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Partial potentials of selected cardiac muscle regions and heart activity model based on single fibres

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ABSTRACT

We present single fibre heart activity model (SFHAM) based on the current flow through the five bunches of fibres of the cardiac muscle (CM). The five effective fibres are identified and assigned to the appropriate segments of CM. Analytical functions describing ionic flows along the fibres are derived and proposed. The parameters determining the shapes and amplitudes of the functions proposed are obtained on the basis of standard 12-lead ECG measurements after numerical fitting procedures concentrating on the QRS-waves. As a consequence, five independent courses of partial, transient potentials are obtained representing: anterior, inferior, lateral, posterior walls, and interventricular septum activities, respectively. Moreover, to check our theoretical results we compare the potentials calculated with those from physical measurements performed on the patient's body surface. We expect that SFHAM will permit detection of pathological changes in particular fragments of CM.

1. Introduction

For classical ECG systems the interpretation of standard electrocardiography signals is usually based on the model introduced by Einthoven. It describes the electric field generated by the cardiac muscle (CM) in terms of a distribution of charges forming an electric dipole. However, there have been many other attempts to describe the heart electric activity in terms of various models. For instance, a more complex structure of charges distributed in the CM volume is proposed by the theory of multipoles [1] permitting analysis of the spatial distribution of potentials appearing around CM [2,3]. Another approach to the electric signals produced by CM is presented in a classical work of Noble [4] based on the Hodgkins–Huxley equations and analysis of potentials in the Purkinje fibre. Very interesting approach to explanation of the heart electrical dynamic is presented in [5] too, where the properties of the cells are described by a function of 23 variables describing 12 types of ionic flows in CM cells. The flows related to the ion transportations (positive, e.g. Na^+, K^+, Ca^{2+} or negative like Cl^-) are nonlinear in character [6–8] and the equations describing their dynamics can be solved only by complex numerical techniques [9]. Analysis of ECG signals is also often performed with the use of various advanced mathematical methods. For instance, Hu et al. [10] described cardiac rhythm using expert systems, whereas neural networks methods have been adapted Minami et al. [11]. Another interesting method has been proposed in [12] where the self-organizing maps have been used. At this point one should also mention the possibility of using the wavelet theory (for instance *see* [13]) or deterministic chaos theory methods [14] in the heart dynamics analysis.

In this paper we propose a single fibre heart activity model (SFHAM). We start our considerations from the definition of the charge waves flowing through the single muscular fibre and then, we extend our considerations to bunches of such fibres spreading across the myocardium. This approach allows a description of the electrical activity of the whole regions of CM and consequently, determination of whether the pathological changes have taken place or not on the basis of standard ECG examination. In particular, we define five effective of fibres (EF) and assign them to the *anterior, inferior, lateral posterior walls* and *interventricular septum*, respectively. In fact, each of these EF corresponds to some real bunches of fibres that are located inside given parts of CM, and these bunches give dominant contribution to the total electric signal of the heart during the depolarization processes. Moreover, contrary to the commonly discussed models of the heart dynamics, SFHAM assumes that partial potentials corresponding to the above-mentioned five regions of CM do not start their evolution simultaneously but in successive moments of time t_a, t_i, t_l, t_p, t_s,

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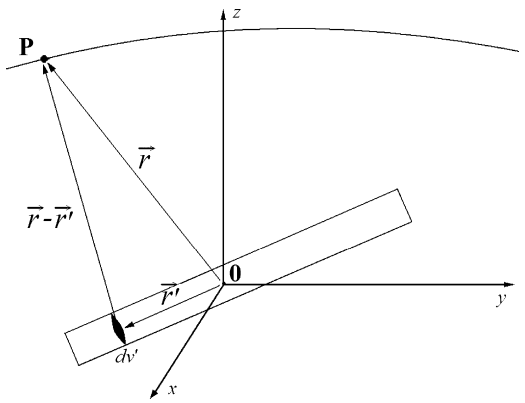

Fig. 1. Exemplary CM fibre and the coordinate system fixed at the centre of the fibre labelled as **0**. Label **P** denotes the point of measurement and dv' denotes an infinitesimally small volume.

respectively. Because of the assumptions made within the model and numerical procedures applied we are able to determine these moments of time. What is important, we are able to determine also other parameters (not only these moments of time) describing the time-evolution of partial potentials—for instance, their amplitudes, or durations. The values of these parameters permit detection of pathological changes in a given part of CM. In particular, we expect that after proper clinical investigation the application of SFHAM will permit diagnosis of coronary heart disease (CHD) or infarction for the patients whose classical ECG examination is inconclusive.

What should be stressed out, in our model we do not consider electrical activities of right ventricle (RV) and atria, since our model concerns the QRS-waves signals only (P and T-waves analysis will be a subject of separate investigations) and hence, we do not take into account depolarization and repolarization processes in atria that are related with the P-wave. Moreover, although the RV is depolarized during the same period of time as the QRS signal is observed, one should keep in mind that the mass of RV is approx. 30% smaller than the mass of the left ventricle (LV). In consequence, electric signals originating from RV are much weaker and broader than those of LV and atria. This fact has been confirmed by the direct measurements performed on the inner and outer surfaces of various fragments of cardiac muscle (for instance, see [15,16]*and the references quoted therein*).

2. The model

What we get from the standard ECG measurement is a time-dependent distribution of the electric potentials at the points located on the surface of the patient's body. The values of such potentials measured originate from the spatial and temporal charge distributions. In our model these charges are related to the charge distributions (and their flows) along single fibres located in CM.

The well known relation between the charge densities and the potential ϕ is given by

$$\phi(\vec{r}, t) = \int \frac{\Delta\rho(\vec{r}'t)}{|\vec{r} - \vec{r}'|}\, dv', \tag{1}$$

where $\Delta\rho(\vec{r}'t)$ is the effective charge density (connected with the cations and anions distributions), dv' is an infinitesimally small volume element and the integration is taken over the whole fibre length. The location of this volume and the point of measurement are determined by the vectors $\vec{r}'$ and $\vec{r}$, respectively. These vectors are defined (at this point) in the coordinate system located at the centre of the single fibre of our interest—see Fig. 1.

One should keep in mind that the properties of the fibre change along its length. Therefore, as it has been done in various papers, we

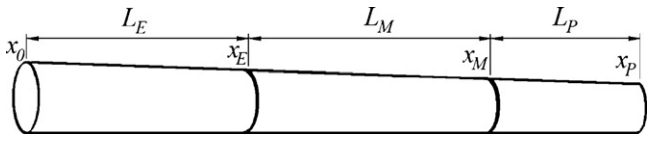

Fig. 2. Single fibre divided into three parts corresponding to *endo-*, internal *myo-* and *pericardial* regions of the lengths L_E, L_M and L_P, respectively.

have divided the fibres discussed onto three parts labelled as E, M and P identified as endo-, internal myo- and peri-cardial regions of the lengths L_E, L_M and L_P, respectively (*see* Fig. 2) [17,18]. Obviously, for a given moment of time these regions are characterized by the charge densities of various values and distributions. Moreover, if we take into account various points on the patient body (P_1 and P_2 in Fig. 3), the superpositions of the potentials from charges related to the regions E, M and P give various values of the potentials (ϕ_1 and ϕ_2) at these points. Note, that for the situation depicted in Fig. 3 we have introduced the parameters $R_{iE}R_{iM}R_{iP}$, $i = \{1, 2\}$ denoting the distances between the points P_i, $i = \{1, 2\}$ and the appropriate regions of the fibre.

From (1) we see that the proper determination of the function describing the charge density distributions (spatial and temporal) is very important. In our model, an increase in the flow of Na^+ ions into the cells causes a change in the positive ρ_+ and negative ρ_- electric charge density in the intra- and extra-cellular areas, respectively. Our further considerations concerning changes in the charge distributions are related to the ionic flows inside the single fibre of CM, and those flows are determined by the conductive properties of the media inside our fibre. Thus, the values of the effective densities $\rho_{\pm\,eff}$ are related to the amount of the charge that appears inside the volume element dv' in the time t and also at some shifted time $t - t_0$:

$$\rho_{\pm\,eff} = \rho_{t\pm} + \rho_{(t-t_0)\pm} \tag{2}$$

We have to take into account the influence of this retardation determined by the time t_0 since, the charge density is related not only to the moving wave-front of the charges at the time t but also to the conductivity of a given part of the fibre (due to this conductivity the charge density given for the earlier time influences the total density determined at a later time we are interested in). It should be stressed that this retardation plays the crucial role in our model. If it is neglected, the densities of negative and positive charges cancel each other leading to the zero value of total charge density. Therefore, in further considerations we shall concentrate on the retarded part of the whole charge density as that giving nonzero contribution to the total density.

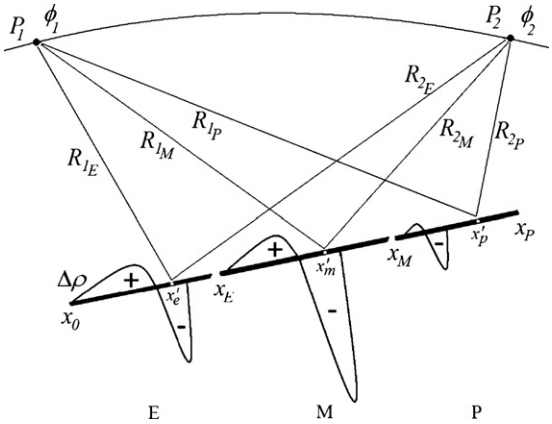

Fig. 3. The effect of charge densities $\Delta\rho$ of individual parts of the CM fibre (labelled as in Fig. 2 by E, M and P) on the electric potentials ϕ_i at the points P_i located on the patient's body surface.