Modeling of Heart Repolarization Using Realistic Action Potentials

M. Tyšler, M. Turzová, J. Švehlíková

Institute of Measurement Science, Slovak Academy of Sciences, Bratislava, Slovakia
Email: umertysl@savba.sk

Abstract. *A computer model for simulation of surface ECG that enables to study heart repolarization changes is introduced. It includes heart geometry and structure description, predefined elemental action potential forms and enables computation of ECG potentials on the surface of an inhomogeneous torso. The influence of the action potentials form on the ST-T part and T-wave of ECG signals is demonstrated.*

Keywords: surface ECG modeling, heart repolarization, action potential of cardiac cells

1. Introduction

While the depolarization process of the heart ventricles is expressed in the QRS complex of the ECG signals and is determined particularly by the spread of the activation of the cells (individual times of their depolarization), the repolarization phase and its expression in the ST-T part of the ECG signals is strongly influenced by the form of the action potential (AP) of myocardial cells. Typical AP form has several parts, main of them are initial rapid depolarization (increase of AP from resting to maximal level), slow repolarization phase (plateau) and a final rapid repolarization phase (Fig. 1b).

Three types of cells with slightly different AP forms and durations were revealed experimentally. The first type was found in the inner, subendocardial layers, the second one in the mid of the wall and the third one in the layers under the outer epicardial heart surface (Fig. 1c). Differences between the APs forms in the endo- mid- and epicardial myocardium layers and transmural distribution of AP duration seem to be important for resultant repolarization process [1] and its projection into surface ECG signals.

When modeling the heart repolariztion process, simplified form of AP is usually supposed and two main parameters can be used its description: AP amplitude defined as the amplitude of the plateau and AP duration usually defined as the interval between the depolarization start and the time instant when the AP drops to 10% of the amplitude of plateau. In this study we employed AP models with different forms, from linear approximation to realistic AP courses with different shapes in endo- mid- and epicardial layers and studied their influence on the surface ECG potentials during ventricular repolarization.

2. Subject and Methods

For better understanding of repolarization process in the heart and possible ways of its changes, finite element model of heart ventricles with elements of $1mm^3$ was employed to simulate normal and pathological cardiac sources. Geometry of ventricles was defined analytically and was based on several ellipsoids. Up to five layers with different properties were defined in both ventricular walls and in septum [2]. Spread of activation was governed by Huygens principle and isotropic myocardial tissue was supposed. Starting points of ventricular activation were set in the endocardial layer with 3 times increased conduction velocity that simulated the role of Purkinje fibers and their positions were in agreement with experimentally observed areas of early activation in normal human heart. Time step of the simulation was equivalent to 3 ms.

Several types of AP forms were considered and resulting body surface potentials were computed. Three types of AP courses in time were used in the study (Fig.1): (a) piecewise linear form, (b) one realistic form and (c) three different realistic forms for endo- mid- and epicardial cells. For realistic AP forms, data measured in canine left ventricular wedge preparation [2] were used. In all simulations, character of experimentally observed transmural distribution of AP duration was preserved. Except of M-cells with the longest AP in the mid layers, AP duration was generally decreasing from endo- to epicardium and transmural dispersion of AP duration was about 40 ms.

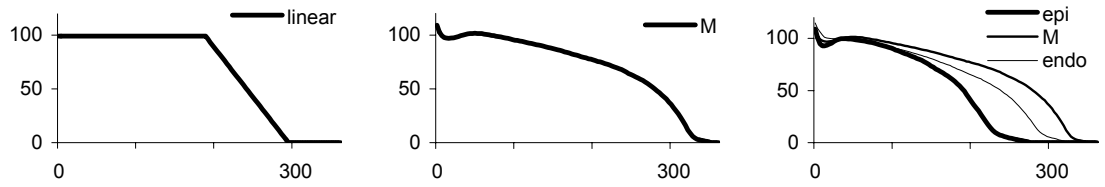


Fig. 1. Three different models of AP forms: a) piecewise linear AP characterized by AP amplitude and duration, b) realistic AP form used throughout the ventricular walls, c) three different realistic AP forms used in different ventricular layers

Equivalent multiple dipole (MD) was used to represent the cardiac electric generator for computation of electric potentials on the surface of a torso volume conductor. Myocardium was divided into 168 segments and activation of each segment was represented by a dipole placed in the weight center of that segment. In every time step of the simulation, each segmental dipole moment was obtained as the sum of dipole moments of elements belonging to the particular segment.

Equivatent cardiac generator was placed into a realistic torso model with basic inhomogeneities. Boundary element method was used for computation of surface potential distribution. Potentials corresponding to particular depolarization-repolarization sequence were computed in 3 ms steps in 198 points on the torso surface. ECG signals in 84 points of a 12x7 surface mapping grid and with 1 ms time step were obtained by linear approximation.

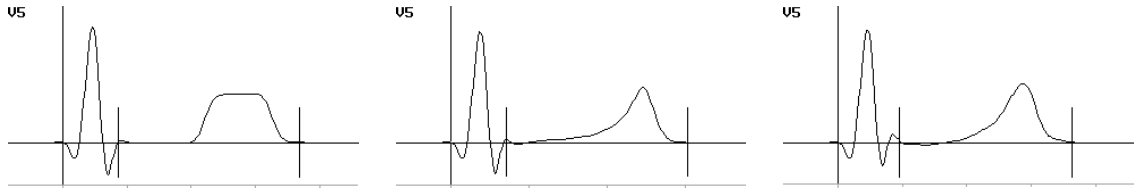
Obtained ECG signals were used to compute body surface potential maps, integral maps and surface distribution of so called activation–repolarization interval (ARI).

Besides normal heart model, also local repolarization changes were simulated. AP duration was shortened by 5 to 25% from the normal value in two typical regions in the left ventricle. The first one (a) was located anteriorly near apex, the second one (b) postero-laterally closer to heart base. Diameters of the regions were 16 to 48 mm and they represented from 1% to 16% of the myocardial volume.

3. Results

At first, the simplest, piecewise linear approximation of AP was used in simulations. AP course was defined by three parameters: AP amplitude, durations of plateau and final rapid repolarization part of the AP (Fig. 1a). With adequately adjusted AP durations in heart layers, simulated potential and integral maps resembled real maps but the shape of T wave in ECG signals was not very realistic (Fig. 2a). This model gives only rough approximation of the repolarization process; however, its main features are preserved. More realistic shapes of T wave (Fig. 2b, c) were obtained if single realistic AP form (Fig. 1b) just with different AP durations in individual layers of the ventricular model was employed. Another improvement

of ECG shapes appeared if three different AP forms (Fig. 1c) were used in particular layers. Their forms and transmural distribution of their durations were derived from experimental measurements [2] Relative differences between these AP forms influenced also the ST-T segment in the ECG signals (Fig. 2c).

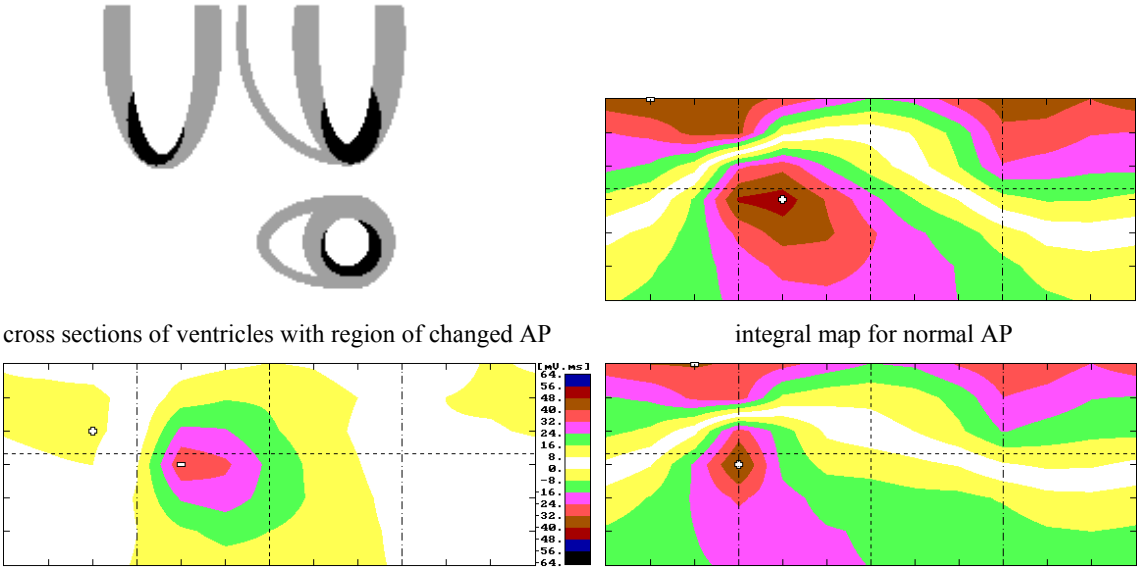


a) b) c)

Fig. 2. Example of simulated surface ECG signals with different T wave shapes corresponding to AP forms shown in Fig.1: a) linear AP, b) single realistic AP form, c) three different realistic AP forms

Similarity between individual simulated and normal measured ECG signals confirmed different degree of ability of the used models to reflect basic relation between the heart activation parameters and simulated ECG potentials. As best results were obtained with different forms of the AP along the transmural direction, this model was used in most experiments where surface potential and integral maps were evaluated.

Projection of local AP changes to surface ECG potentials was studied using body surface potential maps, integral maps and ARI maps. In Fig.3 is an example of simulated surface QRST integral map if the AP was shortened by 20% in a middle sized antero-septal region of the left ventricle. AP shortening is clearly projected on the near-by left anterior torso surface as decrease of the integral. Position, size and amplitude of differences in shown maps reflect the location, dimension of region and degree of AP changes.



cross sections of ventricles with region of changed AP

integral map for normal AP

difference integral map

integral map for locally shortened AP

Fig. 3. Projection of local AP shortening in an antero-septal region into surface QRST integral maps. In the difference map, decrease of integrals can be seen on the left anterior and partially also posterior torso.

4. Discussion

Advantage of presented computer model of ventricular depolarization-repolarization process is its simplicity. It takes into account major factors influencing this process and can be easy implemented. More complex models can yield even more realistic results but on the other hand, influence of too many factors can be hard to manage and understand.

Our model does not simulate processes on the cellular and sub-cellular level; instead, input information on AP form throughout the myocardium is necessary. Systematic in-vivo measurements of cardiac AP distribution exist for some animal hearts (canine, pig). For human hearts, only measurements from several heart regions and from isolated myocyties are available. However, it is known that AP parameters may significantly vary in isolated cells and in-vivo conditions. For example, in intact heart AP are shorter probably due to electrotonic coupling between cells and transmural dispersion of AP changes from about 100 to 30 ms in the left free wall. Careful adjustment of AP duration, as well as other AP characteristics is therefore necessary to obtain realistic results of simulations.

Major limitation of the model is omission of myocardium anisotropy. As reported elsewhere, this can cause inaccuracy of simulated potentials that should be considered when interpreting the results. Other limitations are the size of modeled elements relatively to the ventricular wall thickness and corresponding time step in the simulations that can be too rough to represent some details of the activation process.

5. Conclusions

Presented ECG simulation model enables detailed specification of AP form and duration. This gives the possibility to study surface potentials during ventricular repolarization that might be influenced by pathological changes of AP shape.

Despite the fact that the model can represent just some approximation of real repolarization, it may help to select parameters of surface potentials that are sensitive to expected AP changes. However, because of limitations of the model, validity of the obtained results has to be verified on real data.

Acknowledgements

This work was supported by grant 2/1135/21 from the VEGA grant agency.

References

[1] G. R. Li, J. Feng, L. Yue, M. Carrier. Transmural heterogeneity of action potentials and Ito1 in myo-cytes isolated from the human right ventricle. *Am J Physiol*, 275: H369 – H377, 1998.

[2] G.X.Yan, W.Shimizu, Ch.Antzelevich. Characteristics and distribution of M cells in anterially perfused canine left ventricular wedge preparations. *Circulation*, 98: 1921-1927, 1998.

[3] V. Szathmáry, I. Ruttkay-Nedecký. Model study of effects of different repolarization patterns in the left and right ventricle on the resultant cardiac vectors. In: Electrocardiology 2000*,* 2001, 97-102.