A NEW, FAST, AND ROBUST INDEX FOR HEART RATE VARIABILITY ANALYSIS

M. A. García-González[1], R. Pallàs-Areny[1]
[1]División d'Instrumentació i Bioenginyeria, Departament d'Enginyeria Electrònica, Universitat Politècnica de Catalunya, Barcelona, Spain. E-mail: magarcia@eel.upc.es

Abstract-**The acceleration change index (ACI) to describe heart rate variability (HRV) is presented. It is calculated from the parameters of a time series derived from the RR time series. Evaluating the ACI for simulated signals shows that it correlates with the their fractal dimension. Evaluating the ACI for records from healthy subjects shows that it decreases with periodical breathing and increases during exercise. When the ACI is applied to records from commercial ECG databases, it can discriminate healthy subjects from subjects who had suffered ventricular tachycardia and/or fibrillation and from subjects with myocardial ischemia .**

Keywords **- Heart rate variability, myocardial ischemia, ventricular fibrillation and tachycardia, exercise stress, periodic breathing.**

I. Introduction

Heart rate variability (HRV) carries information about the neural modulation of the cardiovascular system by the autonomous nervous system. HRV analysis can discriminate normal from pathologic subjects by several indexes calculated from the RR time series [1]. The commonest indexes are defined in the time (statistical indexes) and frequency domains (spectral indexes). The usefulness of these HRV indexes depends on their specificity, sensitivity, robustness in front of artifacts (false positive or false negative detections of QRS complexes in the ECG), and time required to compute them. Spectral indexes, as well as indexes based on non-linear dynamics, are prone to fail in the presence of artifacts and need more computing time than statistical indexes. On the other hand, statistical indexes have poor sensitivity and specificity to several cardiovascular diseases as compared to spectral indexes. This work aims to present a new statistical index which is robust to artifacts, very fast to compute, and able to distinguish normal from abnormal RR time series with good specificity and sensitivity.

First, the index is defined. Then, its ability to characterize the dynamics of simulated time series is analyzed by calculating it for fractal signals with known fractal dimension. Next, the index is applied to real RR time series from healthy subjects in order to investigate the influence of the respiratory sinus arrhythmia and exercise stress on its value. Afterward, the index is applied to discriminate healthy subjects from subjects that had suffered ventricular tachycardia and/or fibrillation and subjects with myocardial ischemia. Finally, some limitations of the study are discussed.

II. Index Definition

The differentiated RR time series (DRR) is

$$\mathbf{DRR} = \begin{Bmatrix} RR(2)-RR(1),\ldots RR(n)-RR(n-1), \\ RR(n+1)-RR(n),\ldots RR(N)-RR(N-1) \end{Bmatrix} \quad (1)$$

where $RR(n)$ is the length of the RR interval from beat n to beat $n + 1$, and $N + 1$ is the number of beats. The SDRR is the time series defined by the sign of the DRR series and its elements are either 1 or –1. The sign change (SC) time series is the series whose elements are the positions where SDRR changes from 1 to –1 or conversely. Differentiating SC yields the distance (in beats) between successive changes of sign of the DRR time series. The new time series is named DSC. The Acceleration Change Index (ACI) is defined as

$$\mathrm{ACI} = \frac{k}{M} \quad (2)$$

where k is the number of times that the DSC time series equals 1 and M is the total number of samples of the DSC time series. Fig. 1 shows a sample RR time series and the derived SDRR, DSC and sorted DSC time series. The ACI carries information about the number of times that a local maximum is followed by a local minimum and vice versa. As opposed to most statistical methods, this index depends on the order (dynamics) of the RR time series; the mean and standard deviation, for example, yield the same result when reordering the time series. When compared with spectral indexes, the ACI includes a sign operation that protects from artifacts. The worst-case influence of an artifact on the ACI is to increase k and M by 2, regardless of the artifact's amplitude. For indexes that depend on the variance of the signal (as the spectral indexes), the effect of the artifact depends on its amplitude. Although the definition of the ACI may seem complex, the algorithm to compute it is very fast.

III. Materials and Methods

Four different studies were carried out in order to show the usefulness of the ACI. The first study shows that the ACI correlates well with the fractal dimension of simulated signals. The second study shows changes in the ACI due to changes in breathing patterns in healthy subjects. The third study investigates the variation of the ACI under exercise stress in healthy subjects. The last study compares the ACI from healthy subjects with that from subjects who suffered ventricular

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Abstract

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tachycardia and/or fibrillation and from subjects with myocardial ischemia.

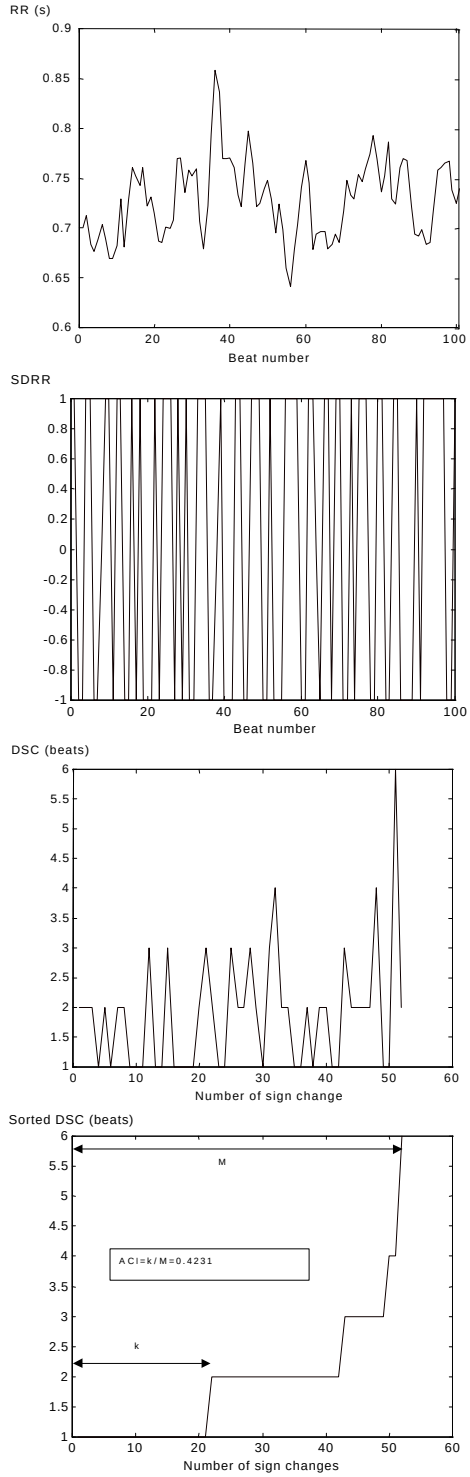

Fig 1. Example of computation of the ACI for a RR time series from a healthy subject.

A. Relationship between the ACI and the fractal dimension on simulated time series

In order to prove that the ACI carries information of the dynamics of the time series analyzed, it was calculated for several simulated time series, whose fractal dimension was known. The simulated series were synthesized by the algorithm proposed in [2]. The length of the simulated time series was 1024 samples. For each fractal dimension (starting at 1, ending at 2, and with a step of 0.01), a hundred realizations were made. The ACI was computed for each realization. The mean ACI and the upper and lower 5 % confidence intervals were computed for each simulated fractal dimension. Another simulation was carried out with 128 samples per simulated signal.

B. Effect of breathing pattern on the ACI

The second study searched the effect of the vagal tone on the ACI. We used periodical breathing to enhance the vagal tone [3]. Twenty healthy subjects (30.9 ± 5.1 years) were enrolled in the study. For each subject, five successive electrocardiographic records were acquired while the subject was in supine position. Each record was 5 minutes long and was sampled at 500 Hz. The RR time series was obtained by QRS detection. The first and fifth records were obtained while the subject was breathing at will. The second and fourth records were obtained while the subject was breathing periodically at 0.15 Hz (synchronously with a trace displayed on an oscilloscope). The third record was obtained while the subject was breathing synchronously with a frequency-modulated signal whose carrier frequency was 0.15 Hz, modulating frequency 0.01 Hz, and frequency deviation 0.05 Hz. Reference [4] further details the experiment. The RR time series are available at [5]. For each RR time series, the ACI was computed. The mean and standard deviation of the ACI was obtained for each breathing pattern. A paired *t*-Student test was used in order to search any significant differences between results.

C. Effect of the exercise stress on the ACI

The third study searched the effect of the sympathetic nervous system on the ACI. We used exercise stress to enhance the modulation of heart rate by the sympathetic nervous system [6]. Eight healthy subjects (31.3 ± 10.5 years) participated in the test by pedaling on a static bicycle for more than 15 minutes. The ECG was acquired at 1 kHz from some time prior to starting pedaling to a time after the exercise when the mean of the hearth rhythm was close to the initial hearth rhythm. RR time series were measured for 2 min before starting to pedal, 2 min at the maximum effort (maximum heart rhythm), and 2 min during the after-exercise recovery stage. The RR time series are available at [5]. For each RR time series the ACI was computed. A paired *t*-Student test was used in order to search any significant differences between results.

D. Comparison of the ACI from healthy subjects and subjects that had suffered ventricular tachycardia, ventricular fibrillation or myocardial ischemia

In order to verify if the ACI can discriminate healthy subjects from subjects with some cardiovascular diseases, we compared the results for healthy subjects (25 people, aged 24 to 55 years) with those for (a) subjects that had suffered ventricular tachycardia and/or fibrillation and (b) subjects with myocardial ischemia. The RR time series for the control group (healthy subjects) was recorded by ambulatory monitoring, with ECG signals sampled at 1 kHz. The RR time series are available at [5]. The patient group A (ventricular fibrillation and/or thachycardia) corresponds to the Creighton University Ventricular Tachyarrhythmia Database [7]. It comprises 35 ECG records sampled at 250 Hz. In each record, the normal QRS positions are annotated and the RR time series are derived from them. The patient group B (myocardial ischemia) is that of the European ST-T Database [8]. It is composed by 90 ECG excerpts of ambulatory ECG recordings sampled at 250 Hz in subjects (from 30 to 71 years) with myocardial ischemia. The same as in group A, the RR time series were obtained from the annotations in the database. After computing the ACI for each RR time series, a *t*-Student test was performed and the sensitivity, specificity, and positive and negative predictive values were calculated by comparing the control group with group A or group B.

III. Results

Fig. 2 shows the ACI for the simulated (fractal) time series. The relationship between the mean ACI and the fractal dimension is linear. The correlation between both magnitudes is 0.999. The 5 % confidence interval depends on the length of the simulated fractal signals. The average standard deviation of the ACI is 0.03 for series with 1024 samples and 0.07 for series with 128 samples. Hence, the relationship between fractal dimension and the ACI depends on the length of the signal. The shorter is the signal, the larger is the variance of the ACI.

Table I shows the mean and standard deviation of the ACI for the 20 subjects participating in the experiment of controlled breathing and for the five breathing patterns involved. Controlled breathing (periodic and FM) enhances the vagal tone and reduces the ACI with respect to free breathing. Table II shows the results of the paired *t*-Student test that were significant. No significant differences ($p > 0.05$) were found among the three measurements at controlled breathing, neither between the two measurements while freely breathing. It seems, therefore, that the breathing pattern affects the ACI.

Table III shows the mean and standard deviation of the ACI for the eight subjects in the three stages of the exercise test: before exercising, at maximal heart rate, and after recovery. The ACI is higher on maximal exercise than before or after exercising. There were no significant differences between the ACI before starting and after rec
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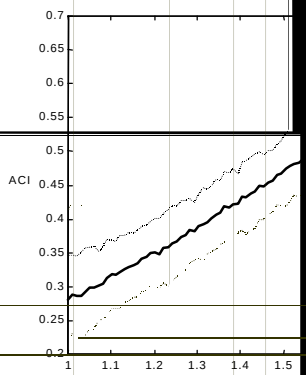

Fig.2. Mean ACI and 5 % confidence i
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TABLE
THE EFFECT OF BREATHING

Breathing pattern	Freely 1	Perio
Mean ACI	0.39	0.22
SD ACI	0.16	0.14

Breathing at will 1	2×10^{-5}	2
Breathing at will 2	3×10^{-4}	

TABL
EFFECT OF EXERCISE ST

Mean ACI	0.81

Mean ACI	0.38	
SD ACI	0.12	

TABLE IV
COMPARISON OF THE ACI FOR HEALTHY (CONTROL) SUBJECTS, SUBJECTS WITH VENTRICULAR FIBRILLATION AND/OR TACHYCARDIA (A) AND SUBJECTS WITH MYOCARDIAL ISCHEMIA (B)

Group	A	B
Control		

TABLE II
SIGNIFICANCE OF THE PAIRED T-STUDENT TEST

p	Periodic breathing 1	FM breathing	Periodi breathing
SD ACI	0.12	0.13	0.22

Table IV shows the mean and standard deviation of the ACI for the control, patient A and patient B groups. The mean ACI is larger in ill subjects than in control subjects. The *t*-Student test yields a significance of $p < 0.0005$ between control and group A and between control and group B. Therefore, the mean ACI is quite different for healthy people and people that suffered ventricular tachycardia, ventricular fibrillation or myocardial ischemia.

In order to calculate the sensitivity, specificity, and positive and negative predictive value of the ACI, we need a threshold. Three different thresholds were computed: the first threshold aims to separate the control group from group A; the second threshold aims to separate the control group from group B; and the third threshold aims to separate the control group (healthy subjects) from the union of groups A and B (ill subjects). If μ_1 is the mean of the ACI in the control group, σ_1 is its standard deviation, and μ_2 is the mean of the other group under test and σ_2 is its standard deviation, each threshold is computed as

$$ACI_{th} = \mu_1 + (\mu_2 - \mu_1)\frac{\sigma_1}{\sigma_1 + \sigma_2} \qquad (3)$$

Table V shows the sensitivity, specificity, and positive and negative predictive values for the three different thresholds. Ill subjects classified as ill were considered true positives (ACI greater than the corresponding threshold). The three thresholds have similar values, a sensitivity of about 90 % and a specificity of 96 %.

TABLE V
RESULTS OF THE SEPARATION OF TWO GROUPS WHEN ACI_{Th} IS APPLIED

	ACI_{Th}	Sensitivity (%)	Specificity (%)	Positive Predictive value (%)	Negative Predictive value (%)
Control-Group A	0.55	91.4	96.0	97.0	88.9
Control-Group B	0.54	89.7	96.0	98.7	72.7
Control-Groups A and B	0.55	87.8	96.0	99.1	61.5

IV. DISCUSSION

The ACI is robust to artifacts because it is independent of the magnitude of the changes in the signal analyzed. The ACI counts the number of times that the heart accelerates and decelerates. Because RR time series from ill subjects contain many abnormal beats, the ACI is very useful to analyze those series; no artifact correction is needed. On the other hand, the ACI is sensitive to the physiological state of the measured subject. The ACI is small when resting and at periodical breathing, and increases when the subject is exercising or breathing freely. Therefore, a good way to compare groups of people could be by averaging the ACI on recordings of 24 hours. Regrettably, no pathological recording lasting 24 h were available for the present study. More studies should be performed in order to compare different groups of people in similar physiological state. The effect of mental stress on the ACI could also be of interest. The ages from control and ill subjects in this study were different. Nevertheless, no correlation was found between age and the ACI in 226 different records (ages from 18 to 57 years).

V. CONCLUSIONS

The ACI is a fast and robust index that reflects the dynamics of the RR time series and correlates well with the fractal dimension. The ACI is affected by both the vagus and the sympathetic nerves: it has a low value during periodic breathing and a high value under exercise stress and free breathing. The ACI can discriminate groups of healthy people from groups of patients who had suffered ventricular tachycardia and/or fibrillation, and from groups of patients with myocardial ischemia. The ACI is lower in healthy subjects than in ill subjects. A threshold near 0.55 separates both groups with sensitivity near 90 % and a specificity of 96 %.

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