ASSESSMENT OF NOISE IMPACT IN SAMPLE ENTROPY FOR THE NON-INVASIVE ORGANIZATION ESTIMATION OF ATRIAL FIBRILLATION

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Abstract: In recent studies, Sample Entropy (SampEn) has demonstrated that can be a very promising non-linear index to assess atrial fibrillation (AF) organization from surface ECG recordings. However, non-linear regularity metrics are notably sensitive to noise. Thereby, in the present work, the effect that noise provokes in AF organization estimation based on SampEn is analyzed. Given that AF organization was estimated by computing SampEn over the atrial activity (AA) signal, to evaluate the noise impact on AA regularity, 25 synthetic signals with different organization degrees were generated following a published model. Noise coming from real ECG recordings with different energy levels was added to the synthesized AA signals to obtain different signal to noise ratios (SNR). Results showed that SampEn, i.e., the AA irregularity, increased with noise, thus hiding the differences between organized and disorganized recordings. Precisely, in the presence of noise, SampEn values were increased, in average, by factors of 1.64, 4.46, 9.46 and 14.23 for SNRs of 24, 15, 9 and 3 dB, respectively. As a conclusion, a successful AF organization evaluation via SampEn requires a proper noise reduction in the AA signal.

1 INTRODUCTION

Non-linear analysis metrics are valuable in the assessment of physiological time series, because "hidden information" related to underlying mechanisms can be sometimes obtained (Pincus and Goldberger, 1994; Richman and Moorman, 2000). To date, a high amount of non-linear complexity measures exists, such as dimensions, Lyapunov exponents and entropies. However, their computation is frequently confronted with the problem of insufficient number of data points (Chen et al., 2009). Additionally, most dimension and entropy definitions present application limitations associated to real world time series, since all recorded data are, to a certain degree, contaminated by noise. In this respect, a 2% noise is serious enough to prevent accurate estimation (Yu et al., 2000).

Recently, a method based on sample entropy (SampEn) has been proposed to estimate organization of atrial fibrillation (AF) (Alcaraz and Rieta, 2009), which is the most common cardiac arrhythmia in clinical practice and whose onset and termination mechanisms are still unknown (Fuster et al., 2006). The study of AF organization is a key aspect in the arrhythmia's knowledge, because it provides information on the number of active reentries (Sih et al., 1999; Everett et al., 2001), which maintain and can perpetuate AF. Thereby, in the present work, the noise effect on this method, which could be useful to predict spontaneous AF termination or the result of aggressive therapies, such as electrical cardioversion or ablation, is exhaustively analyzed.

2 MATERIALS

Given that AF organization has to be estimated by computing SampEn over the atrial activity (AA) signal (Alcaraz and Rieta, 2009) and because AA with

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no noise or ventricular residues cannot be obtained from real ECG recordings, 25 one minute synthetic AA signals were generated. Thus, the noise effect on AA organization estimation could be evaluated. The synthetic AA signals were obtained making use of the model proposed by Stridh et al (Stridh and Sörnmo, 2001). In this model, a sinusoid and $M-1$ harmonics are used to generate a sawtooth-like shape of AF. The non-stationary behavior is created by introducing a time-varying amplitude and cycle length of the sawtooth signal. In every lead of N samples in length, the AA is modelled by:

$$y(n) = -\sum_{i=1}^{M} a_i(n)\sin(i\theta(n)), \qquad n = 1,\dots,N \quad (1)$$

where the term $a_i(n)$ with the sawtooth amplitude, a, the modulation peak amplitude, Δa, and amplitude modulation frequency, f_a, is given by:

$$a_i(n) = \frac{2}{i\pi}\left(a + \Delta a \sin 2\pi \frac{f_a}{F_s} n\right) \quad (2)$$

The fundamental frequency of the fibrillation waveform is assumed to vary around f_0 with a maximum frequency deviation of Δf and modulation frequency given by f_f. The phase, $\theta(n)$, is then given by:

$$\theta(n) = 2\pi \frac{f_0}{F_s} n + \left(\frac{\Delta f}{f_f}\right) \sin 2\pi \frac{f_f}{F_s} n \quad (3)$$

After several tests, the selected parameters were $\Delta f = 3$ Hz, $f_f = 4$ Hz, $\Delta a = 10\mu$V, $f_a = 9$ Hz and $F_s = 1024$ Hz in order to synthesize a signal as close as possible to the real AA. In this respect, Figs. 1(a) and (b) show a real AA signal obtained by applying the averaged QRST cancellation technique and a synthetic AA signal generated with the indicated parameters, respectively. Because of the typical AA fundamental frequency range is 3-9Hz (Bollmann et al., 2006; Stridh et al., 2001), a fundamental frequency f_0 equal to 6 Hz was selected. In order to obtain different regularities, the number of harmonics M and their amplitude a were varied, such that, a higher number of harmonics with lower amplitude will generate a more irregular AA. In this way, M and a were randomly selected between 5 and 15 and between 6 and 18 μV, respectively. Hence, the most irregular AA signal presented 15 harmonics with 6 μV of amplitude. The set of AA signals with different regularities were used to evaluate if the noise effect was regularity-dependent. Finally, available noise in Physionet (Goldberger et al., 2000) coming from real ECG recordings with different energy levels was added to the synthesized AA signals. Concretely, this noise was the recorded signal when the patient front-end is disconnected from the skin electrodes. In

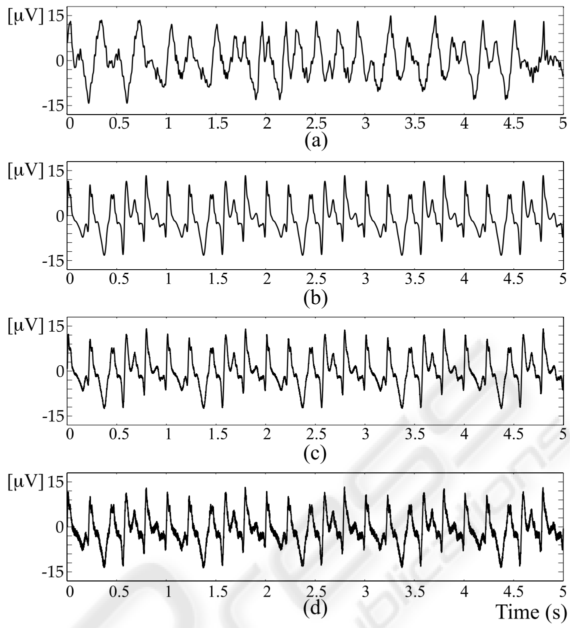

Figure 1: Comparison example between real and synthesized AA signals depending on added noise.(a) Real AA signal obtained from the ECG through averaged QRST cancellation technique. (b) Synthetic AA signal without noise. (c) Synthetic AA signal with added noise and SNR of 15 dB. (d) Synthetic AA signal with added noise and SNR of 9 dB.

Figs. 1(c) and (d), a synthetic AA signal that has been added to the described noise with two different energy levels is shown.

3 METHODS

The 25 synthetic signals were used in order to evaluate the noise impact on AA regularity. The same noise signal was superimposed to all synthetic AA signals, which were generated with different degrees of regularity. Firstly, SampEn values of the AA signals without noise were computed. Next, the noise recording was weighed by different gain factors and added to the synthetic signals in order to obtain different signal to noise ratios (SNR). Finally, SampEn values of the synthetic AA signals contaminated with noise were calculated. This methodology allowed us to evaluate the evolution of AA regularity estimation in the presence of noise.

The SNR of an ECG recording is normally lower than 30 dB (Laguna and Sornmo, 2000). In addition, because of the real AA signal is obtained from ECG recordings using ventricular activity cancellation techniques, the SNR of an AA signal must be lower than the SNR of an ECG signal. In fact, the

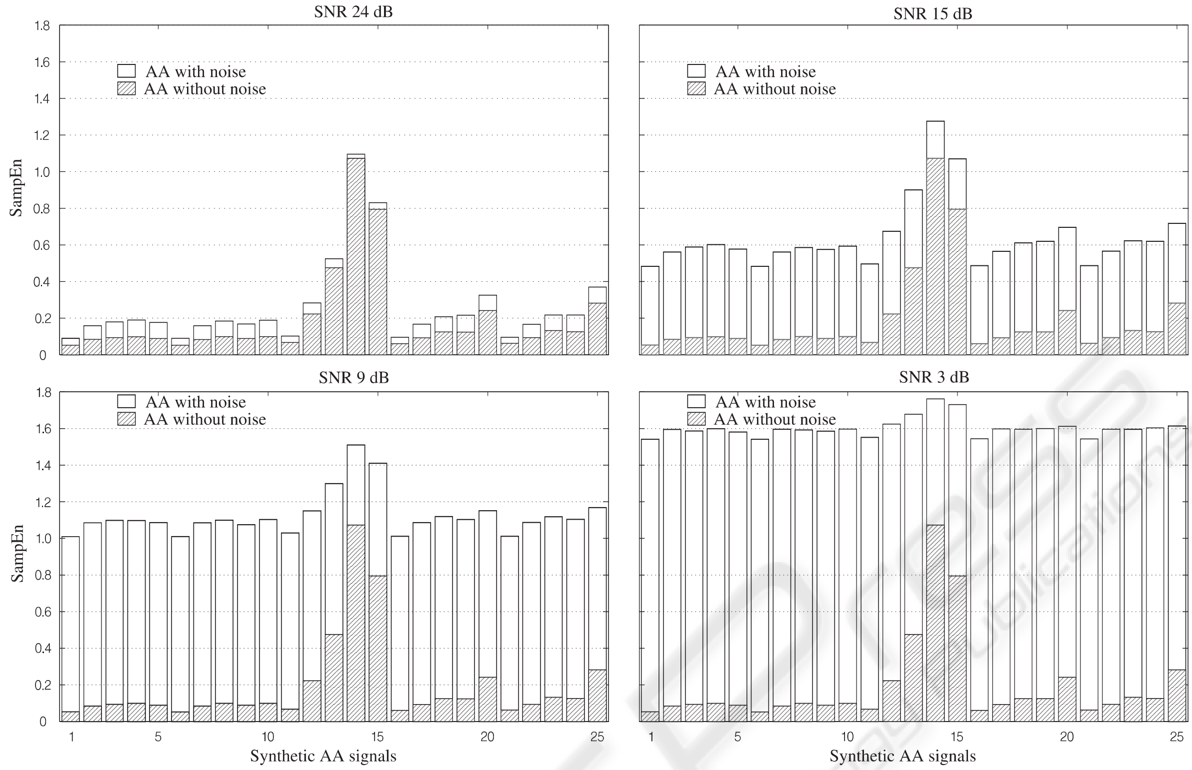

Figure 2: Each plot shows SampEn values of 25 synthetic noise-free AA signals stacked with their corresponding result when SNR is 24, 15, 9, and 3 dB. The presence of noise produces a disorganization increase in the AA signals and reduces the differences between initially organized and disorganized signals. Therefore, noise reduction is essential to assess successfully AF organization with SampEn.

SNRs of the AA signals obtained from 50 real ECGs analyzed in a previous work were within the 16.4–2.7 dB range (Nilsson et al., 2006). In the study, the SNR is defined as the ratio between the mean of the fundamental and first harmonic power magnitudes and the power magnitude of the background noise. Whereby, AA signals with SNR of 24, 15, 9 and 3 dB were generated.

4 RESULTS

Fig. 2 shows the evaluation results of noise effect on AA organization estimation via SampEn. As can be seen, SampEn values for the 25 noise-free synthetic AA signals are shown and increased with their corresponding SampEn values for 24, 15, 9 and 3 dB SNR, respectively. It can be observed that SampEn, i.e., the AA irregularity, increases with noise, thus hiding the differences between organized and disorganized activities. Precisely, in the presence of noise, SampEn values were increased, in average, by factors of 1.64, 4.46, 9.46 and 14.23 for SNRs of 24, 15, 9 and 3 dB, respectively. In addition, the difference between the two signals without noise that presented the highest and lowest SampEn values was reduced by factors of 1.07, 1.29, 2.05 and 4.67 for the signals with SNRs of 24, 15, 9, and 3 dB, respectively.

We also tested the same experiment by adding Gaussian noise instead of ECG noise to the synthesized AA signals and results were very similar, hence, they have been omitted. However, bearing this similar behavior in mind, any other kind of random and non-deterministic contaminating signal should provoke similar results of SampEn.

5 DISCUSSION AND CONCLUSIONS

Results showed that the noise presence masks the differences, evaluated with SampEn, between organized and disorganized activities. Thereby, it could be considered that when AA is contaminated by noise or any other undesired signal, the organization difference between AF episodes are considerably reduced. This fact is crucial, for example, in the successful prediction of paroxysmal AF termination. Considering that the AA obtained from the ECG often presents QRS residua and noise (Petrutiu et al., 2006), the obtained results with synthetic AA signals can be used to justify the poor discrimination outcome reported by other groups when direct AA organization analysis was applied (Nilsson et al., 2006).

Moreover, the results are also coherent with the highly improved paroxysmal AF termination prediction reached by applying SampEn to the fundamental waveform associated to the AA (Alcaraz and Rieta, 2009), its wavelength being the inverse of the dominant atrial frequency (DAF) (Holm et al., 1998). As this signal is obtained by applying a selective filtering to the AA centered on the DAF, most part of the undesired contaminating signals are avoided. As a consequence, to obtain a successful AF organization assessment through SampEn, noise and nuisance interferences in the AA signal should be considerably reduced prior to the computation of the non-linear index.

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