



# A new anatomical view on the vector cardiogram: The mean temporal-spatial isochrones

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## Abstract

**Aim:** This proof of principle study aims to show the direct relationship between cardiac anatomy and the mean cardiac activation path as captured by the 12 lead ECG derived mean temporal-spatial isochrones (mean TSI) path.

**Methods:** To obtain the mean TSI signal a vector cardiographic (VCG) signal is constructed from the 12 lead ECG. The construction of the VCG signal uses a model of the heart and torso with patient specific electrode extracted from a 3D photo. The propagation of the activation through the heart is captured by estimating the mean of a cardiac activation isochrone using this VCG signal. The mean TSI signal is related to the heart model in a standard view using 3 orthogonal heart views, instead of the standard body related orthogonal planes.

**Results:** The mean TSI was computed for 4 patients with the ECG containing ectopic activations like Premature ventricular contractions (PVCs) or pacemaps, and normal His-Purkinje activations. For each patient, a specific model with known electrode positions was available. For each activation, the mean TSI was shown in relation to the cardiac anatomy. The region of origin of the PVC or pacemap could easily be localized from these views. Also the initial trans-septal activation for normal His-Purkinje activations could easily be detected and related to the septum.

**Conclusion:** This proof of principle study showed that the mean path of cardiac activation can be derived from the ECG and related to standard orthogonal heart views: LAO, RAO, and 4 chambers. This new methodology might help to improve the diagnostic value of the ECG, as the interpretation of the mean TSI is easier to be related to the cardiac anatomy, also for less experienced physicians.  
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**Keywords:** Inverse electrocardiography; Non-invasive; iECG; PVC/VT localization

## Introduction

The 12 lead ECG is the standard tool to diagnose the status of the heart. Unfortunately, the advanced ECG interpretation is taught less often by from fewer skilled ECG experts than in the past. Consequently, the interpretation of the ECG is more and more left to ECG machines, resulting in an increasing number of misdiagnoses [1–3]. One way to improve the diagnostic value of the ECG might be to visualize the relation between cardiac anatomy and the ECG signals. Such visualization could support the less experienced ECG reader in relating the ECG wave form morphologies to the atrial or ventricular structures. In this study, an anatomical vector cardiographic method is introduced relating PVC and normal sinus ECG waveforms to the patient specific cardiac anatomy.

The vector cardiogram (VCG) has a history almost as old as the ECG [4,5], with a lot of clinical interest from the 1940s [6,7], until it started to disappear from the clinical field in the 1990s. Currently the vector approach is mainly used to determine the frontal QRS axis and in methods to reconstruct the ECG from limited lead sets, for example the EASI lead system [8,9]. Both the ECG and the VCG suffer from a shortage of well tested algorithms to correct for lead misplacement or take into account the individual heart position. In several studies it was found that the relation between the anatomical heart axis and the mean QRS axis is ambiguous [10,11]. The anatomical heart axis is determined by age and body build. At birth the normal heart has a left right position, i.e. the right chamber is on the right, the left on the left side of the body. Over the years the apex of the heart is rotated upward while bringing the right chamber more forward. The patient specific rotation depends on the space the ribcage offers and the force pushing the heart upward, for instance due to pregnancy or weight increase. The electrical

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heart axis, however, is usually only determined in the frontal plane using the equilateral triangle introduced by Einthoven. This method describes only a part of the 3D rotation of the heart and assumes the heart and the left leg are positioned in the middle of the thorax. Several researchers have tried to correct for the errors caused by the use of the equilateral triangle, for instance, Burger et al., who created an oblique triangle [6,7]. The major problem remained the fact that they assumed a fixed heart orientation for every patient. The reason the electrical axis has limited use in the horizontal or sagittal planes is the fact that the vector direction is extremely sensitive to the ECG electrode placement in close proximity to the heart (V1-V4). Consequently small errors in electrode position can change the electrical heart axis dramatically in the horizontal and sagittal planes.

In this paper, the data from the Cardiac Isochrone Positioning system (CIPS) study [12–14] is used to introduce a novel representation of the VCG signal while correcting for lead placement and heart orientation.

**Methods**

*Patient data collection*

Four patients from the CIPS study were selected for this study, Table 1. In the CIPS study patients were considered eligible when presented to the electrophysiology lab for ablation or electrophysiological study of a ventricular arrhythmia with:

- MRI available, and
- The hearts were structurally normal, i.e. detected scar was less than 10% of the total ventricular volume prior to the procedure.

Each patient signed an informed consent and the study was approved by the UCLA Institutional Review Board (#14–000837). For all four patients, the region of the ventricular arrhythmia origin was determined by electro-anatomical mapping. For the pacemaps the location was described by the operating physician.

For each patient a specific cardiac and torso model were derived from MRI with specific electrode positions obtained from a 3D Kinect camera photo of the chest taken prior to the ablation procedure [12]. The 3D images were then registered

to the patient specific model to allow the accurate positioning of the electrodes on the reconstructed thorax model.

Standard 12-lead ECGs sampled at 977 Hz were recorded during the ablation procedure using Cardiolab (General Electric, Chicago, IL). This system stores the visualized, filtered signal data. From the ECG recorded during the ablation procedure the clinical ECGs containing PVC, VT, or stimulated waveforms were selected and exported from the Cardiolab system for each patient. Fiducial points, i.e. onset and end of the QRS, were determined manually. No additional filtering was applied to any of the used ECG signals.

*The mean temporal-spatial isochrones (mean TSI)*

The mean QRS axis represents the dominant activation direction of the heart, consequently the way the heart is positioned and oriented in the thorax changes this mean QRS axis direction. The VCG represents the mean direction of activation at each time instant of the QRS. The underlying 3D propagating activation front inside the myocardium, can be represented by isochrones on the heart surface [15–18]. This is visualized in Fig. 1a, where the position of the activating surface at  $t = 20$  ms is drawn in grey. The mean or center of this surface is defined as the mean TSI. The activation surface at isochrone 20 ms is pointing in the direction of the activation, i.e. normal to this surface. The mean direction of this 3D surface at this isochrone is approximated by the  $VCG(t = 20$  ms).

In this study the VCG was derived from the ECG while taking the electrode positions into account. The  $\overrightarrow{VCG}$  is computed from the 9 electrodes, building the 12 lead ECG by:

$$\overrightarrow{VCG}(t) = \sum_{el=1}^9 \alpha_{el} ecg_{el}(t) \cdot \frac{\overrightarrow{r_{el}} - \overrightarrow{r_{ref}}}{|\overrightarrow{r_{el}} - \overrightarrow{r_{ref}}|} \tag{4}$$

where  $\frac{\overrightarrow{r_{el}} - \overrightarrow{r_{ref}}}{|\overrightarrow{r_{el}} - \overrightarrow{r_{ref}}|}$  is the normalized vector between a reference position and the electrode position on the thorax. The reference position was initially set to coincide with the center of ventricular mass (CVM). The  $ecg_{el}(t)$  is the value at of the ECG at an electrode at sample t. The correction factor  $\alpha_{el}$  was set to 3 for the unaugmented extremity leads (Vr, VI, and Vf) to correct for the fact that these are further away, and thus with a reduced ECG amplitude. For all other leads the no correction was used, factor was set to 1.

The mean temporal-spatial isochrone (TSI) represents the mean position of the propagating 3D activation surface

Table 1  
The 4 used patient demographics of the CIPS study (UCLA, Los angles); gender, age, weight, height.

Patient ID	Demographics				PVC/PM	Location
	Sex	Age	Weight	Height		
1	m	65	83	1.70	PVC	Right coronary cusp (aorta)
4	f	26	53	1.65	PVC	Left posterior RVOT
					PM	Anterior cardiac vein (epicardial)
8	f	57	60	1.60	PM	Left coronary cusp (aorta)
					PVC	Posteromedial papillary muscle
15	f	80	72	1.60	PVC	Anterolateral papillary muscle

None of these patients had a history of myocardial infarction. Last 2 columns show the type of beat that was used, either PVC or pace map (PM), and the localization of ablation site from the electro-anatomical maps.

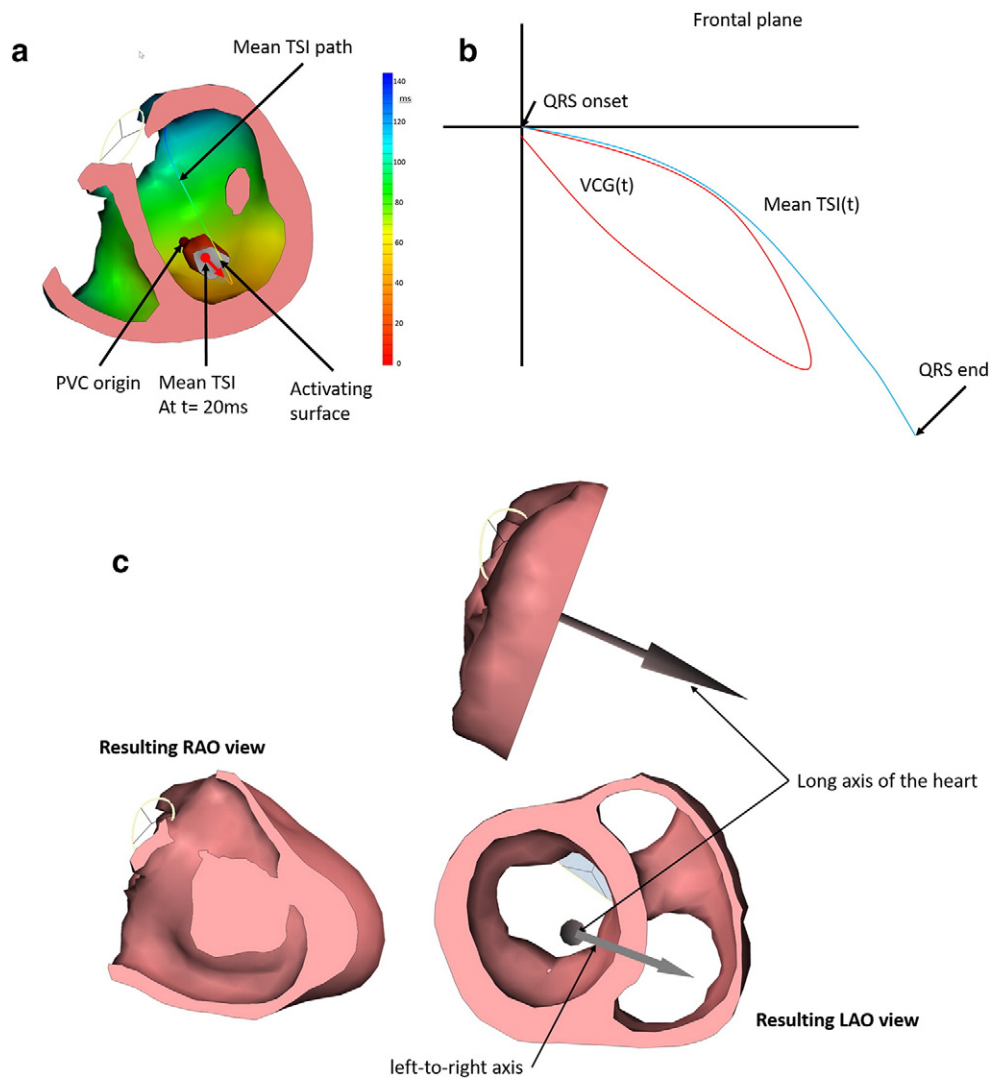


Fig. 1. Panel a): The construction of the mean Temporal-spatial isochrone (TSI) from the activation times on the surface of the heart. The activation surface at 20 ms is shown as the grey surface in the middle of the papillary muscle. The center of this surface is defined as the mean TSI. The direction of this surface (red arrow) is represented by the VCG signals. The relation between VCG signal and derived mean TSI is shown in panel b. The approximated mean TSI moves every ms with a constant velocity in the direction indicated by the VCG. In panel c the relation between the long heart axis and the derived orthogonal planes are shown. The long axis of the heart approximates the plane of the LAO view, the left-to-right axis approximates the ROA view. The 4 chamber view (not shown) is perpendicular to the LOA and RAO plane.

through the heart. However, the mean TSI can also be approximated from the VCG signal. Assuming a homogeneous propagating velocity the change in vector position should approximately move with this velocity in the direction indicated by the VCG signal. Assuming a constant propagation velocity  $v$  in the heart, the *mean TSI* position over time is:

$$\overrightarrow{\text{mean TSI}}(t+1) = \overrightarrow{\text{mean TSI}}(t) + v \cdot \frac{\overrightarrow{\text{VCG}}(t)}{\|\overrightarrow{\text{VCG}}(t)\|},$$

in which the VCG signal is normalized and multiplied by the propagation velocity  $v$  to compute the next mean TSI position (see Fig. 1b). To enable the visualization of the relationship between mean TSI and cardiac anatomy the initial position of the mean TSI needs to be chosen correctly within the cardiac anatomy. In the current study, the mean TSI was computed for ectopic foci, PVCs and pace map, and

normal His-Purkinje activations. For the last one the center of myocardial mass was used as the start position. For the ectopic foci, the position of the focus on the heart was used.

### 2D visualization of the mean TSI

The mean TSI of the QRS should be located inside the ventricular space, i.e. the ventricular myocardium and the included blood cavities. To create 2D representations of the heart, 3 standard orthogonal views were created: LAO (left anterior oblique), RAO (right anterior oblique), and the four-chamber view. As a model of the heart is available in the patient data these views can be automatically created. The LAO view can be approximated by a projection of the heart on a plane defined by the long axis of the heart (Fig. 1c). For the heart models, the long axis was defined as the mean of the mitral and aortic valve (L-valves) to the left

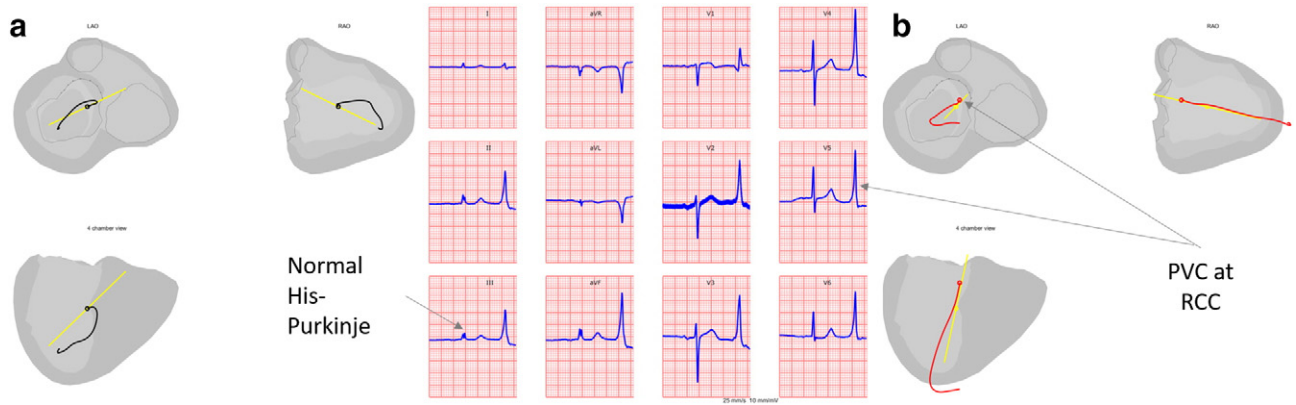


Fig. 2. The mean TSI paths for patient 1. Panel a: the mean TSI of a normal His-Purkinje activation, with a clearly visible transseptal initial part (start is the black circle at the center of heart mass). Panel b: The start of the mean TSI is located at the origin of the PVC at the right coronary cusp of the aortic valve. In the ROA and 4 chamber view it is clear that the mean TSI follows the septum almost straight from base to apex. The yellow line represents the mean QRS axis direction. The yellow circle represents the center of mass of the heart.

ventricular apex. The left-to-right axis was determined as the axis between L-valves and the mean of the tricuspid valve. This axis was used to create the standard ROA view approximation. The third 4 chamber view used the axis perpendicular to the long axis and the left-to-right axis. These orthogonal projection planes were used to project the mean TSI.

## Results

Fig. 2 shows the mean TSI for both a PVC and a normal His-Purkinje activation in patient 1. The PVC originates from the right coronary cusp of the aorta, which can be easily detected from the LAO view of the mean TSI. Notice that the mean TSI predominantly follows the mean QRS axis (yellow line) as the activation is initiated from the base of the heart. The normal His-Purkinje activation shows the initial septal vector very clearly, visible in the LOA and 4 chambers views. The initial septal vector is hardly visible in the RAO view, consequently the activation direction is predominantly from left to right.

Four different activations are visualized for the second patient in Fig. 3. The normal His-Purkinje activations shows same transseptal activation as for patient 1. The mean TSI for the PVC originating from the left posterior RVOT region shows initially an activation moving into the RVOT and then towards the left chamber until the left apical region is reached. The epicardial aspect of the pacemap from the anterior cardiac vein is best seen in the LAO view (Fig. 3c), whereas the mean TSI of the LCC pacemap follows a similar path as the PVC except for the initial part which stays in the left/septal area.

The last two patients show the mean TSI for a PVC originating from the posteriomedial papillary muscle (Fig. 4a) and the anterolateral papillary muscle (Fig. 4b). Notice that the mean QRS axis (yellow line) in both cases crosses the respective papillary muscle. This 2D view thus already helps to discriminate visually the anterolateral from the posteriomedial papillary muscle.

## Discussion

The mean temporal-spatial isochrone is a simple method to compute and display the mean activation path through the heart. In this proof of principle study 6 ectopic and 2 normal His-Purkinje mean TSI paths from 4 patients are presented. The mean TSI paths are plotted in 3 orthogonal heart planes: LAO, RAO and 4 chamber view. By relating the mean TSI to these standardized orthogonal heart planes the anatomical relation between the mean activation path (mean TSI) and relevant cardiac structures becomes clearer than in standard ECG or VCG interpretations. For instance, the cardiac region from which a PVC originates can easily be identified from the mean TSI path (Figs. 2–4). The mean TSI path within the heart model, represented by the 3 heart planes (Figs. 2–4), might support the understanding of the ECG waveforms, as the mean TSI shows the direct relation between cardiac activation and cardiac anatomy.

Traditionally the vector cardiogram is plotted in three orthogonal planes related to the torso. This, however, still leaves the interpretation of the heart orientation influence on the ECG to the physician. Using the 3 orthogonal heart planes might solve this problem, i.e. the physician can directly relate the mean TSI and VCG to the cardiac anatomy. This is both clinically and educationally of importance. In the current study, a patient specific model was used, but our current research shows that the heart orientation might also be estimated from the chest circumference, patient weight and/or height, or a combination of the three.

To show the principle of computing the mean TSI, the origin of the mean TSI is set to the PVC origin location. The example shown in Fig. 2b, the RAO and 4 chamber views, shows clearly a mean TSI path that travels down the septum. The variation in the mean TSI shown in the LAO view is very limited. This is also shown in the PVC and pacemaps shown in Figs. 3 and 4. The mean QRS axis, shown as the yellow line through the center of mass, is followed in at least one of the 3 heart planes, and might be used to identify the region of PVC onset. For the papillary muscle cases, the

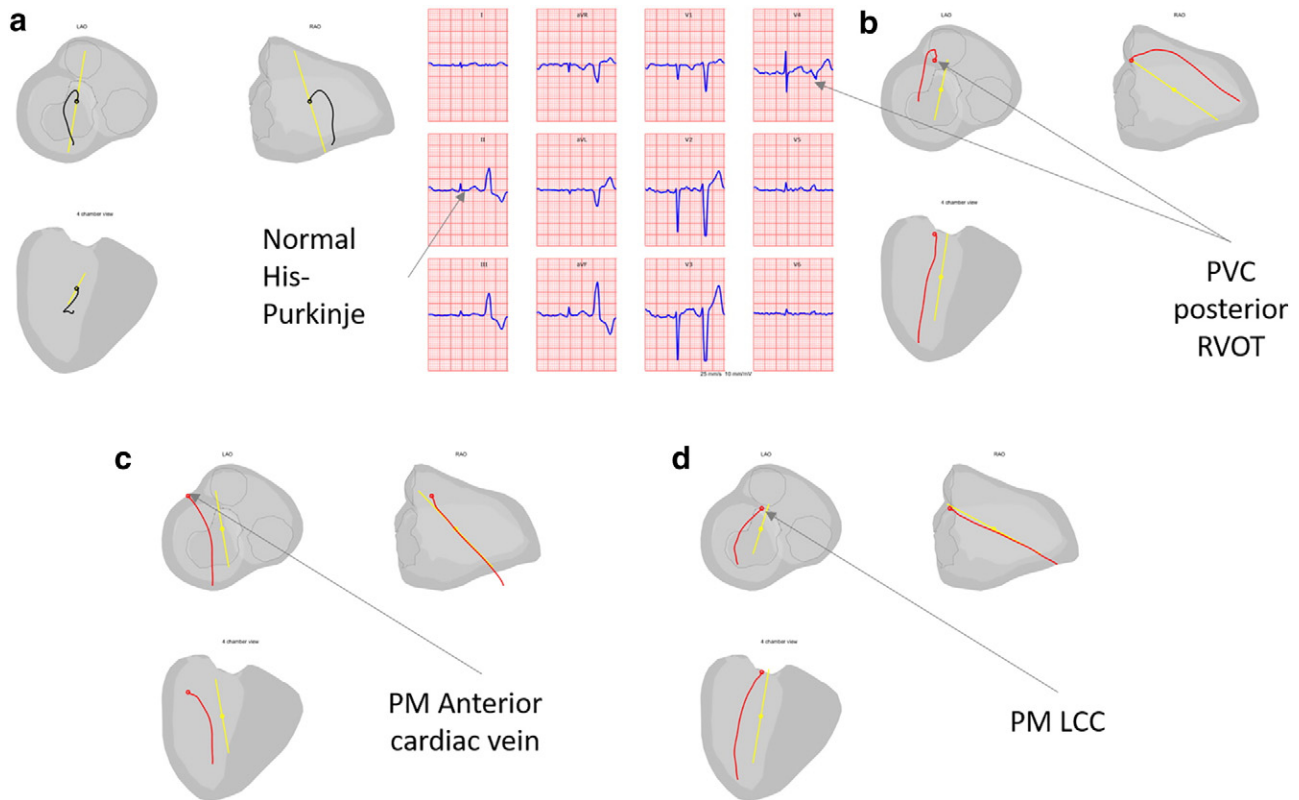


Fig. 3. The mean TSI paths for patient 2. Panel a: the mean TSI of a normal His-Purkinje activation, with a clearly visible transseptal initial part (start is the black circle at the center of heart mass). Panel b: The start of the mean TSI is located at the origin of the PVC at the left posterior RVOT. In the 4 chamber view the mean TSI follows the anterior septum almost straight from base to apex. The initial mean TSI (first 20 ms) is directed towards the anterior aspect of the RVOT. Panel c: The start of the mean TSI is at the epicardium (see LAO view) from where the heart was stimulated. The mean TSI is attracted towards the septum along the mean TSI path. Panel d: This pacemap originates from the left coronary cusp of the aortic valve, so very close to the PVC location (panel b). The mean TSI, however, shows marked differences, especially in the ROA and 4 chamber view. The yellow line represents the mean QRS axis direction. The yellow circle represents the center of mass of the heart.

mean TSI runs from apex to base. The initial part of the anterolateral papillary muscle clearly shows the activation of the papillary muscle, whereas for the posteriomedial this initial part is almost absent, indicating the PVC originates probably more from a basal part of the papillary muscle.

The mean TSI for both normal His-Purkinje activations show paths that are restricted to a much smaller area in the left cavity than the ectopic activations. This was of course expected, as the His-Purkinje activation is initiated from multiple sites, making the mean TSI path change direction opposite to the mean QRS axis.

Computing and displaying the mean TSI is a novel method to visualize the cardiac activation of the heart. Its shape needs much more study, relating known diseased states to mean TSI features. The mean TSI might also be useful in evaluating the presence of left bundle branch block and electrical versus mechanical dys-synchrony in cardiac resynchronization therapy (CRT) patients. The presented mean TSI is explained using the QRS, but might also be applied to the atria, i.e. the P-wave, and maybe even to the T-wave.

### Limitations

This proof of principle study was meant to introduce mean TSI as a method to relate cardiac anatomy with the

mean path of activation of the heart as can be derived from the standard 12 lead ECG. A next study needs to classify the relevant features of the mean TSI for the different PVC and pacemaps available in the CIPS study.

### Conclusions

This proof of principle study showed that the mean path of cardiac activation can be derived from the ECG and related to standard orthogonal heart views: LAO, RAO, and 4 chamber. This new methodology might improve the diagnostic value of the ECG as the interpretation of the mean TSI is easier to be related to the cardiac anatomy, also for less experienced physicians.

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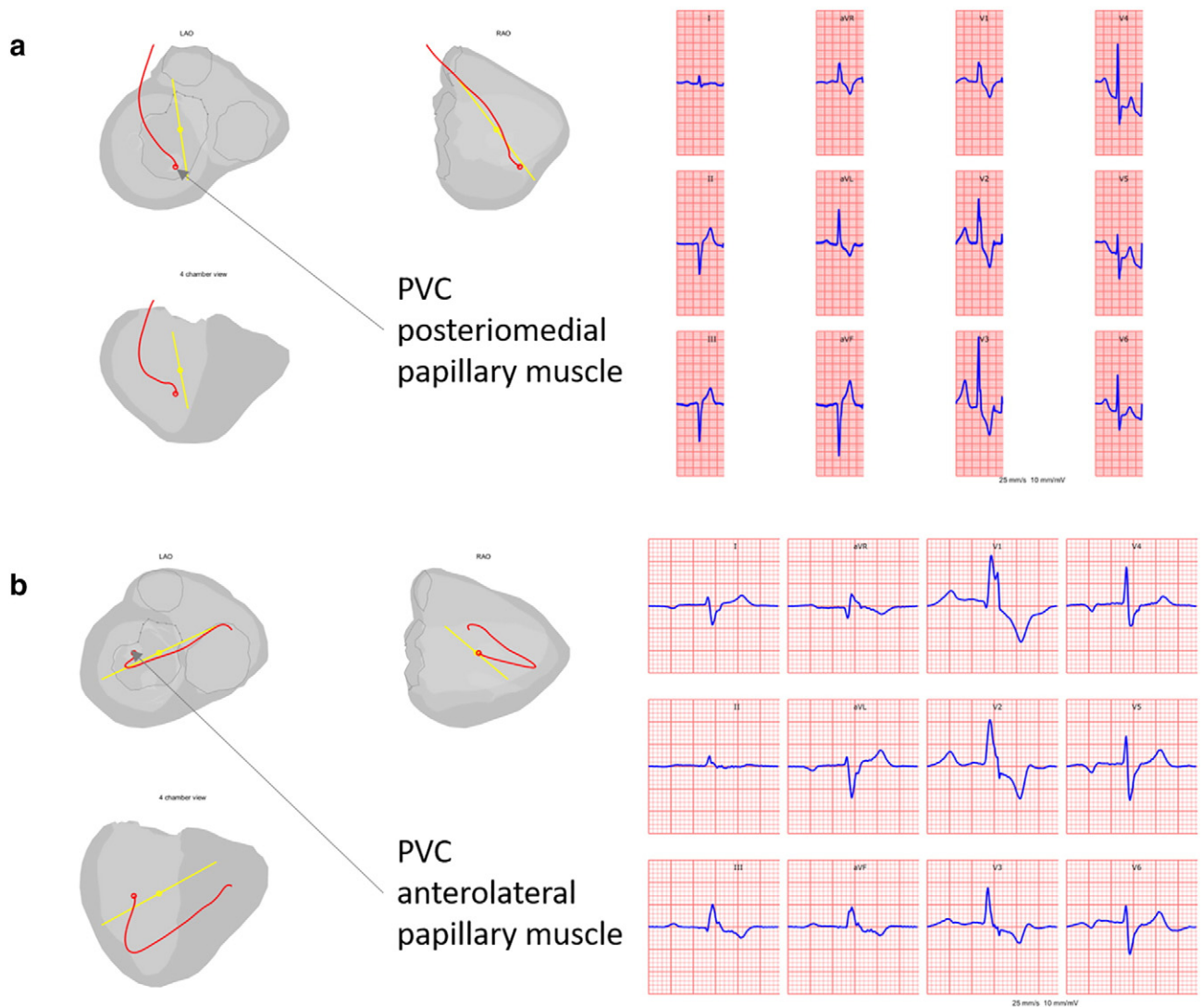


Fig. 4. The mean TSI paths for patient 3 and 4. Panel a: the mean TSI of a PVC originating from the posteriomedial papillary muscle. The initial part of the mean TSI aligns relatively well with the mean QRS axis, which might be caused by an origin of the PVC at the more basal part of the papillary muscle, indicating the origin is most probably located near the apex of apex of the papillary muscle. The yellow line represents the mean QRS axis direction. The yellow circle represents the center of mass of the heart. Panel b: The origin of this PVC is at the anterolateral papillary muscle. The initial part of the mean TSI path approximately follows the papillary muscle, indicating the origin is most probably located near the apex of apex of the papillary muscle. The yellow line represents the mean QRS axis direction. The yellow circle represents the center of mass of the heart.

you so much again Mike, most of all for the numerous times you made me laugh!

Peter van Dam is the owner of Peacs BV.

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