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Quaternion-based study of angular velocity of the cardiac vector during myocardial ischaemia

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ABSTRACT

Background: Early detection of acute ischaemia through non-invasive methods remains a challenge in health research. Ischaemic condition caused by a decrease in the blood supply in a cardiac region induces hypoxia and metabolic abnormalities that contribute to the electrical instability of the heart and to the development of slow conduction in damaged tissue. **Methods:** Herein, a percutaneous transluminal coronary angiography (PTCA) is considered as a model of supply ischaemia. We use the concept of quaternion to develop a robust method for assessing the angular velocity of cardiac vector in the orthogonal XYZ leads obtained from 92 patients undergoing the PTCA procedure. The maxima of angular velocity in both ventricular depolarization and repolarization are combined with traditional linear velocity indexes in order to obtain a detector of ischaemic episodes (Ischaemia Detector, *ID*). **Results:** *ID* achieves 98%/100% of sensitivity/specificity when differentiating healthy subjects from patients with early ischaemia. Furthermore, it also shows high accuracy when the comparison is made between ischaemic subjects and patients with different non-ischaemic pathologic ST-deviations which are known to cause false positives, reaching 95%/98% of sensitivity/specificity. Moreover, the study of significant reductions ($p<0.001$) of angular velocity components allows extraction of distinct ischaemic common features which are useful for analyzing the dependence of vectorcardiogram signal on each site of occlusion. The sensitivity of injury location reaches values of 88% (RCA), 87% (LAD) and 80% (LCx). **Conclusions:** The high performance of the proposed method establishes a promising outcome for application in computerized assistance in clinical practice.

1. Introduction

Coronary thrombosis is one of the major causes of morbidity and mortality worldwide [1]. This fact highlights the ongoing need for a reliable risk index of acute coronary syndrome in order to begin early treatment and avoid possible complications. Conventionally, diagnosis for ischaemic symptoms on the electrocardiogram (ECG) requires a deviation greater than 0.1–0.2 mV of the ST segment in two or more contiguous leads [2]. Several studies have shown that this diagnostic criterion has low sensitivity associated to the reliance on the severity and location of ischaemic region and its relative position with respect to ECG electrodes [3,4].

Ischaemia caused by a decrease in the blood supply in a cardiac region induces local metabolic abnormalities that contribute to electrical instability of the heart. Particularly, extracellular hyperkalemia which is rapidly found in blood flow after a vessel occlusion contributes to the development of slow conduction in ischaemic tissue [5]. The increase in axial resistance on coupling between cells and a possible conductivity disruption also play an important role in slowing the electrical cardiac conduction system [6].

Recently, few methods have been presented to compute the cardiac vector velocities associated to conduction patterns of the heart [7,8]. These methods have been developed noninvasively using the vectorcardiogram (VCG) which has favourable conditions for studying conduction disorders and, in turn, it is increasingly being used in everyday medical practice [9]. In this work, we study the dynamics of the angular velocity of the cardiac vector in ischaemic patients using the quaternion methodology through the orthogonal XYZ system. We hypothesize that angular velocity patterns would be useful for detecting ischaemic characteristics with high accuracy when they are combined with classical linear velocity indexes. Furthermore, we expect that such patterns would also allow the extraction of relevant information about the location of the myocardial affected area associated with an occluded vessel.

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2. Materials and methods

2.1. Populations under study

We have proposed three study populations:

1) **Healthy subjects**, whose ECG recordings have been extracted from Physikalisch-Technische Bundesanstalt (PTB) [10,11] and from Intercity Digital Electrocardiogram Alliance (IDEAL) database [12]. The PTB database has been acquired at the Department of Cardiology of University Clinic Benjamin Franklin in Berlin, Germany, and has been provided to the users of PhysioNet. We have selected all recordings from subjects with no previous cardiovascular diseases (52 volunteers). Ages ranged from 17 to 81 years with a mean of 40; 13 of the subjects were female (25%). Each record included 15 simultaneously measured signals: the 12 standard ECG leads together with the 3 orthogonal Frank leads. Each signal was digitized at 1000 samples per second with 16 bits of amplitude resolution. The IDEAL database, provided by the Telemetric and Holter ECG Warehouse of the University of Rochester NY (THEW), consists of 205 subjects with no previous cardiovascular diseases. The 24-h Holter recordings were acquired using the SpaceLab-Burdick digital Holter (pseudo orthogonal lead configuration) recorder at 200 Hz sampling frequency and 16-bit amplitude resolution. We randomly selected 40 subjects. There is an initial resting supine period for a 20-min duration before starting the ambulatory recording.
2) **Non-ischaemic patients**, whose recordings have been obtained from Ischemia Monitoring and Mapping in the Emergency Department in Appropriate Triage and Evaluation of Acute Ischemic Myocardium (IMMEDIATE AIM - THEW) study [13]. This database includes patients that have been enrolled in the between 2002 and 2004 and 1-year follow-up was completed in December 2005. The 24-h Holter recordings were acquired (standard 12-lead ECG) in cohorts of emergency department patients undergoing evaluation for possible acute coronary syndrome. We have selected 52 patients with non-ischaemic cardiac conditions, amongst others, patients with valvular heart disease, congestive heart failure, pericarditis, new onset arrhythmia, stable angina and patients with non-cardiac conditions such as pneumonia, diabetic ketoacidosis, hyperkalemia, and sepsis. Each signal was digitized at 1000 Hz with 3.75 μV of amplitude resolution. There is an initial resting supine period for a 20-min duration before starting the ambulatory recording.
3) **Ischaemic patients**, whose ECG recordings have been extracted from STAFF III database [14]. This database has been assembled at the Charleston Area Medical Center in West Virginia, United States. It is a part of the STAFF Studies Investigations approved by the Investigational Review Board. The population consisted of 92 patients receiving elective prolonged (4.5 min $\pm$ 1.3 min) percutaneous transluminal coronary angiography (PTCA). It has been shown that balloon-inflation PTCA is a valuable model of supply ischaemia in humans [15]. For each subject the occluded vessel is specified: left anterior descending coronary artery (LAD: 28 subjects), right coronary artery (RCA: 44 subjects), left circumflex coronary artery (LCx: 18 subjects) and left main coronary artery (LM: 2 subjects). The ECG recordings were digitized at 1000 samples per second and an amplitude resolution of 0.6 μV. The XYZ leads have been synthesized from 12 ECG leads using the Kors transform [16].

Finally, it is important to highlight that we have organized the databases into two independent datasets: **learning group** and **testing group**. The former includes 40 healthy subjects (IDEAL) and 40 ischaemic patients (STAFF III). The latter includes 52 healthy subjects (PTB), 52 non-ischaemic patients (IMMEDIATE AIM) and 52 ischaemic patients (STAFF III).

2.2. Methodology

In this work, we present an algorithm that seeks to address two important issues: 1) Rapid detection of ischaemic process and 2) Identification of the damaged area of the myocardium (associated with an occluded vessel). In the first case, the angular and linear velocities are combined to find significant differences between the control subjects (including healthy subjects (**Hs**) and non-ischaemic (**NonIp**) patients) and the patients with early ischaemia (Ip_{1m}, ischaemic patients at the first minute of occlusion). In the second case, we evaluate the temporal evolution of the ischaemic process by means of assessing the dynamics of each (x, y, z) component.

First, the preprocessing of the electrocardiographic signal is applied in order to remove the noises and to select the ventricular depolarization and repolarization loops. Then the linear and angular velocities are obtained for each loop. And finally these velocities are combined in order to detect and locate the damaged zone. In the next subsections, each step is explained and described.

2.2.1. Preprocessing and loop selection

In order to correct the baseline wander, a Butterworth bidirectional 0.5 Hz high-pass filter has been applied. Two fixed width windows have been used to select both ventricular depolarization and repolarization loops: R-wave peak position $\pm$ 60 ms and T-wave peak position $\pm$ 120 ms. The high frequency noise in both signals has been removed using a Butterworth bidirectional low-pass filter (40 Hz for QRS-complexes and 20 Hz for T-waves). All the signals of healthy (IDEAL) database has been resampled to 1 kHz since this is the only database that has a sampling frequency of 200 Hz. Non-ischaemic (IMMEDIATE AIM), ischaemic (STAFFIII) and healthy (PTB) databases use originally 1000 samples per second. Resampling is only for a frequency unification and it does not affect the velocity computation. Both 200 Hz and 1000 Hz velocity parameters have a strong correlation (98.3%). The VCG fiducial points have been automatically delineated using a Wavelet-transform based method [17].

2.2.2. Angular velocity computation

Through the normalization of each VCG sample in XYZ space we can obtain a sequence of consecutive unit vectors. Thus, we can define angular velocity as a path angle of the tip of the cardiac vector per unit time. The T-wave loop (as well as the QRS-complex loop) remains on a dominant plane π in a healthy heart (Fig. 1a). In this situation the magnitude of the angular velocity vector $\vec{\omega}$ changes several times along the loop but its direction n_π should be practically constant. It has been observed that several non-planarity patterns can be found in ischaemic conditions [18]. Also, the increase in the myocardial oxygen demand in ischaemic tissue causes electrical irregularities that slow down or divert the normal conduction [6,19]. From this perspective, it is expected that acute myocardial ischaemia induced by vessel occlusion deflects the ventricular depolarization and repolarization forces (Fig. 1b). This fact may induce significant alterations in the components of the angular velocity and these alterations will be dependent on the site of coronary occlusion.

Computing the angular velocity, in the classical sense, is a hard challenge since transcendental functions should be avoided in order to reduce propagation errors [20]. Recent studies have shown a method to obtain the rate of change of ECG vector angle using a linear approximation of the power series expansion of cosine. This method works properly at the end of the QRS-complex loop but it does not at other regions of the loop because it requires a minimal change of 2° per millisecond. Also, the determination of the orientation

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