randomness, even in the presence of a not too large set of samples, was shown in several works [2-6]. The application of ApEn to characterize serial irregularity of various physiological signals, namely in adult and fetal heart rate, is described by Steve Pincus in [8].

Recently, ApEn has been applied to the characterization of 24 hour records of healthy adult heart rate tracings [10] with the aim of analyzing the dynamics of very short sequences (only N=5 samples!). Applications to fetal heart rate are described in [3] and [7-9] ([9] reports on the findings of [3] and [8]). In [3] ApEn was used to assess fetal condition during labor (normal, presumed distress, acidotic). In [8] ApEn is applied to the assessment of heart rate variability with gestational age. In the present paper we apply ApEn with a different aim. Our intent is to use ApEn as a parameter of FHR behavioral pattern, which could be used (possibly together with other ones) for automatic monitoring fetus condition. In this work we analyzed three FHR patterns: A - calm sleep; C - calm vigilance; FS - pathological flat-sinusoidal condition. We show that ApEn can adequately characterize these FHR patterns.

2. Methods

Approximate entropy is based on the idea of determining how a correlation measure for blocks of m signal samples evolves with m. Let x_i and x_j denote any pair of m-sized blocks of samples of a signal $u(1),u(2),\ldots,u(N)$. The following distance measure is defined:

$$d(x_i, x_j) = \max_{p=1,\ldots,m} \left(\left| u(i+p-1) - u(j+p-1) \right| \right)$$

Based on this distance measure, the following correlation measure is defined:

$$C_i^m(r) = (\text{nr of } j \text{ such that } d(x_i, x_j) \le r)/(N-m+1),$$

where r is a given positive number that sets the upper bound on considering x_i similar to x_j. It's easily shown that this correlation measure varies between $1/(N-m+1)$ and 1. Now, define the following function which adds up the contributions of the log of the correlations:

$$\Phi^m(r) = \sum_{i=1}^{N-m+1} \log C_i^m(r)/(N-m+1)$$

The approximate entropy of order $m > 0$ is now defined as:

$$\mathrm{ApEn}(m,r)=\begin{cases}\lim\limits_{N\to\infty}\left\{\Phi^{m}(r)-\Phi^{m+1}(r)\right\}, & m>0\\ \lim\limits_{N\to\infty}\left\{-\Phi^{1}(r)\right\}, & m=0\end{cases}$$

Therefore, ApEn measures the logarithmic frequency with which vectors with m components that are close (within resolution r) remain close when increasing the number of vector components by one.

We evaluated ApEn for 43 tracings of FHR pattern A; 22 of pattern C; 27 of pattern FS. All tracings were acquired with fetal monitors driven by our SisPorto system [11] and unanimously classified by three expert obstetricians. All tracings were "pure", i.e., they did not contain any overlaps of other patterns. The average duration of the tracings was about 20 minutes; the number of samples was in [2347,3288] for pattern A; in [884, 2867] for pattern C; in [1472,3040] for pattern FS.

Usually ApEn is measured for low values of m. We evaluated for m=1,2 as used by other authors. Concerning the resolution r, we evaluated ApEn according to three methods:

- M1: In normal clinical practice obstetricians consider a difference of consecutive heart beat rates below 5 bpm as not meaningful. We took a more conservative view and in our M1 method we set r = 3 bpm.
- M2: In this method ApEn was evaluated for binary sequences describing FHR dynamics in the following way: an increase in consecutive heart rates is codified as 1; a decrease or a tie was codified as 0. This method was used with interesting results in [10].
- M3: In this method ApEn was evaluated with r set to a certain percentage of the standard deviation of the tracings. Following indications in [3] we set r = 0.2SD. The rationale for using this method is the scale invariance achieved by this normalization.

3. Results

Mean values, standard deviations and ranges of ApEn for the three methods are summarized for m=2 in Table 1. Almost identical results were obtained for m=1 (with significantly high correlations).

Table 1. Mean ± SD for the 3 methods, with m=2.

	M1	M2	M3
A	0.190 ± 0.082	0.551 ± 0.051	0.903 ± 0.325
	[0.105, 0.499]	[0.463, 0.648]	[0.295, 1.522]
C	0.449 ± 0.156	0.600 ± 0.043	0.712 ± 0.221
	[0.216, 0.741]	[0.523, 0.658]	[0.361, 1.085]
FS	0.059 ± 0.023	0.342 ± 0.064	0.602 ± 0.116
	[0.003, 0.099]	[0.230, 0.465]	[0.397, 0.823]

Applying the Kruskal-Wallis test to the results of M1 and M2 we verified a significant ($p \approx 0$) discrimination of the ApEn distributions for the three pattern classes. This was not verified for the M3 results which yielded wide overlapping distributions. For this reason we didn't carry further the analysis of the M3 results.

Mann-Whitney tests confirmed a good pairwise discrimination for all pattern pairs.

Figure 1 shows the box plot for ApEn for m=2 (ApEn2) computed with method M1. There is practically no overlapping of the FS distribution with the other two. The overlapping for patterns A and C is quite small.

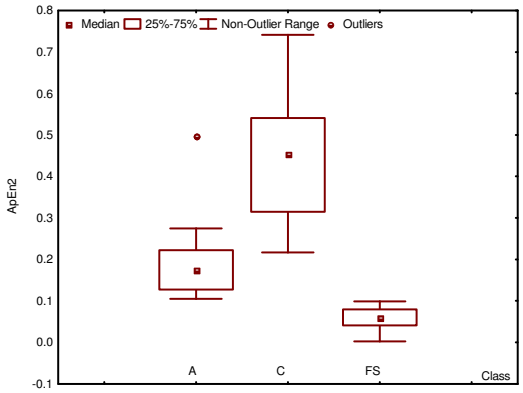

Fig. 1. Box plot for ApEn2 computed with method M1.

The very low values of ApEn2 for pattern FS are a clear indication of an irregularity loss, associated with this pathological condition and assessed in clinical practice with the time domain variability indexes STV and LTV.

The linear discriminant classification error based on ApEn2 is about 10% (SD ≈ 5%).

Table 2. Linear discrimination with ApEn2.

		Observed		
Predicted	% Correct	A	C	FS
A	95.3	41	2	0
C	72.7	6	16	0
FS	96.3	1	0	26
Total	90.2	48	18	26

When using the binary sequences of method M2 we obtained less discriminating capability. For instance the overall linear discrimination error (for either value of m) was about 23%. Responsible for this degradation was the large overlap of ApEn values for classes A and C.

4. Discussion and conclusions

We analyzed the approximate entropy of three classes

of fetal heart rate, using three distinct methods. In [3] ApEn was computed with method M3 which yielded bad results in our experiments. The cause of this may be attributed to the fact that fetal heart rate is more than the result of a unique and continuous time series generator endowed with a certain amount of randomness. One has to take into account the discontinuous occurrence of acceleration and deceleration events caused by the behavioral stages of the fetus and the influence of its environment. These events may trigger large departures from the basal heart rate and have a profound influence on the standard deviation. (In our view, not taking into account the different behavioral stages as in works [3] and [8] leads to a sort of "pooled" ApEn for completely different time series, whose interpretation is difficult, to say the least.) It was also for this reason that in the present study we limited ourselves to normal patterns A and C. Calm sleep and calm vigilance exhibit a much smaller number of acceleration and deceleration events than patterns of REM sleep and active vigilance. In this way we are more confident that we are assessing the basic FHR randomness that clinicians evaluate with STV and LTV indexes.

We found out, as expected, that calm vigilance displays a higher rate of irregularity than calm sleep and that both are far more irregular than the pathological FS pattern. In experiments that we performed in 14 adult heart rate tracings (in vigilance stage) we found out average ApEn values higher than for FHR (ApEn2 $\approx$ 0.6). This finding, together with results published in [8] and [10] (in [8] ApEn was found to increase from about 0.05 to about 0.3 for the 16th to the 41st gestation week) provides some evidence that ApEn may adequately reflect the steady increase of heart rate irregularity from the early stages of gestation to the adulthood.

Furthermore ApEn2 computed by method M1 succeeded in discriminating the 3 pattern classes quite well (about 10% error). As a comparison the typical error rate using the LTV and STV features is about 30% [1]; this entitles ApEn2 as a good feature for FHR pattern recognition.

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