Post Extrasystolic T Wave Change in Subjects With Structural Healthy Ventricles – Measurement and Simulation

Gustavo Lenis [1], Yannick Lutz[1], Gunnar Seeman[1], Arcadi García-Alberola[2], José Luis Rojo-Álvarez[3], Óscar Barquero-Pérez[3], Eduardo Gil[4], Olaf Doessel[1]

[1] Institute of Biomedical Engineering, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany
[2] Arrhythmia Unit, Hospital Universitario Virgen de la Arrixaca de Murcia, Spain
[3] Department of Signal Theory and Communications, Rey Juan Carlos University, Madrid, Spain
[4] Aragón Institute of Engineering Research (I3A), Universidad de Zaragoza, Spain and Centro de Investigacin Biomdica en Red en Bioingeniera, Biomateriales y Nanomedicina (CIBERBBN)

Abstract

The risk stratification of sudden cardiac death after myocardial infarction plays an important role in cardiology. It influences the treatment of a patient and the use of implantable devices. However, the majority of well known methods for stratifying risk still fail to predict sudden cardiac death with high accuracy. The heart rate turbulence delivers good results that could be complemented by studying ECG morphology. For this purpose, the post extrasystolic T wave change was studied in this work. 10 patients with structural healthy ventricles were paced in the right ventricular apex and the subsequent response of the heart was measured in the ECG. Complementary, computer simulations of the human transmembrane voltages and posterior ECG reconstruction were also carried out. Morphological changes in the post extrasystolic T wave and its restitution to the original shape were measurable in every patient of this study. The patients presented diminished or alternating postectopic T waves and prolongation of T wave duration. However, the simulation does not present significant T wave changes. Furthermore, the new morphological parameters do not seem to correlate with the standard HRT parameters.

1. Introduction

Risk prediction of sudden cardiac death in patients with history of myocardial infarction has been a relevant topic of research for the last decades [1]. Risk stratification has an important impact on the treatment of the patient and supports the decision of implanting pacemakers or defibrillators [1]. Standard methods based on rhythmical properties of the electrocardiogram (ECG) like the heart rate variability (HRV) [1] deliver predictions that are not entirely satisfying. The ultimate ECG based risk stratification parameter is still missing. However, one of the risk stratifiers that has become very popular in the last ten years is the heart rate turbulance (HRT) [2]. The two HRT parameters TO and TS achieve a sensitivity and positive predictive value of around 30 %. This method could be complemented by looking into the morphology of the ECG during the same period of time where the HRT takes place. The post extrasystolic T wave change (PEST) has been observed and qualitatively analyze in patients with different pathological conditions. However, only the first normal T wave after the ventricular ectopic beat (VEB) has been taken into consideration. The dynamical restitution of the T wave morphology to its original form has not been studied. A first attempt to quantify this phenomenon was presented in [3]. In addition, it has not been fully investigated how PEST manifests in patients with structural healthy ventricles.

2. Methods

2.1. Clinical and simulated data

For a deep investigation of HRT and its relation to the coupling interval of the VEB and the resting heart rate of the patient, a special electrophysiological (EP) study was created and used in previous works [4]. 10 patients with structural healthy ventricles, that had to go through ablation because of supraventricular tachycardia, were paced in the right ventricular apex. The standard 12 lead surface ECG was recorded at a sample frequency of 2 kHz. The stimulation was carried out every 20 sinus beats. On the other hand, a monodomain simulation was carried out including a full torso model that was introduced in [5]. The electrophysiological model of ten Tuscher et al. was used for the simulation of the transmembrane voltages in the ventricles. A forward calculation was done to generate the

surface ECG. The P wave was not simulated in this study since it is not believed to have any influence on the post ectopic T wave. In addition, no ion channels activated through mechanical stress were considered in the model either, so that purely electrical phenomena in the ventricles were recreated by this simulation. 5 normal beats followed by a VEB placed also in the right ventricular apex and 9 post ectopic normal beats were simulated one after the other. The RR intervals between the simulated beats were chosen to deliver normal HRT parameters. Figure 1 shows a portion of the simulated ECG. The simulation became then "patient #11".

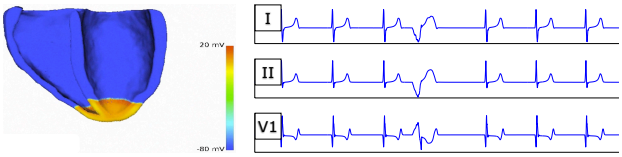

Figure 1. Simulated transmembrane voltages in the heart and reconstructed ECG.

2.2. QRS detection and classification

The paced VEB presents a low amplitude and large width in the majority of the measured ECG leads. This complicates the automatic QRS detection. Therefore, a special linear combination of the 8 independent ECG channels and VEBs was carried out. The idea was to create such an optimal set of virtual channels containing a spiky QRS complexes and VEBs. First, the channel with dominant QRS complexes is created using a mixing vector called **w**. It is normalized to have unit length and therefore preserve signal energy after transformation. If the ECG signal is interpreted as a multivariate statistic where every channel represents a random variable, then the vector pointing in the direction of the multidimensional QRS loop can be chosen to be **w**. The vector **w** must be found prior to QRS detection. In addition, the algorithm should have a short computational time. The designed procedure works as follows:

- First, an offset compensation in every channel is carried out.
- Every ECG channel is corrected to have a QRS complex pointing upwards. Then, the mean positive amplitude of each ECG channel is chosen to be the corresponding component of the vector **w**.
- The linear combination is then a matrix vector product:

$$\mathbf{y} = \mathbf{X} \cdot \mathbf{w} \tag{1}$$

Every column of the matrix **X** contains a channel of the measured ECG. **y** is the resulting virtual channel with optimized QRS complex amplitude.

Figure 2A shows exemplary three of the original ECG channels measured for patient #1 displayed as a multivariate statistic. The red vector **w** points in the desired direction of the normal QRS complex loop. However, the ventricular ectopic beat does not necessarily has a large amplitude in that first virtual channel **y**. Therefore, other channels are needed to ensure the presence of a large amplitude VEB. For this purpose, the vector **w** is used to span a hyperplane where the ECG is projected onto (figure 2A). In this space of reduced dimensionality, a principal component analysis (PCA) is carried out. The scores of the PCA are virtual ECG channels themselves. The number of virtual channels chosen for further analysis is set to preserve at least 90% of the total energy in the ECG. The VEB will have a strong amplitude in some of the resulting transformed ECG channels and the automatic QRS detection algorithm will find it easily. In addition, all resulting channels are orthogonal and does not contain redundant information. Finally, a multichannel synchronization of the detected QRS complexes ensures the robustness of the algorithm. Figure 2B shows the first three resulting ECG channels after transformation. The second and third channels present a VEB with large amplitude. Beat classification is carried out by a support vector machine [3].

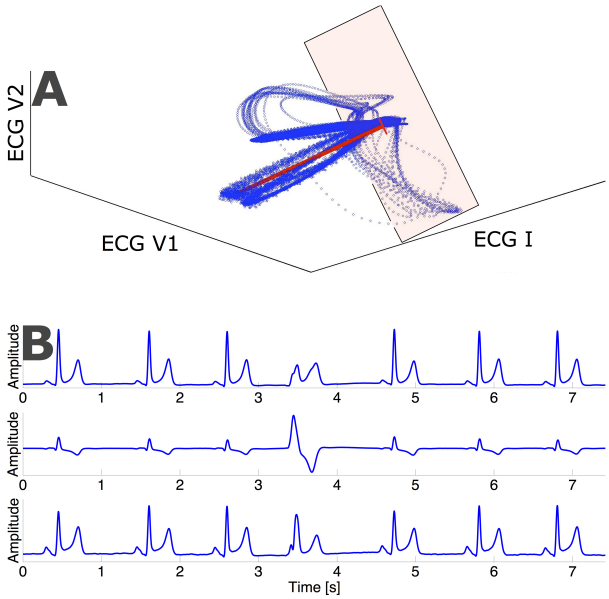

Figure 2. A: Original ECG as multivariate statistic and direction of QRS loop (red). B: Reconstructed channels for optimal QRS detection.

2.3. Maximization of T wave amplitude

The likelihood of measuring PEST should increase if a virtual ECG channel is specially mixed to have T waves with large amplitude. For this purpose, the same virtual

channels introduced in the previous sections are used here. Furthermore, a T wave template is built for every virtual channel. The mixing vector **w** for the linear combination is entirely given by the maximal amplitude of the T wave template of each channel. Figure 3 shows the resulting virtual channel maximizing T wave amplitude.

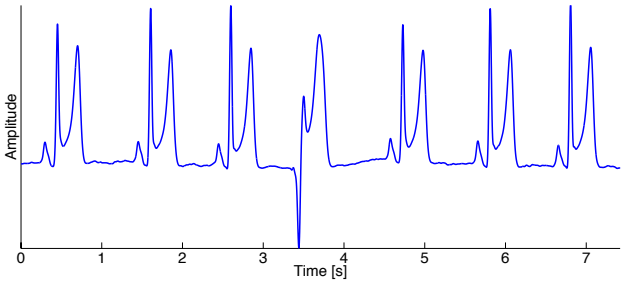

Figure 3. Virtual ECG channel with T wave of maximal amplitude for best PEST analysis.

2.4. Quantifying of PEST

Since comparison T wave prior and posterior to the VEB is necessary, a special similarity measure is introduced. The operator used here is well known in the field of information theory and is called the Sørensen index. We generalize this index for any two signals $x(t)$ and $y(t)$. The measurement of similarity will be called "$l\_operator$" because it is closely related to the norm or length of the difference signal between $x(t)$ and $y(t)$ if the signals are discrete time vectors. It is defined as:

$$l\_operator\{x(t), y(t)\} = \frac{2 \cdot E\{x(t) \cdot y(t)\}}{E\{x^2(t)\} + E\{y^2(t)\}} \quad (2)$$

$E\{\cdot\}$ denotes the expected value operator. The $l\_operator$ has delivers values in interval $[-1, +1]$. It is equal to $+1$ only if the two signals $x(t)$ and $y(t)$ are perfectly equal. This operator, in contrast to the correlation coefficient, is sensitive to offsetting and scaling any of the two signals. The next step is to quantify PEST and the dynamical restitution of the morphology of the T wave. First, 5 beats prior to the VEB and 15 after it are taken into consideration. For each one of those beats, the corresponding T wave is segmented. Every T wave is labeled with an integer number $n \in [-5; +16]$. All T waves labeled with a particular n are combined to form a mean T wave for that same label. In the end, a T wave reference template is created out of the first four mean T waves extracted. Similarity is measured applying the $l\_operator$ to every mean T wave and the template.

$$lop(n) = l\_operator\{T_n(t), Template(t)\} \quad (3)$$

Finally, the PEST parameters, morphological change onset (MCO) and morphological change slope (MCS), are defined as follows:

$$MCO = \frac{lop(1) - \frac{1}{4}\sum_{n=-5}^{-2} lop(n)}{\frac{1}{4}\sum_{n=-5}^{-2} lop(n)} \cdot 1000\ [‰] \quad (4)$$

$$MCS = \frac{lop(2) - lop(1)}{RR(2)} \cdot 1000\ [‰/s] \quad (5)$$

3. Results

Table 1 presents the obtained parameters. In the table, the patient number together with the the number of usable VEBs and the new morphological parameters are presented.

Table 1. Results showing PEST parameters for the patients examined (#1 to #10) and simulated (#11).

Patient #.	Nr. VEB	MCO [‰]	MCS [‰/s]
1	14	-0.68	0.65
2	20	-11.17	11.41
3	16	-7.72	7.78
4	17	-5.10	2.38
5	11	-1.17	1.44
6	18	-12.70	14.22
7	12	-14.50	20.47
8	13	-49.64	66.29
9	18	-7.03	7.38
10	11	-2.41	2.10
11	1	-1.07	1.16

3.1. Manifestation of PEST among patients

All patients presented a measurable PEST. However, in some of them it is more notorious than in others. For instance, a group of 2 patients presented almost no post ectopic T wave change. In contrast, 5 patients had a reduction in their T wave amplitude. Further 3 patients had an alternating amplitude in the T wave morphology after the VEB. The simulation presented almost no change in the postectopic T wave. Figure 4 shows exemplary PEST in patient #2 and #7. Patient #2 presents a diminished post ectopic T wave with longer duration. The second T wave after the VEB has a slightly reduced amplitude but its duration is almost normal. Patient #7 presents an alternating T wave morphology. The first T wave after the VEB has an increased amplitude. The second post extrasystolic T wave presents a reduced amplitude when compared to the template.

3.2. First statistical impressions

A basic statistical analysis was carried out. Since the number of patients is small, this results should only present

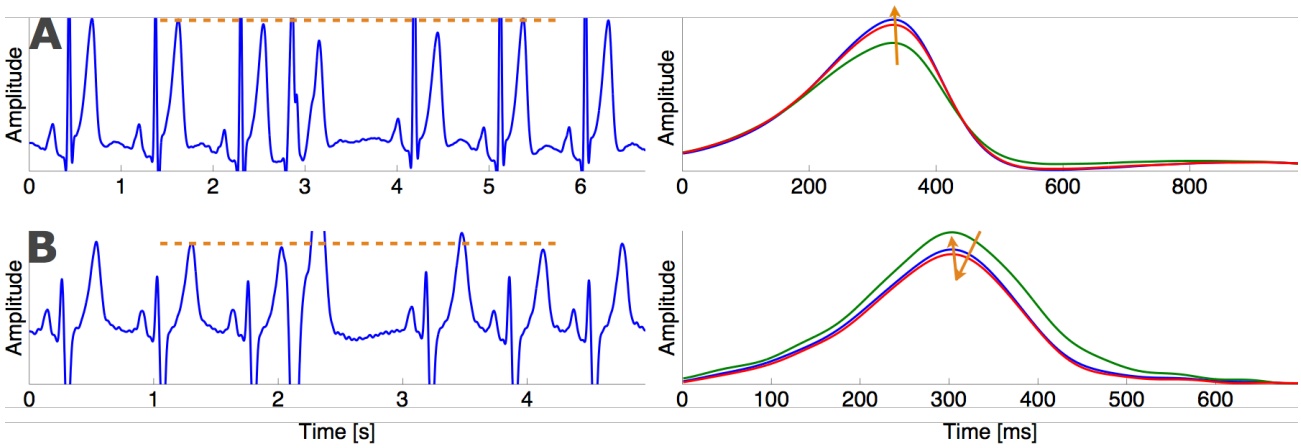

Figure 4. A: Patient #2 with decreased post ectopic T wave amplitude. B: Patient #7 with alternating post ectopic T wave amplitude. The orange arrows show the dynamical morphological restitution after the VEB. Blue: reference T wave template. Green: first postectopic wave. Red: second post ectopic wave.

first impressions on how PEST may manifest in subjects with structural healthy ventricles. For this purpose, table 2 presents the correlation coefficient between some of the patients most relevant features like the basal RR interval, the HRT parameters TO and TS with the morphological parameters MCO and MCS. In general, no strong correlation can be observed between the standard HRT parameters TO and TS and the new introduced morphological parameters. The basal RR interval seems to be weakly correlated to both MCO and MCS.

Table 2. Correlation coefficient between standard parameters obtained from the ECG, HRT and PEST.

	MCO [‰]	MCS [‰/s]
Basal RR [ms]	0.51	-0.55
TO [%]	-0.14	0.08
TS [ms/beat]	-0.18	0.13

4. Discussion and conclusion

Even though the patients have structural healthy ventricles, different morphological changes were observed for the post extrasystolic T wave. PEST can manifest as a modification of T wave amplitude or a prolongation of T wave duration. We conclude that PEST seems to arise differently on every subject, even if no pathological condition is present in the ventricles. The simulation results could mean that that PEST is not entirely explained by pure electrical phenomena. Furthermore, all patients presenting noticeable PEST had an almost complete morphological recovery after no more than two T waves. This could mean that healthy subjects should be able to rapidly recover original T wave shape after the VEB. In addition, the new introduced parameter MCO and MCS used to characterize PEST, does not seem to correlate with the standard HRT parameters. It could be postulated that they might contain new undiscovered information that could be useful for risk stratification. Finally, the weakly correlated basal RR interval length and PEST parameters points to a relationship between basal and restitution of the original T wave morphology. In conclusion, PEST is a phenomenon worth of study and more research is needed to fully understand it.

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Address for correspondence:

Gustavo Lenis
Fritz-Haber-Weg 1, 76131 Karlsruhe, Germany
Gustavo.Lenis@kit.edu