ORIGINAL ARTICLES

Influence of Paper Electrocardiogram Digitizing on T Wave and QRS Complex Morphology Parameters

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Background: Many morphological parameters of the electrocardiogram (ECG) can be calculated from a digital ECG and paper prints of ECG after digitizing. However, the digitizing process, including printing, scanning, ECG contour extraction, and alignment, can produce changes to the signals, reducing the reliability of some sensitive parameters of QRS complex and T wave.

Methods: The influence of the digitizing process on the parameters of T wave and QRS complex morphology was studied by comparing systematically the values of the nine ECG morphology parameters, computed from the digital ECG and the corresponding paper ECG. The robustness of the parameters to the digitizing process and their discrimination ability between healthy subjects and postinfarction patients were investigated.

Results: The standard T wave parameters and all selected dipolar loop-parameters retained their robustness and discrimination ability during the digitizing process of the paper ECGs. The non-dipolar parameters distorted strongly, especially those of the QRS complex. The T wave-based non-dipolar parameters retained their discrimination ability during the digitizing process.

Conclusions: The selected standard T wave parameters and the dipolar loop-parameters calculated from properly digitized ECG paper prints can be utilized in patient studies. Non-dipolar parameters distort strongly but T wave-based parameters retain discriminatory information.

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electrocardiography; vectorcardiography; T wave loop; QRS loop; alignment; digitizing;
non-dipolar; SVD

Various morphological parameters of the QRS complex and T Wave can be calculated from digital electrocardiographic signals. Many studies have shown that the vectorcardiographic dipolar loops do not include all the information of the electrocardiogram (ECG).^{1–3} The most common method to measure the properties beyond the dipole of the ECG is the singular value decomposition (SVD) technique. The SVD is used to decompose the eight independent channels of electrocardiographic signal to an eight-dimensional orthogonal space with axes representing the uncorrelated components of ECG.⁴ The first three components contain over 98% of the variability of the ECG and describe the dipolar components. The rest of the components describe the so-called non-dipolar components. The dipolar and

non-dipolar components have been shown to include prognostic information in many studies.^{5–10}

Most of the currently available commercial equipment provide electrocardiographic signals in a digital form and allow their registration in a local archive. The recovery of past ECGs from graph paper is still needed, however, since ECGs are a valuable source of information in many databases. Dozens of digitizing methods for paper ECGs have been developed for this purpose.^{11–15} In general, the paper ECGs are first scanned by a flatbed-scanner and the resulting raster image is converted to a desired digital data format. The digitizing process introduces some technical problems that have not been addressed adequately in the literature thus far. First, printing, scanning and digitizing

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introduce changes to electrocardiographic signal reducing the reliability of some sensitive parameters. Second, ECG channels are often recorded in two blocks on separate papers: the first block including the limb leads (I, II, III, aVR, aVL, and aVF) and the second block the precordial leads (V_1 – V_6). This introduces a time-alignment problem between the channel groups.¹⁶ Third, older ECG devices record the two channel groups separately with a couple of seconds delay, in which case the complete alignment is not possible even in theory.

The purpose of this study was; first, to determine how accurately the most common SVD-based electrocardiographic loop parameters and non-dipolar parameters can be calculated from the digitized paper ECGs. To demonstrate the effect of distortions on more common standard ECG parameters, we chose T wave amplitude and T wave area parameters. T wave was selected due to its low amplitude and signal-to-noise ratio, and thus, high potential susceptibility to distortions during the digitizing process. Second, as many of these parameters have been shown to discriminate between high-risk and low-risk patients when the parameters are analyzed from digital ECGs,^{4,9} we studied whether these parameters have discriminating power between postinfarction patients and healthy subjects when the parameters are analyzed from the digitized paper ECGs. The robustness of the digitizing process and the discriminating power of the parameters between the study groups were studied by comparing the parameters analyzed from digital ECGs and from the paper ECGs which were produced from the same digital ECGs.

METHODS

Analysis of Digital and Paper ECG

The basic idea of the experimental setup was to print the samples of 12-lead digital ECG onto paper and digitize it back to the computer in order to produce the effects of the real paper recording process. The two channel groups can straightforwardly be extracted separately from the paper print through the digitizing process and be aligned in the computer as is done when 12 channels are needed for computations. For comparative purposes, the two channel groups were separated from the original digital ECG as well, and then aligned with the same method as above. This makes it possible to find out how large contributions the alignment and digitizing process have on the results.

Five different cases were defined for experimentation. In the first three cases, the original digital 12-lead ECG signal was analyzed in order to test the effects of the channel group alignment and the nonsimultaneous sampling between the channel groups. In the last two cases, the digitized paper ECGs were analyzed from simultaneous and non-simultaneous data. The five cases for computing the morphological parameters are described in detail below:

Case D: The calculations were done from the original 12-lead digital (**D**) electrocardiographic signal. This case represents an ideal situation for estimating parameters because none of the distorting modifications occur. These parameter values are used as a reference to the parameters of the other cases.

Case DA: The calculations were done from the original digital (**D**) signal, but the two simultaneously sampled channel groups were aligned (**A**) first. This case simulates the situation in which electrocardiographic signal is recorded onto two papers. The alignment between limb and precordial leads was performed with an inhouse software that includes a graphical user interface for visual inspection and mouse-controlled group alignment functionality. The alignment is performed by pointing with a cursor to the earliest QRS start point of limb and precordial leads separately. Alignment based on R wave peak detection was also tested, but the aforementioned alignment method was found to be more accurate.

Case DANs: The digital signal was analyzed as in case **DA**, but the precordial lead signals were selected from the recording from 4 to 6 seconds later than limb lead signals (nonsimultaneous sampling, **Ns**). This simulates the situation with some older ECG recorders in which the precordial and limb lead groups are printed onto the same paper sequentially.

Case P: The 12 channels of digital ECG were printed onto one ECG paper (**P**) in 12 time-synchronized rows. The printed papers were digitized back to a digital format and then analyzed. The digitizing process is described more fully in section 2.3. This case tested the error of the digitizing process alone, excluding the alignment problem.

Case PANs: The original digital signal was printed out and scanned as in case **P**. However, the precordial leads were selected from the recording from 4 to 6 seconds later than limb lead signals, as in case **DANs**. In this case, the error caused by not only paper process but also by alignment and non-simultaneous sampling was also tested. This case

contains the largest selection of distortions to electrocardiographic signal.

Case PA for paper processing with alignment and simultaneous signals was not considered, because case DA examines essentially the same alignment problem.

ECG Recording and Digitising Processes

The study groups consist of healthy subjects ($n = 15$, age 44 ± 10 [mean $\pm$ SD] years) and patients who were recovering from myocardial infarction ($n = 15$, age 63 ± 15 [mean $\pm$ SD] years). All patients had recovered from the first myocardial infarction, and all patients with re-infarctions were excluded. Neither the infarction type nor the severity or location of the infarction were evaluated for this study. Digital 8-lead electrocardiographic data was recorded with a Welch Allyn Cardiocontrol BV digital ECG recorder (Welch Allyn Inc., Skaneateles Falls, USA) at University Hospital of Oulu. All 10-second recordings were taken in the same room and the patients were lying supine. The sampling frequency was 600 Hz.

Four calculatory ECG-channels, that is, limb leads III, aVR, aVF, aVL, were calculated from eight measured leads.¹⁷ Digital data thus included all the 12 standard leads, which are commonly used in most paper ECGs. The digital ECG recordings included artefacts caused by muscle movement and power line interference. Wavelet filtering was applied in this work due to its earlier success in reducing noise from the ECG.^{18,19} The coiflet wavelet (Coif5) of order 5 was used, because it has the lowest denoising error among Coiflet-functions with ECG data.¹⁸

The digital signal was printed on blank paper to reduce the amount of practical work. The actual ECG paper has a red grid on it, but the grid is easy to remove in the scanner device by adjusting the threshold value. This simplification reduces slightly the distortions to ECG as compared with actual practice. The digital signals were printed with Hewlett Packard's laserprinter LaserJet 4050N at resolution of 600 dpi. Three special scaling markings in a known geometric configuration were printed on the same paper, so that the scale of printed signals could be determined from the scanned image.

ECG printouts were scanned using an optical flatbed scanner Epson Perfection 1250 (Seiko EP-

SON Corp, UK), with 600 dpi resolution and black-white option. These raster images were then input to Un-Scan-It Graph Digitizing System 6.0 (Silk Scientific Corporation, Utah, USA) for tracking and digitizing the ECG contours in the images. The files were saved in ASCII format.

QRS and T Wave Morphology Analysis

The analysis window of each beat was defined to start in the middle of the iso-electric section before the P wave and to end in the middle of the next corresponding location. A linear baseline fit was estimated from the start and end points and subtracted from the signal. Segmentation of the ECG sample to QRS complex and T wave were made simultaneously to each 12 lead. The QRS complex was defined from the earliest point of the complex to the latest J point. The T wave was defined to start directly after QRS complex and end at the latest end of the T wave.

The parameters used in this study are listed in Table 1. T wave amplitude was calculated from channel V4 as the biggest amplitude difference between the baseline and T wave. T wave area was calculated from the ECG signal and the baseline from J point to T wave end from channel V4. The baseline was defined from the inelectric state before P wave of two consecutive beats.

Several SVD-based loop parameters and non-dipolar parameters were calculated.⁴⁻⁶ The first three singular values (S1-S3) of the segment of the ECG represent the dipolar while the rest (S4-S8) are the non-dipolar components of the signal. SVD was calculated for 12-lead ECG data, but only the first eight singular values were used,⁵ because the remaining four components contain mostly noise. The singular values were calculated separately for QRS complex and T wave (S(i)-QRS and S(i)-T, for $i = 1, \dots, 8$, respectively). Three loop-parameters included in this study were: TCRT, PCA2-QRS, and PCA2-T. Three strongest SVD-components can be visualized as loops in orthogonal three-dimensional space. Parameter TCRT is a measure of the total cosine of the angle between the main vectors of QRS and T wave loops.⁴ PCA ratio 2 for QRS complex (PCA2-QRS) and T wave (PCA2-T) were calculated as a ratio of S2 and S1.⁴ The absolute non-dipolar energy of T wave (A-TWR) and QRS complex (A-QRSR) were calculated as the sum of the squared singular values S4-S8 of QRS and T wave,

Table 1. The ECG Parameters Used in the Study

Parameter	Type	Definition
T wave amplitude	Standard	Amplitude of T wave, measured from channel V ₄
T wave area	Standard	Measured from J-point to T wave end from channel V ₄ . The area is a total area between ECG signal and the baseline defined by inelectric state before P wave.
TCRT	Loop	Total cosine of R-to-T wave
PCA2_QRS	Loop	$\frac{(S_{QRS}^2)}{(S_{QRS1}^2)} \times 100$, Singular value ratio for QRS complex
PCA2_T	Loop	$\frac{(S_T^2)}{(S_{T1}^2)} \times 100$, Singular value ratio for T wave
A-QRSR	Non-dipolar	$\sum_{i=4}^8 (S_{QRS}(i))^2$, Absolute non-dipolar energy of QRS complex
A-TWR	Non-dipolar	$\sum_{i=4}^8 (S_T(i))^2$, Absolute non-dipolar energy of T wave
R-QRSR	Non-dipolar	$\frac{\sum_{i=4}^8 (S_{QRS}(i))^2}{\sum_{i=1}^8 (S_{QRS}(i))^2}$, Relative non-dipolar energy of QRS complex
R-TWR	Non-dipolar	$\frac{\sum_{i=4}^8 (S_T(i))^2}{\sum_{i=1}^8 (S_T(i))^2}$, Relative non-dipolar energy of T wave

respectively. The corresponding relative non-dipolar energies (R-TWR and R-QRSR) were determined by dividing the absolute non-dipolar energy by the sum of squared singular values S1–S8.⁵ All non-dipolar parameters were normalized by dividing them by the length of the wave. The morphology analysis was carried out with an inhouse Windows based QRS and T wave analysis software.

Statistical Methods

The calculated parameters were analyzed with SPSS software, version 14.0.1 (SPSS Inc., Chicago, IL). The robustness of the parameters to digitizing process was assessed using Bland–Altman method.²⁰ In this graphical method, the differences between two techniques are plotted against the averages of the two techniques. Because of the restricted size of the material, we used median values in place of mean values and a median absolute deviation (MAD) in place of a standard deviation.

The discrimination ability of parameters between healthy and infarction groups was studied with the nonparametric Mann–Whitney test in all processing cases. The null hypothesis was that the medians of the parameters in the healthy and infarction

groups are identical. A small P-value indicates that the discrimination ability is high. A value of $P < 0.05$ was considered statistically significant in both cases.

RESULTS

To obtain an overall view of the signal distortions, root mean square (RMS) error between the original digital signal (case D) and the digitized signal (case P) was first calculated. The RMS error varied between 10% and 12% of the original signal power, both in the healthy and in the heart disease group. Examples of the signals are shown in Figure 1.

Bland–Altman method was applied to all case pairs (D-DA, D-DANs, D-P, and D-PANs). Bland–Altman plot of TCRT is shown in Figure 2. Other plots are not shown in this paper due to space limitation, but the results are shown as tables. We observed that the results in the healthy and heart disease groups were similar in terms of relative distortions, and thus decided to combine them so that the medians of the relative differences in Table 2a are the average values of the results of these two study groups.

Figure 1. Digital, digitized, and difference signal from channel V₄. An example of the signal distortion between cases D and P.

Robustness of Standard and Loop Parameters

The medians and quartiles of the standard and loop parameters are summarized in Figure 3. The medians of the relative differences between the cases are listed in Table 2a.

The misalignment and the nonsimultaneous limb and chest leads naturally did not affect the one-lead parameters T wave amplitude and T wave area. The

median of TCRT decreased in the infarction group from the value 0.326 to 0.024, while the distribution width remained practically the same. There was almost no change in T wave amplitude and TCRT distribution properties. The relative differences between cases D and PANs were smallest in T wave amplitude ($-1.7\% \pm 5.4\%$) and TCRT ($0.5\% \pm 6.5\%$). Also, the other loop and standard parameters appeared more robust than the non-dipolar parameters.

Figure 2. Bland–Altman plot of TCRT-parameter. The comparison methods in this figure are case D and case PANs and the results are calculated to the healthy study group.

Robustness of Non-dipolar Parameters

The medians and quartiles of the non-dipolar parameters are illustrated in Figure 4. The medians of the relative differences between the cases describing robustness are listed in Table 2a.

The cumulative effect of the processing stages on the distribution width is clearly seen with parameters A-QRSR and R-QRSR. The distributions of them widened in the paper processing (cases **P** and **PANs**) even to ten-fold as compared to the original digital signal (case **D**). Mere alignment (case **DA**) impaired the robustness of these parameters, while nonsimultaneous sampling (case **DANs**) affected even more. Alignment or nonsimultaneous sampling did not influence significantly the T wave-based non-dipolar components.

The median of the relative differences between cases D and PANs ranges between 53% and 741% in the non-dipolar parameters (see Table 3). The largest changes were observed in A-QRSR ($-741\% \pm 699\%$) and R-QRSR ($-640\% \pm 486\%$).

The Discriminating Ability between the Healthy Subjects and Postinfarction Patients

The differences between healthy and infarction groups are illustrated in Figures 3 and 4. The statistical significances are shown in Table 2b. TCRT and all the T wave-based parameters, except for T wave area, retained their statistically significant discriminating power between healthy subjects and postinfarction patients after final processing (D vs PANs) (see Table 3). Also, the T wave-based non-dipolar parameters (A-TWR and R-TWR) retained their discrimination power despite of their low robustness in digitizing process. None of the QRS-based parameters had a statistically significant discriminating power between the study groups. This was observed both in cases D and PANs. It is interesting to note that PCA2 discriminated well in the case of the T wave, but not in the case of the QRS complex.

DISCUSSION

The distributions of most of the T wave and QRS complex based non-dipolar parameters widened clearly when processing steps added up. Particularly, the parameters of the QRS complex were very susceptible to inaccuracies caused by the digitizing process of paper ECG. In general, both median and

Table 2. (a) Robustness. Relative difference between two cases ± 2 MAD. Values are given as percentages. (b) Discrimination ability. P-values between healthy and patient groups, Mann-Whitney U test. $P < 0.05$ was considered statistically significant, marked with symbol (*)

(a)	T Wave		T Wave		TCRT		PCA2-QRS		PCA2-T		A-QRSR		A-TWR		R-QRSR		R-TWR	
	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area	Amplitude	Area
D/DA:	0.0 ± 0.0	0.0 ± 2.1	0.0 ± 0.0	0.0 ± 2.1	-0.2 ± 1.4	-0.2 ± 1.4	-3.2 ± 7.4	-3.2 ± 7.4	1.6 ± 4.9	1.6 ± 4.9	-99.4 ± 229	-99.4 ± 229	0.2 ± 19.0	0.2 ± 19.0	-113 ± 279	-113 ± 279	-3.6 ± 29.3	-3.6 ± 29.3
D/DANs:	0.0 ± 0.0	0.2 ± 4.1	0.0 ± 0.0	0.2 ± 4.1	-0.5 ± 3.6	-0.5 ± 3.6	1.5 ± 13.2	1.5 ± 13.2	7.5 ± 22.4	7.5 ± 22.4	-347 ± 380	-347 ± 380	-30.1 ± 82.5	-30.1 ± 82.5	-312 ± 317	-312 ± 317	-26.3 ± 46.4	-26.3 ± 46.4
D/P:	-1.7 ± 5.4	18.8 ± 20.5	-1.7 ± 5.4	18.8 ± 20.5	-3.5 ± 7.3	-3.5 ± 7.3	13.5 ± 26.1	13.5 ± 26.1	11.1 ± 28.4	11.1 ± 28.4	-578 ± 609	-578 ± 609	-97.6 ± 74.3	-97.6 ± 74.3	-490 ± 424	-490 ± 424	-65.7 ± 57.4	-65.7 ± 57.4
D/PANs:	-1.7 ± 5.4	18.6 ± 21.1	-1.7 ± 5.4	18.6 ± 21.1	0.5 ± 6.5	0.5 ± 6.5	-13.1 ± 23	-13.1 ± 23	7.4 ± 25.5	7.4 ± 25.5	-741 ± 699	-741 ± 699	-94.2 ± 75.7	-94.2 ± 75.7	-640 ± 486	-640 ± 486	-52.7 ± 74.6	-52.7 ± 74.6
(b)																		
D:	0.001^*	0.762	0.013^*	0.762	0.013^*	0.013^*	0.496	0.496	0.003^*	0.003^*	0.705	0.705	0.049^*	0.049^*	0.257	0.257	0.003^*	0.003^*
DA:	0.001^*	0.940	0.007^*	0.940	0.007^*	0.007^*	0.597	0.597	0.001^*	0.001^*	0.880	0.880	0.174	0.174	0.406	0.406	0.004^*	0.004^*
DANs:	0.001^*	0.841	0.013^*	0.841	0.013^*	0.013^*	0.824	0.824	0.001^*	0.001^*	0.257	0.257	0.406	0.406	0.940	0.940	0.001^*	0.001^*
P:	$<0.001^*$	0.112	0.003^*	0.112	0.003^*	0.003^*	0.315	0.315	$<0.001^*$	$<0.001^*$	0.257	0.257	0.028^*	0.028^*	0.545	0.545	$<0.001^*$	$<0.001^*$
PANs:	$<0.001^*$	0.131	0.023^*	0.131	0.023^*	0.023^*	0.989	0.989	0.001^*	0.001^*	0.450	0.450	0.034^*	0.034^*	0.545	0.545	$<0.001^*$	$<0.001^*$

Figure 3. Distributions of standard and loop parameters: (A) T-wave amplitude, (B) T wave area, (C) TCRT, (D) PCA2_QRS, and (E) PCA2_T.

distribution width increased significantly with QRS complex based parameters. The median values of the non-dipolar parameters of QRS complex and T wave increased clearly. This can be explained by the noise sensitivity of these parameters as they measure signal energy in higher dimensions than the first three principal components of the space. Paper processing adds noise in all dimensions, leading to higher singular values and thus higher values of non-dipolar energy.

Parameter TCRT quantifies the angle between the main axes of the QRS loop and the T wave loop. The angle appears to be robust to alignment and scanning noise. The loop structure of QRS complex changes radically with infarction. The QRS loop is quite planar for healthy subjects, while it possesses a strong three-dimensional geometry for patients with myocardial infarction. The change in the loop geometry is likely due to the different path of the activation wave front when it passes the infarcted

Figure 4. Distributions of non-dipolar parameters of QRS complex (A–B) and T wave (C–D): (A) A-QRSR and (B) R-QRSR. The explanations of the abbreviations are in Figure 3.

myocardium. Alignment and scanning introduce noise to all dimensions and affect more those dimensions with less energy initially. An interesting observation can be made from the data concerning distribution width of the non-dipolar energy between QRS complex and T wave. The distribution

width for A-QRS and R-QRS are strongly affected by the processing steps, while this is not the case with A-TWR and R-TWR.

TCRT and all the T wave-based parameters, except for T wave area, remained powerful discriminators between healthy subjects and postinfarction

Table 3. Summary of Results.

Parameter	Type	Robustness: Relative Median Error Between D and PANs (%)	Discrimination Ability: P-Values between Healthy and Infarction Groups in D / PANs Cases
T wave amplitude	Standard	-1.7 ± 5.4	0.001* / <0.001*
T wave area	Standard	18.6 ± 21.1	0.762 / 0.131
TCRT	Loop	0.5 ± 6.5	0.013* / 0.023*
PCA2_QRS	Loop	-13.1 ± 23.0	0.496/0.989
PCA2_T	Loop	7.4 ± 25.5	0.003*/0.001*
A_QRSR	Non-dipolar	-741 ± 699	0.705 / 0.450
A-TWR	Non-dipolar	-94.2 ± 75.7	0.049* / 0.034*
R_QRSR	Non-dipolar	-640 ± 486	0.257 / 0.545
R-TWR	Non-dipolar	-52.7 ± 74.6	0.003* / <0.001*

The boldface values of the robustness represent the high robustness of the parameters in the digitizing process. The boldface values of the discrimination ability describe the high ability to discriminate healthy and infarction groups despite the digitizing process. Statistical significance is marked with symbol (*)

patients when the parameters were analyzed from the paper ECGs. None of the QRS-based parameters retained their robustness or discriminating power between the study groups when the parameters were analyzed from the paper ECGs.

The study limitations include that the study populations were not carefully matched in terms of confounding variables, such as gender and age, with the healthy controls. For example, the data from the patient group had a worse signal-to-noise-ratio than healthy group due to increased trembling of the muscles and body weight in postinfarction patients. From the technical point of view, this facilitates the discrimination of the patient groups. However, our primary aim was not to develop new methods for the discrimination, but to test how well some novel parameters retain their performance after the digitizing process.

The paper ECGs in this study were produced with a laser printer producing clean and sharp curves, but in practice paper prints are not always as optimal. Fading of the prints is a severe problem with older ECG papers. We tested the thickening of the paper ECG curve with a pen and the parameter values increased even to ten-fold. Thus the usual procedure of manual thickening is not recommended when calculating these parameters. Other factors that cause additional noise are the background grid of ECG papers, extra markings on the papers, photocopying, and low-quality plotters of older ECG recorders.

In summary, the standard T wave parameters and all the SVD-based loop-parameters retained their robustness during the digitizing process of the paper ECGs. The parameters that originally had discriminating power between the healthy and the patient groups retained it after the digitizing process. Secondly, the non-dipolar parameters distorted strongly during the digitizing process. Especially, the non-dipolar parameters of the QRS complex were vulnerable to large changes. Despite the distortion, the T wave-based non-dipolar parameters retained their discrimination ability during the digitizing process. However, analysis of these parameters from the paper ECGs can be risky. For example, the combining of sample sets should be performed with caution if they are derived from different scanning protocols.

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