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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 $\mu V$ 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 $\mu V$. 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 $\pi$ 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 $n_\pi$ 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

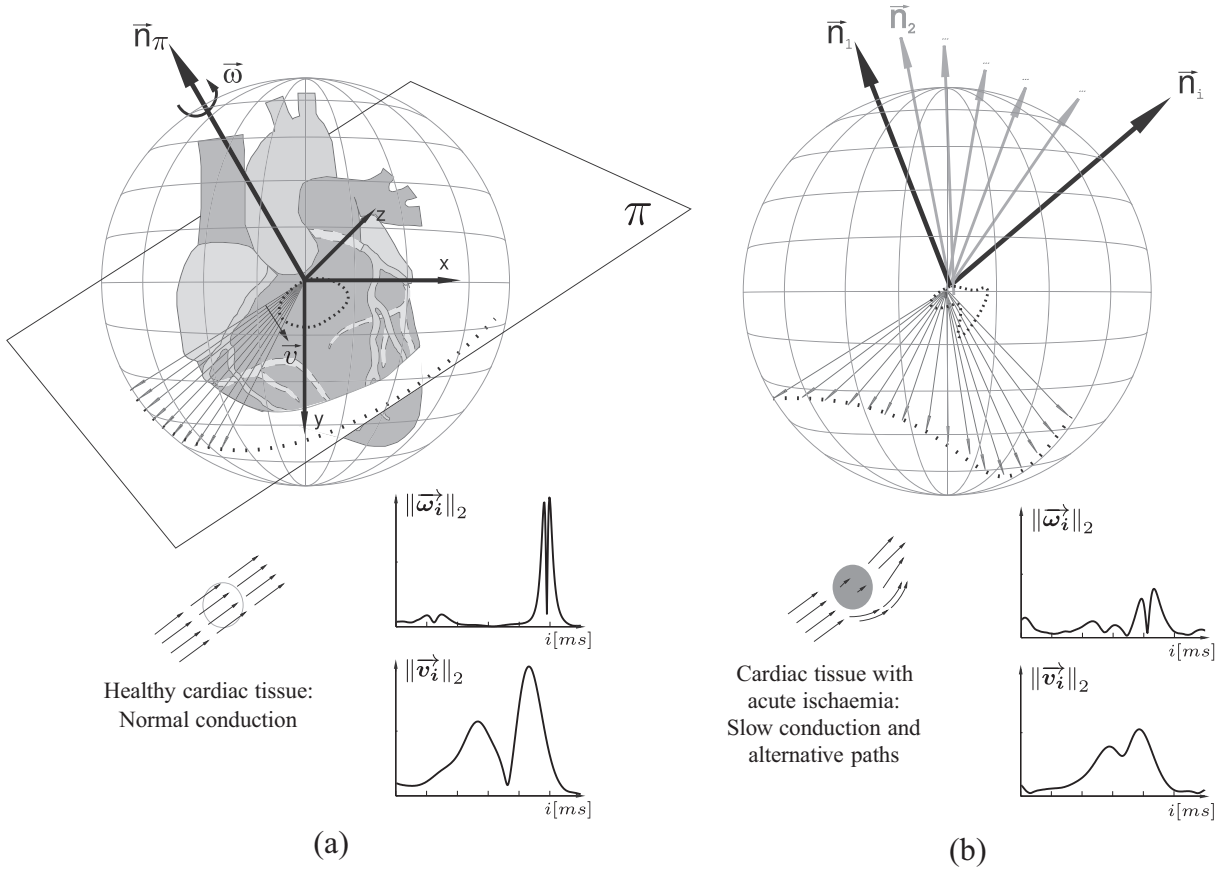


**Fig. 1.** Effects of ischaemia in conductivity of tissues: (a) In healthy subjects the T-wave loops (dotted line) remain each one in a plane (as well as the QRS-complex loops). Linear velocity ($\vec{v}$) is obtained by differentiation of samples and it is tangential to displacement of the tip of cardiac vector. Angular velocity ($\vec{\omega}$) is obtained in normalized loop using the concept of quaternion and it is orthogonal to displacement; (b) Abnormal conduction provoked by ischaemia induces non-planarity patterns. Instantaneous normal vectors ($\vec{n_i}$) may change in each sample.

becomes uncertain at low amplitude signals [7]. We have recently introduced a more general solution for obtaining the angular velocity of the cardiac vector by working on the non-commutative field of quaternions [8]. While it is an advanced algebra, it has been shown that the computation of rotations is quite simple and it is used over many technology areas. Moreover, it presents very high speed of signals processing, stability and high robustness to noise and distortions arising from numerical inaccuracies caused by floating point computations [20]. In the present work the instantaneous quaternions are obtained through the dot and cross products:

$$\mathbf{q_i} = (P_i \bullet P_{i+1}; P_i \times P_{i+1}) \tag{1}$$

where

$$\begin{cases} P_i \bullet P_{i+1} = \| P_i \|_2 . \| P_{i+1} \|_2 . cos(\alpha) \\ P_i \times P_{i+1} = \| P_i \|_2 . \| P_{i+1} \|_2 . sin(\alpha) . \vec{n} \end{cases} \tag{2}$$

$P_i$ and $P_{i+1}$ represent a pair of consecutive points in XYZ space normalized to the unit-radius sphere and they are separated by an angle $\alpha$. Each quaternion has a scalar part directly related to the magnitude of rotation and a vector part associated to the normal vector of the plane of instantaneous movement. The angular velocity can be calculated from the Poisson differential equation for instantaneous double-angle values:

$$\dot{\mathbf{q}}_\mathbf{i} = \frac{1}{2} . \vec{\omega}_i . \mathbf{q}_\mathbf{i}^{-1} \tag{3}$$

Expressing the inverse of the quaternion in terms of its conjugate and its norm, we can solve Eq. (3) using difference equations taking into account the sampling period *Ts*. Therefore, we obtain the angular velocity at *i*th sample point ($\vec{\omega_i}$) as follows

$$\vec{\omega_i} = (\omega_{xi}; \omega_{yi}; \omega_{zi}) = \left( \frac{\mathbf{q_{i+1}} - \mathbf{q_i}}{Ts} \right) \cdot \frac{\bar{\mathbf{q}}_\mathbf{i}}{\|\mathbf{q_i}\|^2} \tag{4}$$

### 2.2.3. Linear velocity computation

The average linear velocity was initially associated with the relationship between the durations and distances of depolarization forces in different time periods [21]. We have previously shown that the maximum instantaneous velocity values are useful in detecting infarcted patients when such values are combined with the angular velocity ones [8]. Using the sampling period *Ts*, the instantaneous linear velocity can be directly found by differentiation of VCG signal (Eq. (5)).

$$\vec{v_i} = (v_{xi}; v_{yi}; v_{zi}) = \frac{P_i(x,y,z) - P_{i+1}(x,y,z)}{Ts} \tag{5}$$

### 2.2.4. Ischaemia detection and damaged area identification

Taking into account the fact that both angular and linear velocities are diverted or reduced as a consequence of ischaemia, we can define our ischaemia detector (*ID*) as an adequate weighted combination of maximum values through T-wave and QRS-complex loops:

$$ID = k_1 . \omega_M{}^{(T)} + k_2 . v_M{}^{(T)} + k_3 . \omega_M{}^{(QRS)} + k_4 . v_M{}^{(QRS)} \tag{6}$$

where $\omega_M = max(\| \vec{\omega}_i \|_2)$ and $v_M = max(\| v_i \|_2)$. $\vec{\omega}_i$ and $\vec{v}_i$ are computed by solving Eqs. (4) and (5) over an average of ten beats. The superscripts identify the loop on which each parameter is obtained. The weights $(k_1, \ldots k_4)$ are chosen in order to ensure similar orders of magnitude without the need of a fine-tune process to improve sensitivity and specificity in the ischaemia detection. This is convenient as it strengthens the reproducibility of the method and its robustness in terms of accuracy. The first statistical test provides information necessary for determination of the $k_1, \ldots k_4$ values (see Section 2.3 below).

Moreover, we study the instantaneous components of such velocities for identification of the affected area. While in healthy conditions $\vec{\omega}$ has a constant direction, the same cannot be said of $\vec{v}_i$ whose direction is constantly rotating tangentially to the loop. Whereupon, it is expected that only $\vec{\omega}$ components are useful for locating the area of damaged cardiac tissue. This is evaluated using statistical methods by virtue of the significant variation in the components of each vector. The comparison is made between the first 10 s of vessel occlusions and acute ischaemia (after the third minute of occlusion).

### 2.3. Statistical analysis

Due to the need to detect early myocardial ischaemia, all recordings within the first minute of occlusion are grouped together (in both learning and testing processes) to constitute the ischaemic patients group ($\mathbf{Ip_{1\,m}}$). The first statistical test is undertaken for the purpose of assessing significant differences between healthy subjects **Hs** and $\mathrm{Ip_{1m}}$ patients in the learning population. Using a two-sided Wilcoxon signed rank test, we have obtained the $p$-values for each velocity: $\omega_M^{(\mathrm{T})}$, $v_M^{(\mathrm{T})}$, $\omega_M^{(\mathrm{QRS})}$ and $v_M^{(\mathrm{QRS})}$, which are the variables of the *ID* index (Eq. (6)). The constants $k_1, \ldots k_4$ are estimated in order to get values of the same order of magnitude in accordance with those statistically significant variables ($p < 10^{-5}$). Furthermore, for each variable, performance bounds of mean values have been obtained through 1000 bootstrap trials [22].

The diagnostic value of *ID* index is determined in the testing populations by obtaining the receiver operator characteristic (ROC) curve. We have reported the decision criterion that achieves the best pair of sensitivity and specificity, as well as the area under the ROC curve (AUC). The comparison is done on the one hand between healthy individuals and ischaemic patients and on the other hand between ischaemic and non-ischaemic patients (**NonIp**).

Finally, we have evaluated the significant changes in the rotation of the velocity vectors in both the T-wave and the QRS-complex. For this purpose, a second Wilcoxon test is used to compare the components $\Delta\omega_x$, $\Delta\omega_y$ and $\Delta\omega_z$ of each velocity in the first 10 s and after 3 min of vessel occlusion (being $\Delta\omega_i = \omega_i^{3min} - \omega_i^{10sec}, i = x,y,z$). Those patients whose variations fall inside the expected range of significance are considered as true positives.

## 3. Results

In Fig. 2 we show the statistical results obtained for the variables of the *ID* index (Eq. 6). In a box and whisker diagram are compared the maximum values of the linear and angular velocities in T-wave and QRS-complex. During the **learning process**, the highest statistical differences were found in $v_M^{(\mathrm{QRS})}$ with $p < 10^{-16}$. The angular and linear velocities of the T-wave reached significance values of $p < 10^{-13}$ and $p < 10^{-14}$ respectively. The values of the variables during the **testing process** are also shown in Fig. 2. It can be seen that in those statistically significant variables both healthy and non-ischaemic populations show higher velocity values than ischaemic population.

In order to compute the *ID* index (Eq. 6) we have taken into account the aforementioned significance values and we have selected the weights to ensure similar orders of magnitude. $k_3$ has been set at zero since no statistically significant differences were found in $\omega_M^{(\mathrm{QRS})}$. The *ID* index has been then computed as

$$ID = 4.\omega_M{}^{(\mathrm{T})} + 10.v_M{}^{(\mathrm{T})} + 1.v_M{}^{(\mathrm{QRS})} \quad (7)$$

reaching a significance value of $p < 10^{-20}$.

A separate sensitivity/specificity pair can then be computed for each parameter during both **learning process** and **testing process**. Table 1 summarizes these results along with the performance values of the *ID* index in the discrimination between patients with early ischaemia ($\mathrm{Ip_{1m}}$) and healthy subjects (**Hs**). A comparison with non-ischaemic patients (**NonIp**) has also been carried out.

We underscore the fact that, although individual parameters are highly accurate, in non-ischemic conditions they reduce their specificity. This is one of the main advantages of combining velocities instead of using single parameters. Furthermore, in Fig. 3 we present a temporal evolution graph for the *ID* index during ischaemic process in two patients for each vessel occlusion. The ability of the index to detect ischaemia whether or not there are noticeable deviations in the ST segment can be seen.

In order to compare the performance of our approach with the conventional parameters, we have computed, using the populations of the testing group, the conventional ST-segment deviation criteria [2,23]. This criterion implies the following ECG alterations: ST segment elevation at the J point in two or more contiguous leads with the cut-off point >0.1 mV in all leads other than V2-V3 where the thresholds are >0.15 mV for women, >0.25 mV in young men (< 40 years) and >0.2 mV in middle-aged men (> 40 years); or ST-segment depression >0.05 mV in at least two contiguous leads. Contiguous leads are lead groups: anterior leads (V1:V6) and limb leads (aVL:I, I:-aVR, -aVR:II, II:aVF, aVF:III). The evaluation of **Hs** versus $\mathbf{Ip_{1m}}$ populations reached a sensitivity of 60% and specificity of 89% (See Table 1). These values are consistent with those obtained by other authors [24]. As well, the specificity fell to 75% when the comparison was made with **NonIp** population.

An additional study of the statistically significant changes of angular velocity in each component of the XYZ system is carried out. As detailed in Section 2.3, the comparison was made between the velocity values after 3 min of vessel occlusion and the values in the first 10 s after begin PTCA procedure. The linear velocity has not shown significant differences. Each coronary occlusion has shown a particular pattern of velocity alterations based on the location of the affected region. The maximum of $\omega_x^{(T)}$, $\omega_y^{(T)}$ and $\omega_z^{(T)}$ shown significant decreases $\Delta\omega_x^{(T)}$ ($-20 \pm 5$ mil/ms), $\Delta\omega_y^{(T)}$ ($-20 \pm 5$ mil/ms) and $\Delta\omega_z^{(T)}$ ($-7 \pm 3$ mil/ms) for LAD occlusion, reaching a sensitivity of 87% in whole ischaemic population during testing process. For LCx occlusion significant decreases have been found in $\Delta\omega_x^{(T)}$ ($-10 \pm 4$ mil/ms) and $\Delta\omega_x^{(QRS)}$ ($-40 \pm 15$ mil/ms) in 80% of patients. Finally, for RCA occlusion, we found significant differences in both $\Delta\omega_y^{(QRS)}$ ($-40 \pm 11$ mil/ms) and $\Delta\omega_z^{(QRS)}$ ($-4 \pm 1$ mil/ms) reaching a sensitivity of 88%.

## 4. Discussion

### 4.1. Ischaemia detection

We have presented a robust method for the extraction of ischaemic patterns from velocity of the tip of the electric cardiac vector. The angular velocity obtained through the quaternion approach provide high robustness to noise and numerical inaccuracies [20], which is a major benefit in comparison to other methods [7,25]. In this work, we have shown an additional advantage: The angular velocity can be obtained at any time of the cardiac cycle (ventricular depolarization and repolarization) even in those time intervals with minimal changes of angle per millisecond. The high values

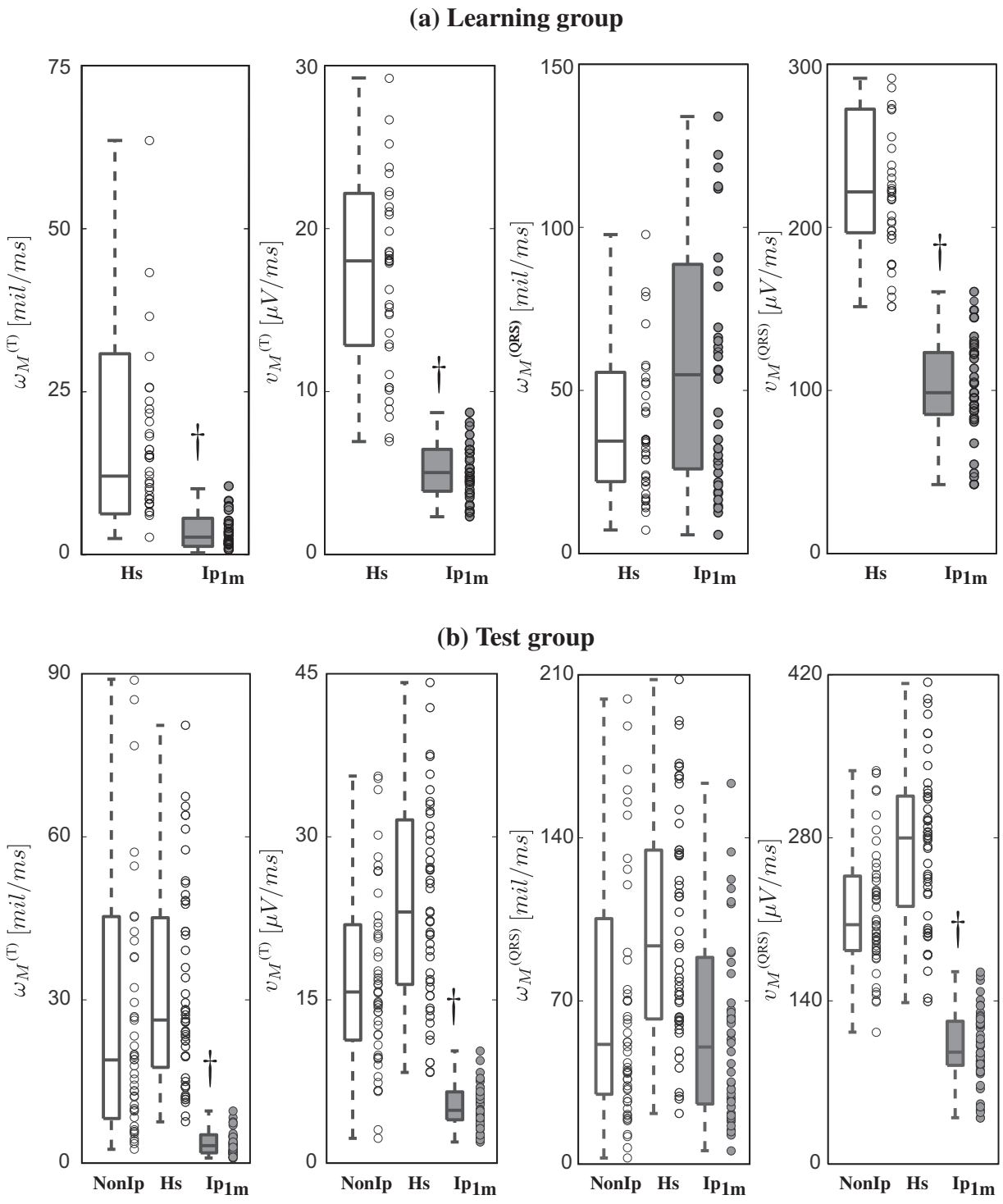


**Fig. 2.** Box and whisker diagrams of linear and angular velocities in both ventricular depolarization and repolarization processes: (a) Comparison between healthy and ischaemic populations, in the learning process; (b) Comparison of healthy, ischaemic and non-ischaemic subjects, in the testing process. The statistically significant differences ($p < 10^{-5}$) have been indicated with a † mark. Individual data points are presented next to each diagram.

of sensitivity and specificity obtained with Eq. (7) show the high efficiency of *ID* index to differentiate between **Hs** and $\mathbf{Ip_{1m}}$ populations. In addition, the value of accuracy of the index remains high when the comparison is made with patients with different non-ischemic pathologic ST-deviations which are known to cause many false positives (**NonIp**). It has been shown that conventional electrocardiographic markers of ischaemia, such as the measurement of ST deviation at the J-point, have very limited sensitivity [26]. Our results agree with that, and furthermore, we have observed that conventional ECG analysis shows a drop in specificity when patients with non-ischaemic ST-deviations are included. Some studies have been successful in detecting ischaemia using linear [18] and non-linear [24] discriminant functions. However, these methods often require the combination of a large number of parameters and high precision in the coefficients. In this regard, the weights used in the *ID* index do not require a fine-tuned process since they are only scaling

**Table 1**
Statistical results obtained for each parameter. The mean values are shown with a confidence interval of 95% obtained from bootstrap method (1000 trials). The performance values in terms of sensitivity and specificity for the velocity parameters, the ID index and the ST conventional criteria are also shown.

| | Group | $\omega_M^{(T)}$ | $v_M^{(T)}$ | $v_M^{(QRS)}$ | *ID* |
|---|---|---|---|---|---|
| | | Mean (CI 95%) | Mean (CI 95%) | Mean (CI 95%) | Mean (CI 95%) |
| Learning process | **Hs** | 17.5 (13.5 to 23.6) | 17.9 (15.9 to 20.2) | 238.4 (222.4 to 273.5) | 537.1 (479.5 to 617.3) |
| | **$lp_{1m}$** | 3.8 (2.8 to 4.9) | 5.4 (4.7 to 6.1) | 93.7 (84.8 to 104.3) | 174.6 (159.5 to 189.4) |
| | Sn/Sp | 89%/98% | 88%/98% | 91%/98% | 97%/100% |
| Test process | **Hs** | 30.3 (25.7 to 35.0) | 24.6 (22.0 to 27.5) | 270.1 (252.0 to 287.7) | 644.5 (595.6 to 701.4) |
| | **$lp_{1m}$** | 3.5 (2.9 to 4.1) | 5.6 (5.1 to 6.2) | 100.6 (91.7 to 108.5) | 175.4 (162.6 to 189.5) |
| | **NonIp** | 21.6 (17.1 to 28.1) | 17.2 (15.1 to 19.5) | 200.9 (187.1 to 216.8) | 484.5 (436.9 to 532.8) |
| | Sn/Sp (Hs) | 90%/97% | 92%/97% | 95%/97% | 98%/100% |
| | Sn/Sp (NonIp) | 90%/60% | 92%/77% | 95%/88% | 95%/98% |
| | Method | Group | Sensitivity | Specificity | Criterion |
| Comparative test results | *ID* | **Hs** vs **$lp_{1m}$** | 98% | 100% | $< 298$ |
| | | **NonIp** vs **$lp_{1m}$** | 95% | 98% | |
| | *ST* | **Hs** vs **$lp_{1m}$** | 60% | 89% | Conventional criteria |
| | | **NonIp** vs **$lp_{1m}$** | 60% | 74% | |

factors. This fact constitutes a significant improvement over actual methods. Moreover, the method presented in this work does not need any prior ECG records of the patients.

Recently, it has been shown that the combination of the QRS angles is useful for early detection of acute ischaemia [25]. We have consistent results since these angles are directly linked to the velocity of the tip of the cardiac vector. Additionally, the calculation in the field of quaternions avoids the use of transcendental functions as the *arctangent* and *exponential* functions. Moreover, as discussed below, the study of the dynamics of angular velocity components

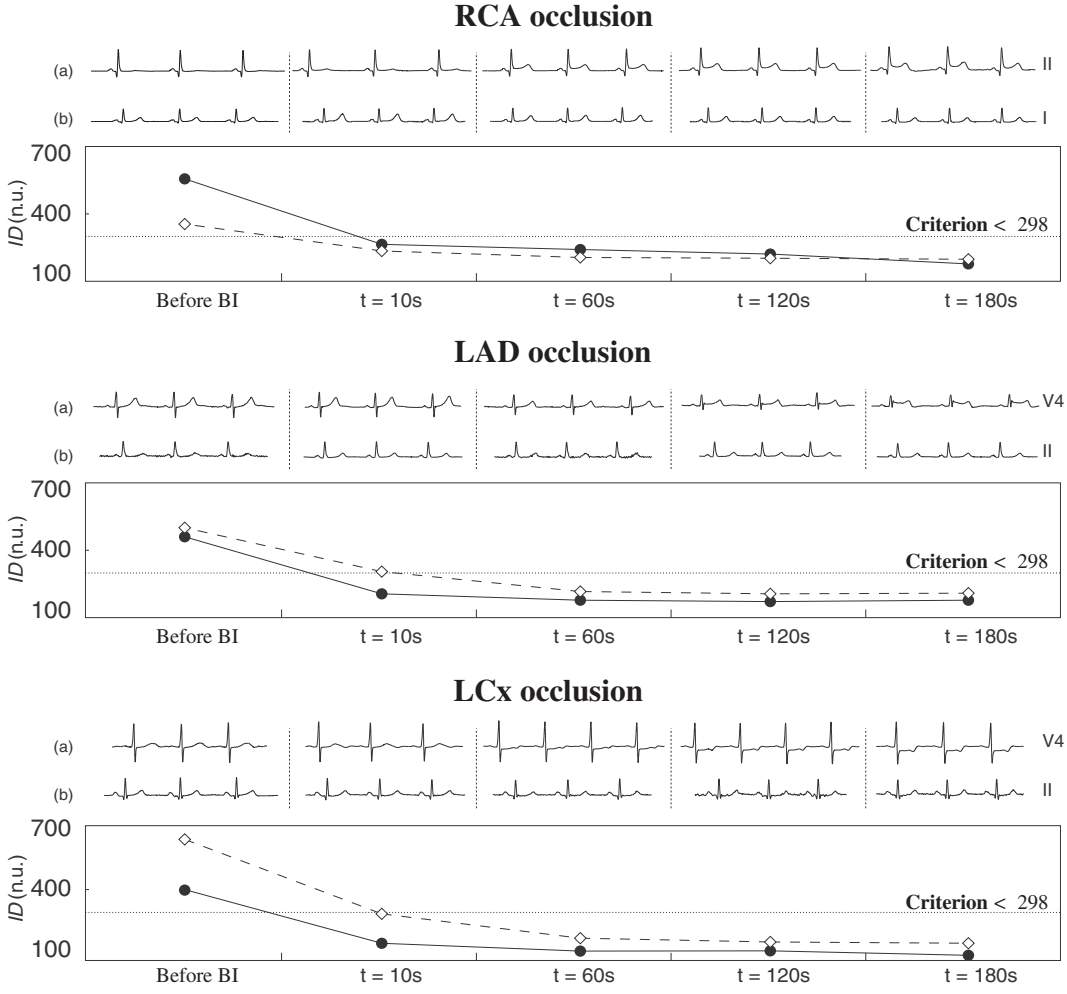


**Fig. 3.** Temporal evolution of *ID* index in two ischaemic patients for each vessel occlusion. (a) Patients with evident ST changes (shown as ◊); (b) Patients without noticeable ST changes (shown as •). 'Before BI' refers to the ECG recording during control situation before PTCA ballon inflation. Above each graph, a single ECG signal extracted from lead where largest ST deviation was found is plotted.

$(\omega_x; \omega_y; \omega_z)$ allows extraction of distinct ischaemic common features which may be useful for analyzing the dependence of VCG signal on each site of occlusion.

### 4.2. Location of myocardial damaged area

The RCA-related ischaemia induced by inflation of the PTCA balloon mainly affects the inferior wall of the heart. Moreover, the ST-segment deviation is usually observed in leads II, III, aVF and V1-V4 [27]. Both the vector of the base of heart and the right axis of the mean QRS vector traverse the affected area significantly reducing their magnitude. This causes a shift of the cardiac axis in the XY (frontal) plane and it alters the $z$ component of angular velocity ($\omega_z$). Also, the electrical activity in XZ (transverse) plane is strongly affected by the bad conditioning of the inferior wall. The results presented in this work are consistent with the aforementioned considerations since we have observed significant alterations in $\omega_y$ and $\omega_z$ during ventricular depolarization as we can see in Section 3. Also, it would seem that RCA-related ischaemia does not cause changes in the YZ (sagittal) plane because $\omega_x$ has not shown significant changes.

On the other hand, in those patients whose LCx coronary artery was occluded, we have detected statistically significant reductions in $\omega_x$ for both ventricular depolarization and repolarization processes. This is a reasonable result considering that $x$ axis traverses a part of the left ventricle and the lateral wall of the heart (affected region) (see Section 3).

Finally, for the group of patients whose LAD coronary artery was occluded, the angular velocity has shown significant reductions in its three components $(\omega_x; \omega_y; \omega_z)$ during ventricular repolarization process (see Section 3). Usually ischaemia caused by occlusion of LAD coronary artery is detected in leads II, aVF, and V1-V6 [4,27]. This might be due to the reduction in conductivity of the left anterior wall caused by the arising current flow loops [19], which occurs in the direction of the cardiac axis during ventricular repolarization.

## 5. Conclusions

We have shown the advantages of a careful study of the angular velocity of the tip of the cardiac vector. Our findings suggest that this method not only achieves very high sensitivity and specificity for early myocardial ischaemia detection through the proposed *ID* index, but also it is useful to identify the damaged area. Moreover, it is robust when non-ischaemic pathologic ST-deviations are included. Since our work is based on a model of supply ischaemia through the PTCA procedure, further investigations are needed to evaluate the reproducibility and to validate the results obtained using other databases with large numbers of unselected chest-pain patients. The quaternion approach for obtaining the angular velocity and the simplicity of the presented algorithm establish a promising outcome for application in computerized assistance in clinical practice.

## Conflicts of interest

The authors declare that there are no conflicts of interest.

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