Beat-to-Beat Variation of Three-Dimensional QRS-T Angle Measures during Exercise Test

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Abstract

Dynamical beat-to-beat behavior of the spatial QRS-T angle features is largely unknown. In this study, an automatic beat-to-beat method for calculating the features from standard 12-lead ECG was developed, and the variability of three QRS-T angle measures (TCRT, cos(QRST-angle), and cos(PlaneAngle)) during an incremental exercise on a bicycle ergometer was specified. The trend of the TCRT during exercise was negative, and it was more negative in healthy subjects (n=10) compared to coronary artery disease (CAD) patients (n=10), p-value was 0.01 between the groups. However, all the QRS-T angle measures did not appear to behave similarly, and therefore, they should not be paralleled with each other. In addition, beat-to-beat variability of all the QRS-T-angle measures was so extensive, that it should be taken into account when considering the reliability of one-beat analyses of the angle measures.

1. Introduction

The relationship between the QRS complex and the T wave, expressed as an angle in three-dimensional space, has been a subject of interest during the last decade. The spatial QRS-T angle is defined as the angle between the directions of ventricular depolarization and repolarization, and it has shown to be a strong and independent marker of cardiovascular mortality in general populations and cardiac patients [1-4]. Especially the parameter named 'Total Cosine R-to-T' (TCRT) has been shown to have a remarkable prognostic value as a predictor of the outcomes of the coronary artery disease [5,6].

However, dynamical beat-to-beat behavior of the QRS-T angle features is largely unknown, and in most of the studies, the angle features have been calculated only for one single beat. Furthermore, TCRT has been often paralleled to spatial QRS-T angle as a measure of the deviation between QRS and T loops [7,8], but the similarity of the measures is not sufficiently studied.

The aims of the study were:

1) to develop an automatic beat-to-beat method to calculate the QRS-T angle measures from standard 12-lead ECG,

2) to specify the variability of three QRS-T angle measures during an incremental exercise and recovery both healthy people and CAD patients, and

3) to explain potential differences between the three QRS-T angle measures during exercise.

2. Automatic beat-to-beat analysis

The automated 12 lead ECG beat-to-beat analysis to calculate three-dimensional QRS-T angle measures is based on digital filters, an R-detector, the removal of the extrasystoles, and the heart-rate normalized segmentation of the QRS and T waveforms. Dynamic analysis is shortly described as follows:

1) R-peak detector. R-peaks were detected automatically from the ECG based on thresholds for amplitude and the first derivative.
2) Removal of extrasystoles. Method "ES+1", described in [9], was used.
3) Beat segmentation. Beats were segmented from 'R-peak minus *a*' to 'next R-peak minus *b*', where *a* and *b* were time-constants.
4) Heart-rate normalized segmentation of the waveforms from the PCA-based resultant vector.
5) For analysis of each QRS-complex and T-wave, see next Chapter.

3. Three-dimensional QRS-T angle measures

The three vectorcardiographic (VCG) angle measures used in the study were the TCRT parameter, the cosine of the three-dimensional QRS-T angle (cos(QRST-angle)), and the cosine of the angle between the normal vectors of the spatial QRS and T planes (cos(PlaneAngle)). Cosine-values of the angles were used for better comparability with TCRT, which already is a cosine value.

1) TCRT: One of the most often used parameter for measuring the QRS-T angle was developed by Acar et al. in 1999 [7]. The parameter is the averaged cosine of the QRS-T angle, 'total cosine R-to-T' (TCRT). For TCRT, 12 lead standard ECG is firstly converted to a minimum dimensional space within the optimized SVD (Singular Value Decomposition). Furthermore, TCRT parameter is calculated as the averaged measure of the angles between the threshold vectors of QRS (all the vectors upside a threshold value around the R-spike) and the maximum of the unit vector, which reflects the orientation of the T wave loop. More detailed description of the algorithm can be found in the original article [7].

2) cos(QRST-angle): The parameter cos(QRST-angle) is defined as cosine of the angle between maximum vectors of the QRS and T waves calculated from the magnitude vector of the three most powerful SVD components. In Figure 6, the cos(QRST-angle) is the cosine of the angle between the vectors with green and black dots.

3) cos(PlaneAngle): The proposed method for estimating a novel parameter named PlaneAngle is comprised of the following stages. First, the 3D SVD-data, used in previous items 1-2, is resampled with respect to the arc-length to obtain equidistantly placed points on both the QRS and T wave loop structures. Second, a total least squares plane fit is made to yield global information on the orientation of the loop structures. A Total Least Squares (TLS) plane fit is made to the 3D vectorcardiografic data points. The data is centered by subtracting the mean. Then, the normal vector of the hyper plane is found using SVD on QRS or T loop data as the right singular vector. Now the cos(PlaneAngle) is the cosine of the angle between the normal vectors of the QRS and T loop planes. A more detailed description of the algorithm can be found in [10,11]. It is noteworthy, that, because PlaneAngle is the angle between two planes, it can vary only between 0 and $\pi/2$ (and therefore the cos(PlaneAngle) between 0 and +1), in contrast to TCRT and cos(QRST-angle), which can vary between -1 and +1.

4. Study population

Study groups consisted of coronary artery disease (CAD) patients (n=10) and healthy age-matched subjects (n=10). The subjects performed a graded maximal exercise test on an 839E Monark cycle ergometer (Stockholm, Sweden). The test was started at 2 min sitting period and directly continued at 30 W cycling. Work rate was increased by 10W/15W (women/men) every 2 min until exhaustion. The subjects were encouraged to continue cycling until they could no longer maintain the required pace, at which time the test was terminated. After the termination, the subjects were asked to go supine position, and 12 lead ECG recording was continued for 10 min.

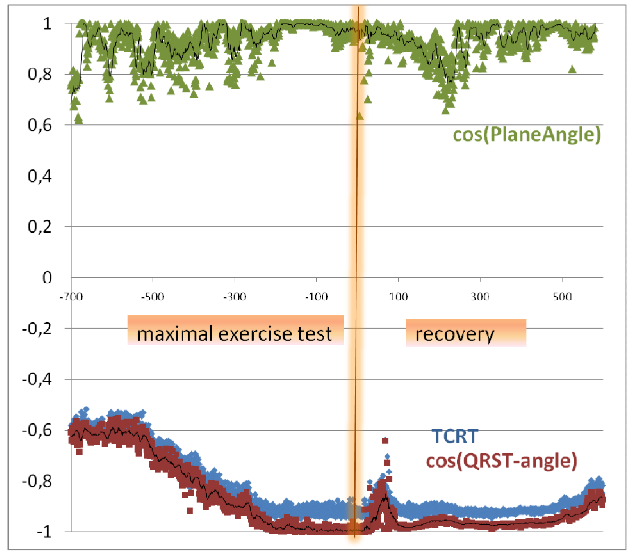

Figure 1. A typical example of the beat-to-beat angle measures as function of time (in seconds) calculated from a CAD patient during maximal exercise test and 10 minutes recovery time.

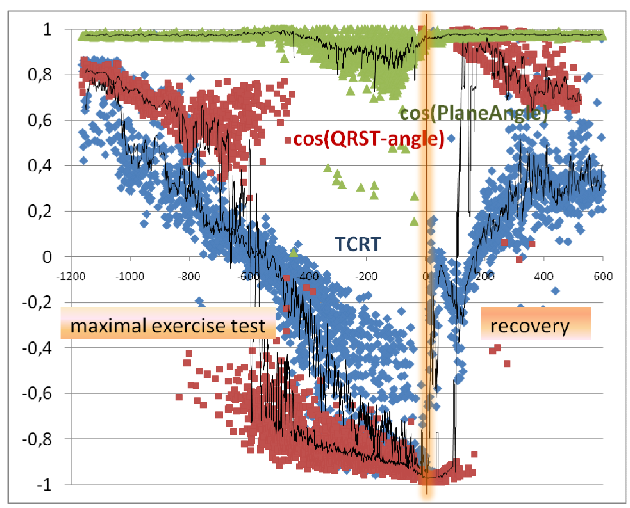

Figure 2. A typical example of the beat-to-beat angle measures as function of time (in seconds) calculated from a healthy person during maximal exercise test and 10 minutes recovery time.

5. Results and discussion

The results of the study are shown in Table 1 and in Figures 1-6. A typical example of the QRS-T angle measures in a CAD patient is shown in Figure 1 and in healthy person in Figure 2. The yellow vertical line marks the end point of the exercise test and the starting of the recovery time. Black lines are moving averages (at 10 points period) of the angle data points.

For estimating the trends of the beat-to-beat angle measures during exercise test, the changes of the measures were supposed to be line-like (see Figure 3). The slopes (1/minutes) of the linear trend lines are shown in Table 1. Both TCRT and cos(QRST-angle) had negative trends during exercise, whereas the behavior of the cos(PlaneAngle) had not any correlation with time during the exercise test. The trends during recovery time were not calculated, but on the grounds of the figures, they seemed to be roughly inversed, compared to the exercise time.

With healthy people, the slopes of the linear trend line of the TCRT were more negative, compared to CAD patients. This may partly be due to lower starting values with CAD patients (which occurs also in Figures 1 and 2). The trend of the TCRT during exercise was negative, and it was more negative in healthy subjects compared to CAD patients (p=0.01). The trends of the cos(QRST-angle) (p=0.13) and cos(PlaneAngle) (p=0.54) were not statistically significant in either study group, however.

The results show that a respiratory sinus arythmia (RSA) -like modulation in the frequency band of the breathing occurs in all three angle measures during exercise, see Figure 4. In the rest, the modulation was about 10% of the range of the cosine values, but during exercise even 50-60% of the range. ECG changes, due to RSA, naturally reflect to loop-parameters, but the varying-scale seems to be so extensive that one-beat analysis should dissect carefully because of the potential low repeatability.

The angle between spatial QRS and T planes (measured by cos(PlaneAngle)) seemed to “live its own life”. Because of that, the dissimilarity only between TCRT and cos(QRST-angle) was studied. Two factors were found to explain the differing behavior of the TCRT and cos(QRS-T Angle).

Firstly, very wide and three-dimensional curved QRS loops are frequent, making any representation by a single vector clearly problematic. For this reason, the approach of measuring the vectorial deviation between QRS complex and T wave by integrating the dominant parts of both loops has been proposed and found to provide a stable expression of the spatial difference [12]. A case like that is visualized in Figure 2, where cos(QRST-

Table 1. The slopes of the linear trendline of the angle measures during exercise test with healthy people and CAD patients. An unit is 1/minute.

	Healthy group	CAD-patients	p-value
TCRT	-0,067	-0,011	0.01
cos(QRST-angle)	-0.0606	-0.0195	0.13
cos(PlaneAngle)	0.00026	-0.00033	0.54

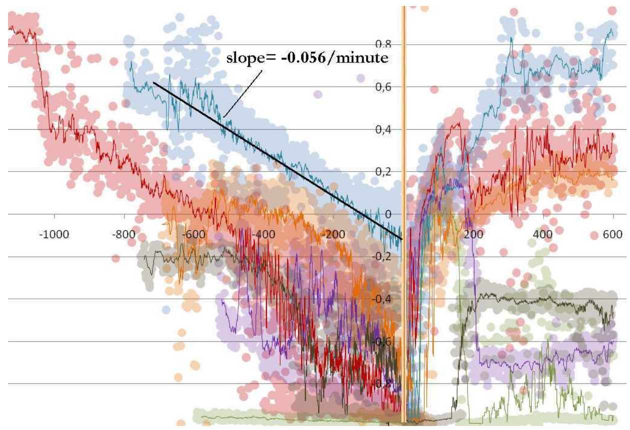

Figure 3. Few representative TCRT data sets collected to a combined figure with synchronized end times of the exercise. Time is given in seconds.

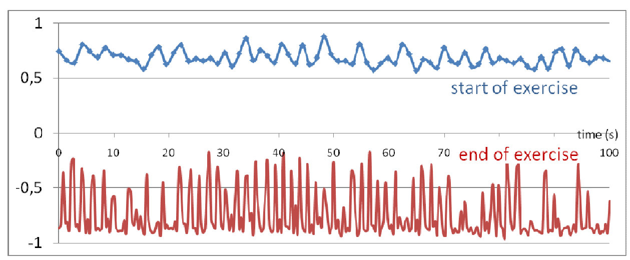

Figure 4. RSA-like modulation with TCRT parameter.

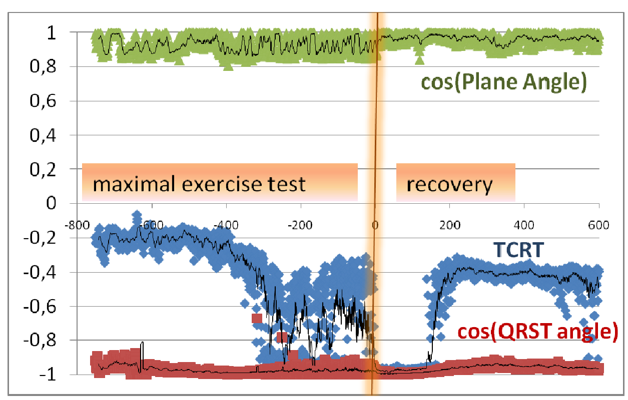

Figure 5. Beat-to-beat angle measures as function of time (s) calculated from healthy person. The TCRT and the cos(QRST-angle) are not similar.

angle) leaps in points -600 seconds and +100 seconds. The real changes in QRS or T loops were not so radical at all. The SVD components, the resultant vector and the 3D loops behind the difference are visualized in Figure 6. Only a slight change in ECG waveforms (Figure 6a) can move the main QRS vector from the black mark to the red mark (Figure 6c). Therefore, the cos(QRST-angle) is not a complete QRS-T angle measure.

Secondly, the sensitivity of the TCRT algorithm to the asymmetry of the QRS also seemed to be a reason for a difference between TCRT and cos(QRST-angle). In Figure 6, the TCRT is the mean of the angles around both red and black dots. Therefore, TCRT consists of the cosines of the minor and major angles (Figure 6b.). In this case, the sub-angles are fully polarized due to QRS loop morphology. For that reason, the TCRT value is ~(-0.2) at (-600s) in Figure 5, whereas cos(QRST-angle) is ~(-1). Averaging operation included in TCRT algorithm may result an unrealistic value, which decrease the exactness of the TCRT. Therefore, the TCRT is not a complete QRS-T angle measure, either.

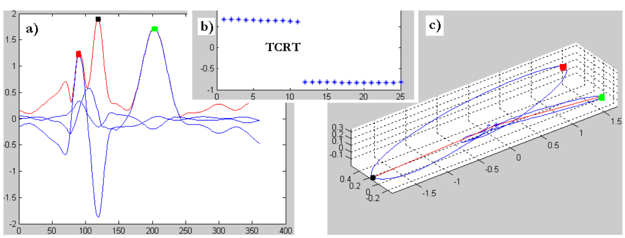

Figure 6. a) Three decomposed SVD signals that contain the most of the ECG beat's energy (blue lines) and their magnitude vector (red line). b) The TCRT is the total sum of the sub-angles. c) The same data visualized in 3D loop space.

6. Conclusion

In conclusion, the trend of the TCRT during exercise was negative, and it was more negative in healthy subjects compared to coronary artery disease (CAD) patients. However, all the QRS-T angle measures did not appear to behave similarly during the exercise test or the rest, and therefore, they should not be paralleled with each other. In addition, the breathing significantly affects the beat-to-beat variability of all the QRS-T-angle measures, which should be taken into account when considering the reliability of one-beat analyses of the angle measures. A beat-to-beat analysis would be much more informative than a single beat analysis, and it would increase the reliability of the QRS-T angle as a diagnostic or prognostic value.

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