Repolarization Stratification for Dipole Electrocardiotopography

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Abstract. *The dipole component of the heart electric field has been analyzed in the context of distribution of the action potential onset timing and its duration. It has been demonstrated that the process of repolarization can be visualized as a sequence of layers with equal action potential (AP) completion time. Dipole moments of these layers can be calculated from the repolarization part of VCG and visualized as by dipole electrocardiography method (DECARTO) with the use of simple biophysical models. Such presentation will be useful for the analysis of heterogeneity of action potential characteristics in the ventricular myocardium and evaluation of its vulnerability to life-threatening arrhythmias.*

Keywords: Dipolar Electrocardiotopography, Repolarization.

1. Introduction

Association between the heterogeneity of the myocardium repolarization process and its vulnerability to life-threatening arrhythmias has been demonstrated in multiple studies [1, 2]. Moreover, pronounced morphological changes in the repolarization part of the ECG (T-wave) in response to biochemical alterations in the myocardium have been found [3, 4]. A number of T-wave characteristics have been proposed and tested for their diagnostic validity. Basing on these characteristics, new diagnostic criteria have been developed [5-7].

The possibilities of the dipole electrocardiotopography (DECARTO) [8] can be extended by a more detailed analysis of the ventricular repolarization and graphical representation of this process on the spherical quasiepicardium (or image sphere) with the use of simple biophysical models based on three-component vectorcardiograms (measured directly by the vectorcardiographic leads or synthesized from the 12 standard leads).

2. Subject and Methods

Heterogeneity of the repolarization process is primarily determined by the diversity of action potential (AP) duration in the myocardium. The typical shape of AP in the ventricular cardiomyocytes and analytical approximations commonly used in model studies are shown in Fig. 1.

Distribution of AP duration may be calculated from local AP onset and completion timings. Rapid upstroke (duration 1-2 ms) facilitates calculations of the spreading depolarization wave. In DECARTO, it is visualized as a sequence of equivalent spherical double electric layers whose dipole moments are calculated from orthogonal electrocardiograms, whereas the calculation of distribution of AP completion time is much more problematic. During repolarization, VCG is a sum of dipole moments of layers with different values of AP completion time.

The aim of this study was to calculate dipole moments of consecutively turned-off myocardial layers and visualize them similarly to the process of activation. For this purpose, let us consider the process of stratification of the depolarization part of VCG by the moments of AP onset and then turn to analyzing the possibility of stratification of the repolarization part.

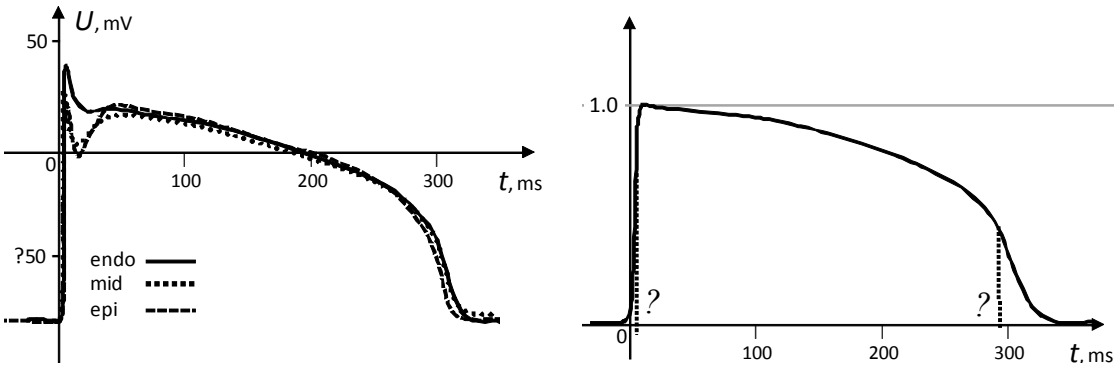

Fig. 1. The action potential of cardiomyocyte (transmembrane potential change when cell is stimulated at time t = 0). On the left, the measured transmembrane action potentials in the endocardium (endo), midmyocardium (mid) and epicardium (epi). The curves are adopted from [9] and aligned by the depolarization onset. On the right, an example of analytical AP approximation used in theoretical and model studies [10].

Depolarization Stratification

The heart vector or dipole moment vector $\mathbf{d}(t)$ at an instant t is expressed as integral of current density $\mathbf{J}(t, \boldsymbol{r})$ over the excitable media region $\mathcal{M}$ ($\boldsymbol{r} \in \mathcal{M}$). For bidomain model of the excitable media, the current density is determined by gradient of the transmembrane potential [11]. Then the result is an expression for the dipole moment:

$$\mathbf{d}(t) = \int_{\mathcal{M}} \mathbf{J}(t, \boldsymbol{r})\, \mathrm{d}v_{\boldsymbol{r}} = -\sigma_{\mathrm{i}} \int_{\mathcal{M}} \nabla \mathrm{U}(t - \tau(\boldsymbol{r}), \kappa)\, \mathrm{d}v_{\boldsymbol{r}}\,;\ \boldsymbol{r} \in \mathcal{M} \qquad (1)$$

where σ_{i} – intracellular conductivity,

$\mathrm{U}(t - \tau(\boldsymbol{r}), \kappa)$, action potential (AP), i.e. the time course of transmembrane potential at point r of myocardium;

τ, the AP onset time, and $\tau(\boldsymbol{r})$ is its distribution over myocardium;

κ, some characteristics of the AP increase rate.

The whole volume of the myocardium may be divided into layers by the time τ of the AP onset. Suppose that κ is always the same for all points in a single layer, i.e. AP upstroke is quite the same for points of the layer, and therefore the potential gradient is zero along the layer. With a suitable choice of curvilinear coordinates in Eq. 1, so that AP upstroke varied along one of them, and remained unchanged along the other, and after simple manipulations, the expression for dipole moment is obtained:

$$\mathbf{d}(t) = -\sigma_{\mathrm{i}} \int_{\mathrm{I}_{\mathrm{QRS}}} \frac{\partial \mathrm{U}(t - \tau, \kappa)}{\partial \tau}\, \mathbf{g}(\tau)\, \mathrm{d}\tau\ ; \quad t, \tau \in \mathrm{I}_{\mathrm{QRS}}\,; \qquad (2)$$

where $\mathrm{I}_{\mathrm{QRS}}$, QRS complex (depolarization) time interval;

τ, as well as above, is the AP onset time;

$\mathbf{g}(\tau)$, dipole moment of the layer τ if potential gradient across the layer equals 1.

AP ascending part is relatively small period of time from the viewpoint of electrocardiography, about 1-2 ms. It can be replaced by Heaviside step function multiplied by AP amplitude, and its gradient across the layer τ is proportional to delta function:

$$\mathbf{d}(t) = a\,\sigma_{\mathrm{i}} \int_{\mathrm{I}_{\mathrm{QRS}}} \delta(t-\tau)\mathbf{g}(\tau)\ \mathrm{d}\tau = a\sigma_{\mathrm{i}}\ \mathbf{g}(t)\,. \tag{3}$$

Functions **d** and **g** coincide up to a constant multiplier. In DECARTO, the ventricular depolarization is presented as a sequence of successively activating double layers of the current sources that are spherical segments with the dipole moments proportional to the equivalent generator **g**(t).

Repolarization Stratification

Equations 1 and 2 can also be applied for the analysis of repolarization with the AP downstroke time θ instead of AP upstroke time τ, repolarization time interval I_{T} instead of time interval $\mathrm{I}_{\mathrm{QRS}}$, and κ to be some characteristics of the AP decrease rate:

$$\mathbf{d}(t) = -\sigma_{\mathrm{i}} \int_{\mathrm{I}_{\mathrm{T}}} \frac{\partial\,\mathrm{U}(t-\theta,\,\kappa)}{\partial\theta}\,\mathbf{g}(\theta)\ \mathrm{d}\theta;\ \ t,\theta \in \mathrm{I}_{\mathrm{T}} \tag{4}$$

AP descending part takes a considerable period of time relatively to the AP duration and all the layers contribute to the heart vector during the repolarization. The summary dipole moment is a convolution of two functions – the t layer dipole moment $\mathbf{g}(t)$ and AP derivative $\mathrm{u}(t,\,\kappa)$:

$$\mathbf{d}(t) = \sigma_{\mathrm{i}} \int_{\mathrm{I}_{\mathrm{T}}} \mathrm{u}(t-\theta,\,\kappa)\,\mathbf{g}(\theta)\ \mathrm{d}\theta = \mathrm{u}^{*}\mathbf{g};\quad \mathrm{u}(t,\,\kappa) = \frac{\partial\,\mathrm{U}(t,\,\kappa)}{\partial t};\ \ t,\theta \in \mathrm{I}_{\mathrm{T}} \tag{5}$$

The deconvolution is needed to present the ventricular repolarization as a sequence of successively deactivating double layers of the current sources that are spherical segments with the dipole moments proportional to the equivalent generator **g**(t).

3. Results

The deconvolution algorithm was developed for the repolarization part of orthogonal ECG to present it as a sequence of successively deactivating double layers in a form similar to the visual graphical representation of depolarization process in DECARTO method [8].

The algorithm solves a nonlinear least squares minimization problem [12] to find both: the approximation for the spline representation of the layer dipole **g**(t) (as function of AP downstroke time), and the AP decrease rate characteristics of an analytical AP time course representation. As deconvolution method is ill-posed, regularization methods are applied.

4. Discussion

The proposed deconvolution algorithm of repolarization stratification needs to be investigated on real clinical data as a diagnostic tool for evaluating the heterogeneities of action potential characteristics in the ventricular myocardium and its vulnerability to life-threatening arrhythmias; diagnostic criteria should be developed and validated.

Acknowledgements

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