Quantifying Alterations over Time in ST-segment/T-wave Amplitudes During Elective Percutaneous Coronary Intervention

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Abstract

In this work, we evaluate the inter-patient magnitude of electrocardiography (ECG) alterations over time during ischemia. The freely available STAFF III database provides 12-lead ECG recordings of patients before, during, and after elective percutaneous coronary intervention (PCI), where a coronary vessel is widened with a balloon inflation. Patients undergoing this procedure often do not show standard ECG findings and thereby cannot be assessed by the subject-independent and absolute thresholds defined in clinical guidelines. We compute alterations of ST-segment and T-wave amplitudes w.r.t. QRS amplitude over time for each patient and lead. We demonstrate that quantifying these relative amplitudes changes over time is feasible in standard and non-standard ECG recordings. To demonstrate clinical relevance, we use the features for differentiating N=54 patients with atherosclerotic plaque in either the right coronary artery (RCA) or left anterior descending (LAD). Results show significant differences in five leads for ST-segment alterations and three leads for T-wave alterations, which are also suggested by clinical guidelines for ischemia detection.

1. Introduction

In elective PCI the chronically narrowed coronary arteries are opened to enable sufficient oxygen supply of the heart itself and improve quality of life for patients suffering from coronary artery diseases (CAD). In this non-surgical technique a catheter is inserted into an artery and advanced to the heart. After the exact location of the narrowed coronary vessel is determined, a balloon is inflated to widen the artery. In early days of PCI, the focus was on prolonged balloon inflation time in order to compress the atherosclerotic plaque with high pressure against the arterial wall, resulting in improved blood flow [1].

ECGs recorded during this – nowadays outdated – technique imitate the ECG alterations resulting from blocked coronary vessels, since there is strongly reduced blood flow in the vessel during balloon inflation. In the last decades, brief inflations with lower pressure and the usage of metal or plastic stents have been established to further reduce risk of life threatening complications [2]. Patients undergoing elective PCI have pre-existing heart conditions and often show non-standard ECG recordings, e.g. permanently altered amplitudes of the ST-segment and T-wave, which are hard to interpret using clinical guidelines [3, 4]. Analyzing relative ST-segment/T-wave amplitudes over longer time – instead of absolute mV values extracted from 10-second ECGs as suggested in guidelines – could offer a novel view on non-standard ECGs.

Hence, in this work we work towards this aim by analyzing changes over time in the ST-segment and T-wave of patients undergoing PCI in either the RCA or LAD and use this information to differentiate both groups. The first supplies the posterior right side of the heart while the latter supplies the left anterior side of the heart and often shows laterally reversed ECG findings. We use the ST-segment amplitude as the slowed electric impulse, pointing in the direction of the ischemic region, can be detected on the affected site as ST-elevation and on the non-affected side as ST-depression [5].

2. Methods

We aim for quantifying ECG alterations over time in ischemic conditions. Thereby, we selected data of patients undergoing PCI and focus on the amplitude of the ST-segment, where regularly no electric activity of the heart can be measured in physiologic ECG recordings, and the amplitude of the T-wave, representing the repolarization of the ventricles. Both features are based on clinical guidelines for diagnosis of ischemia with the amplitude of the

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ST-segment being an established parameter [5–7].

Dataset The STAFF III database contains 12-lead ECGs from 104 patients treated with the outdated technique of elective prolonged balloon inflation in a major coronary artery [8]. The ECGs were acquired from 1995 to 1996 at Charleston Area Medical Center (WV, USA) and sampled at $1000\,\mathrm{Hz}$ with an amplitude resolution of $0.6\,\mu\mathrm{V}$. Custom-made equipment by Siemens-Elema AB (Sweden) was used to record standard chest leads and limb leads in the Mason-Likar configuration.

The pre- and post-inflation ECGs were both recorded $5\,\mathrm{min}$ in supine position at rest, in a baseline room before and lying in the catheter lab after PCI. The mean inflation time was $4\,\mathrm{min}\;23\,\mathrm{s}$, ranging from $1\,\mathrm{min}\;30\,\mathrm{s}$ to $9\,\mathrm{min}\;54\,\mathrm{s}$ with exact annotations provided, including time and localization of the balloon inflation [8].

All patients that underwent primary balloon inflation in the RCA or LAD were processed. We analyze 23 patients (age: 60 ± 12 years; 48% female) with balloon inflation in the LAD and 31 patients (age: 58 ± 8 years; 42% female) with balloon inflation in the RCA. For each patient, several ECGs were measured at three different stages: i) pre-inflation, ii) during-inflation and iii) post-inflation.

Preprocessing In order to reduce noise, a single representative beat [9] is calculated using the function `ecg_segment` of the open-source library Neurokit2 [10]. For this computation, single heart beats are temporally aligned using the R-peaks detected by Kalidas algorithm [11]. Additionally, the quality of these heart beats is calculated using the function `ecg_quality` of Neurokit2 [10] and only heart beats with at least $80\,\%$ similarity to the others are included. After selecting the lead with the highest R-peak amplitude, the ECG signal is delineated using the function `ecg_peaks` of Neurokit2 [10]. The T-, P- and R-peaks of this lead are then transferred to all other leads and their positions are corrected within a range of $40\,\mathrm{ms}$ to address minimal deviations between leads.

Feature engineering We define the ST-segment as a $40\,\mathrm{ms}$ segment starting $85\,\mathrm{ms}$ after the R-peak according to García *et al.* [6]. The isoelectric line is defined as the mean amplitude of the TP-interval, calculated within physiologic boundaries of $50\,\mathrm{ms}$ after the T-peak and $40\,\mathrm{ms}$ before the P-peak. This enables to evaluate the amplitudes of the ST-segment and the T-peak in relation to QRS-amplitude, which we will denote "ST feature" and "T feature", respectively. According to Aslanger *et al.*, this approach based on relative differences has the advantage of including the cardiac vector information in contrast to absolute quantification in mV [5].

For each patient and lead, features are computed in overlapping intervals of $50\,\mathrm{s}$ with steps of $10\,\mathrm{s}$. In order to quantify the dynamic of the features measured during stages pre-inflation (i) and during-inflation (ii), the difference between average values of both stages is computed (ii-i), which we will denote "ΔST" and "ΔT".

Statistical analysis In order to evaluate the differences in alterations over time between LAD and RCA patients, we test for statistical differences. First, the null hypotheses whether the groups are normally distributed is tested in every lead using a Jarque–Bera test. Second, the null hypothesis is tested that the variances of both groups do not differ for every lead and feature using a two-sided t-test.

3. Results

Fig. 1 shows representative beats (panel 1,3) and the alterations over time (panels 2,4) for an RCA and LAD patient, respectively. Lead V2 shows alterations over time for ST mainly within the balloon inflation time. During occlusion of RCA, this results in a constant decrease of ST and T features, visible in the representative beat (panel 1) and the calculated relative values (panel 2). In contrast, an occlusion of LAD results in a constant increase of ST and T within the representative beat (panel 3) and relative values (panel 4). The LAD patient shows a non-standard ECG, presumably due to a pre-damaged heart, which is expressed by ST-elevation before balloon inflation. Regarding the T feature, alterations over time (panels 2, 4) show a similar behavior in the during-inflation stage.

Fig. 2 summarizes ΔST and ΔT features representing the differences between the stages pre-inflation and during-inflation in every lead and patient. For ΔST, leads V2-V4 show higher values for LAD patients compared to RCA patients. In leads II-III the results are reversed with RCA patients showing higher values. Regarding ΔT, in leads V2-V4 the same effect as in ΔST can be seen, while leads II-III do not show clearly effects. The differences in leads V2-V3 and II-III are highly significant for ΔST, whereas in ΔT only V2-V3 are highly significant.

4. Discussion

This work was motivated by the assumption that changes in relative ST-segment/T-wave amplitudes over time could be a useful feature in non-standard ECGs.

The proposed dynamic for ischemic ECG alterations over time in patients undergoing prolonged balloon inflation show a potential for differentiating LAD and RCA patients. The features in the LAD patients are very similar to clinical findings, where standard ECGs show characteristic ST-elevation in leads V2-V4 with contralateral ST-depressions in leads II and III [5]. *Vice versa*, laterally-reversed ECG findings can be found in RCA patients using our features which is also covered by clinical guidelines [5].

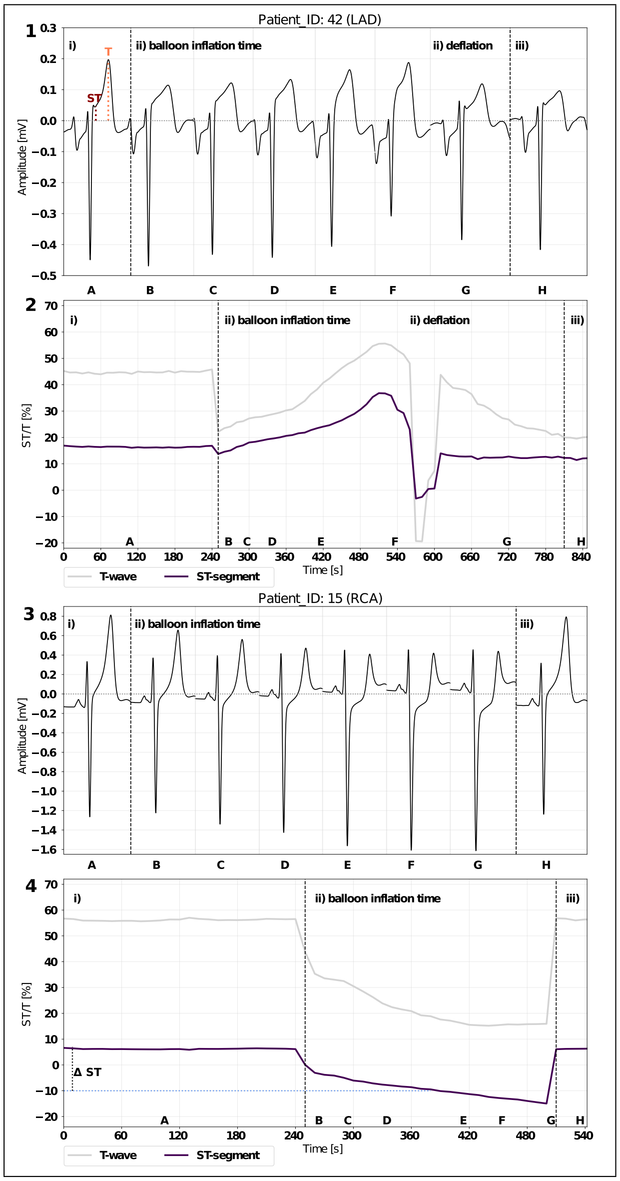

Figure 1: Lead V2 features during elective PCI for an RCA patient (panels 1-2) and LAD patient (3-4). Representative beats (1,3) and ST and T feature (2,4) computed over time during three stages are shown: i) pre-inflation ii) during-inflation iii) post-inflation. In the LAD patient, stage ii) additionally shows the moment of balloon deflation within the recording. Vertical, dashed lines mark interruptions in measurements due to medical intervention. A-H show occurrences in time of the representative beats and their value w.r.t. QRS amplitude. In panel 1, the ST and T feature of the first representative beat are shown. In panel 4 bottom left, the computation of the alterations over time ΔST are depicted exemplary.

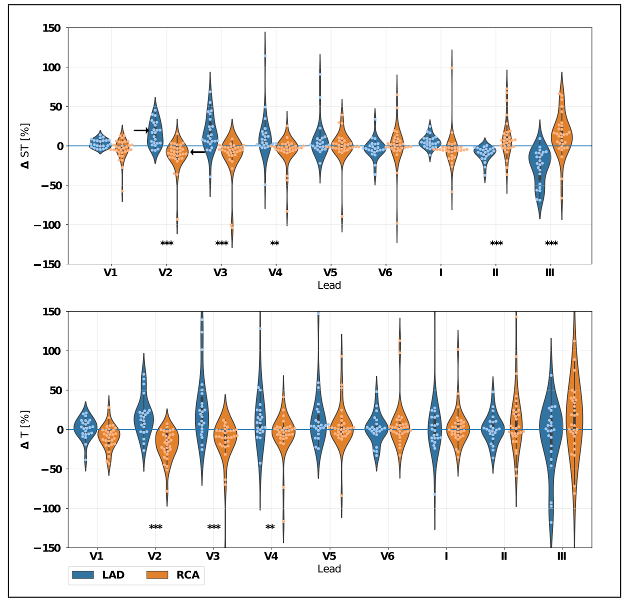

Figure 2: ΔST and ΔT features of LAD (blue) and RCA (orange) patients. Each point corresponds to a patient. In leads V2-V4 both groups can be easily distinguished from each other. The black arrows indicate the data points for patients 42 and 15 in ΔST. $***$ indicates a significance with $p \leq 0.001$ and $**$ indicates $0.001 < p \leq 0.01$.

However, clinical guidelines use 10-second 12-lead ECGs representing only a snapshot of the current cardiac activity and look for absolute alterations in mV. We demonstrate that it is also feasible to detect alterations over time based on relative values as proposed by cardiologists [8] and researchers [5]. In Fig. 1 the pre-inflation ECG of LAD patient 42 already shows an elevated ST-segment amplitude. This ST-elevation is problematic as the conventional assessment prevents proper diagnosis of life-threatening restenosis. However, our proposed dynamic w.r.t. ΔST and ΔT show characteristic changes over time, which could be an avenue for future work for more accurate diagnosis.

In the recent guideline for evaluation of chest pain, the T-wave is not taken into account considerably. However, there are many researchers trying to improve diagnosis based on T-wave features [7]. Within the STAFF III database, García et al. [6] found that in 72% of patients with ST-segment amplitude changes were also showing T-wave amplitude changes. Martínez et al. [12] studied the prevalence, magnitude and spatio-temporal relationship between T-wave alternans and ischemia. They analyzed the ECGs beat by beat and found T-wave alterations in 33.7% of the patients. A reason why usage of T-waves is challenging can be seen in the pre-inflation ECG of patient 42 (panel 1) in Fig. 1: The T-wave (A) shows a similar height as during balloon inflation (F), highlighting its morphological variability. A potential explanation could be that the ECG was detached and re-attached between both stages. Our results also indicate that the T-wave might be a useful additional feature for monitoring of ischemic ECG alterations if the device is constantly attached.

A limitation of this work is that we only analyzed a single database. Therefore, investigating whether the observed alterations can also be noticed in other patient cohorts and is not present in healthy subjects is an avenue for future work. Additionally, we plan to extend the investigation on other coronary vessels like left circumflexum (LCx) since this type of ischemia is often underdiagnosed. In these ECGs, anterior ST-depression dynamics could potentially point towards posterior ST-elevation which could be checked by using additional leads V7-V9 [8].

5. Conclusions

In this work, two established ECG features, namely the amplitudes of the ST-segment and T-wave [2, 13], were extended by quantifying them i) over time and ii) as relative values w.r.t. QRS complex amplitude. Using these novel features, we found significant differences between LAD and RCA patients when comparing ECGs before and during PCI. This approach extends the state-of-the-art based on subject-independent and absolute thresholds defined in clinical guidelines. The dynamic of the features could be useful for patients in which these "one size fits all" thresholds fail, e.g. in patients showing only subtle alterations [14] or with permanent ST-alterations [15]. However, further studies with different patient cohorts and larger datasets in general are required to investigate whether the proposed dynamic could further improve the detection of cardiac ischemia using standard 12-lead ECGs.

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