

ECGSIM: Interactive Simulation of the ECG for Teaching and Research Purposes

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Abstract

The expression of the electric activity of the heart in the ECG waveforms is complex. The understanding of this relation can be facilitated by using an interactive tool that enables the user to introduce changes in the electrical activity of the heart and to observe the effect on the ECG. **ECGSIM** (version 1.3) is such an interactive simulation tool. It has been found to be effective both in teaching and basic research. A new version (2.0) of **ECGSIM** is introduced, in which the expression of atrial activity has been included and the functionality has been extended.

1. Introduction

The expression of the electric activity of the heart in the ECG waveforms is complex. Since Einthoven's day[1], the development of diagnostic ECG criteria has been accompanied by the development of biophysical models aimed at linking the electrophysiology of cardiac function with the waveforms of the ECG signals observed on the body surface. In such an approach two aspects of the bioelectric generator need to be specified, a source model of the cardiac electric activity, as well as a model for describing the passive effects on the observed data of the body tissues that surround the active electric sources: a volume conductor model. The understanding of the electrical activity of the heart and its phenomena recorded on the body surface can be facilitated by using these models.

ECGSIM is such a simulation tool. It enables the user to interactively introduce changes in the electrical activity of the heart and observe their effect on the ECG. Its development started in the early 1990s, with an initial (dos) version released in 1993 [2]. The first windows/mac version appeared in 2002 [3].

This contribution describes the latest version (2.0), which is the result of a redesign of the software and the inclusion of several new options. Whereas the earlier release was restricted to the simulation of the signals resulting from the electric activity of the ventricles (the QRST segment), version (2.0) includes the option of

simulating atrial activity. Moreover, the spatial resolution of the geometries involved has been increased more than fivefold and their realism has been improved. The geometries of different (patient) cases may be uploaded into the program, enabling teaching and research of patient specific phenomena. Currently the data of three normal subjects are provided as well those of one WPW patient. The new features will enhance the applicability of this tool in education and research.

In this paper, a brief summary is given of the basis of the simulation and the basic use of the **ECGSIM** tool. The emphasis lies on the presentation of some of the latest options. A more complete documentation can be found in the manual of **ECGSIM**, which is included in the software that can be downloaded, free of charge, from www.ecgsim.org.

2. Methods

ECGSIM is based on a biophysical model that links the local transmembrane potential (TMP) at the surface of the myocardial tissue to the ECG at the body surface. It includes atrial, ventricular and torso geometries, reconstructed from human MR images.

The source model used in the simulation is the equivalent double layer (EDL). This model expresses the entire electrical activity within the atria or ventricles by means of a double layer source situated on the closed surface bounding either the atrial or the ventricular myocardium: epicardium, endocardium and base. Both surfaces are discretized by triangular meshes, the vertices (nodes) of which are carrying the elementary electric sources. In version (2.0) as many as 1500 nodes specify each of these geometries.

For any position on the surface (node), the time course of the local source strength is taken to be proportional to the TMP, $V_m(t)$, of the nearby myocytes [4,5,6].

The transfer between the EDL source elements and the potentials on the thorax is dominated by the position and orientation of the heart inside the thorax, the

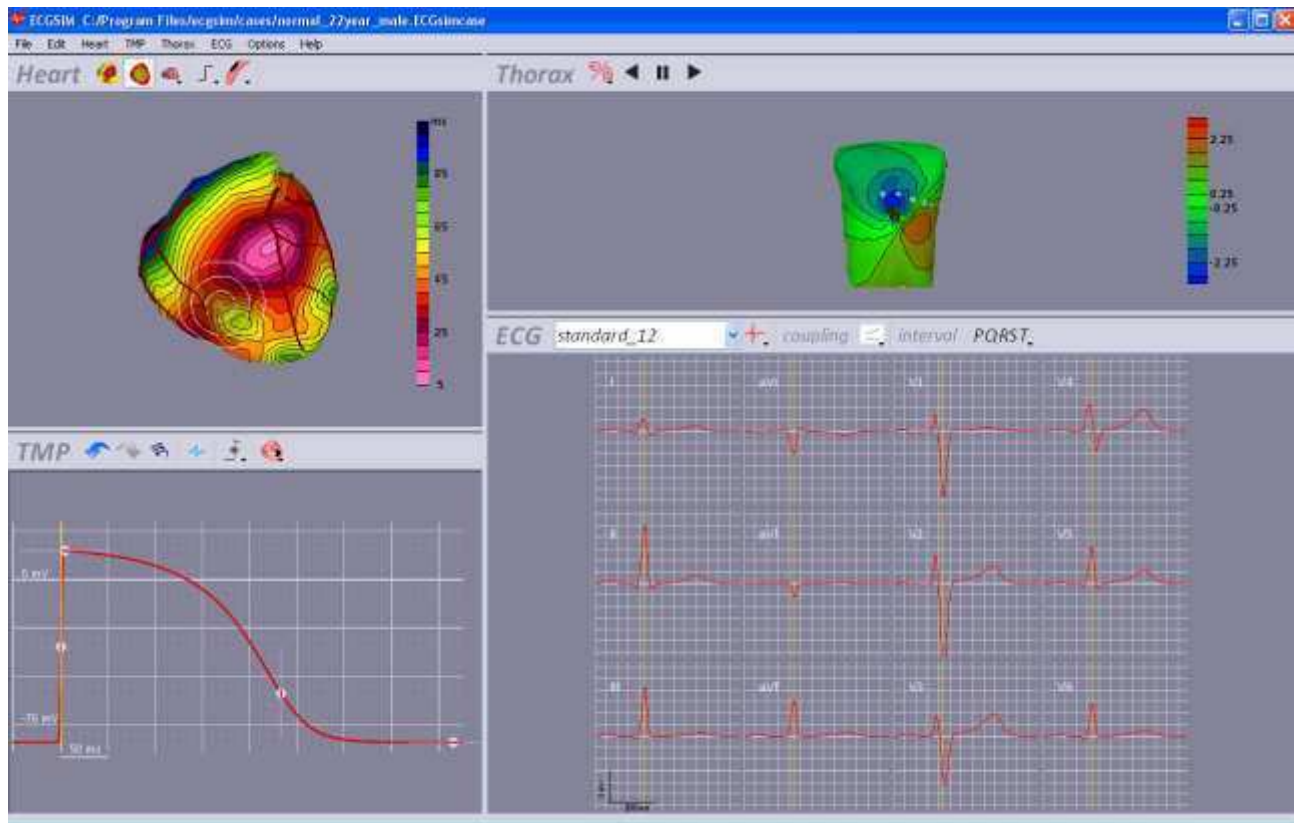


Figure 1 The main window of ECGSIM, comprising 4 panes; **Upper-left:** the Heart-pane, in which either the atrial or ventricular geometry can be shown. Note the single node highlighted and the shaded region around it, the significance of which is explained in the text. **Lower-left:** the TMP-pane, the TMP (EDL-source strength) assigned to the node highlighted on the Heart-pane. **Lower-right:** the ECGs-pane, displaying the standard 12-lead ECG simulated on the basis of a distribution of TMPs over the heart surface. **Upper-right:** the Thorax-pane: a frontal view of the thorax, on which the simulated body surface potential map (BSPM) is displayed corresponding to the time marked by the yellow vertical line in ECG traces shown on the ECGs-pane.

position of the electrodes on the thorax, and the overall geometry of the thorax. Other major factors used are those regions that have an electric conductivity that is substantially different to that of the neighboring tissue, e.g. the relatively high conductive blood and the relatively low conductive lungs. In ECGSIM 2.0, seven parameters are used to describe the TMP analytically: 1) the depolarization time, 2) the repolarization time, 3) the resting potential, 4) the maximum amplitude, 5) the depolarization slope, 6) the plateau slope and 7) the repolarization slope (left-lower pane Figure 1). The user may change any of these parameters at any section of the heart surface or globally; the effects of such changes on the ECG are displayed instantaneously.

3. Using ECGSIM

Upon installing the ECGSIM software a window comes into view, consisting of four sections referred to as “panes” (Figure 1).

The upper-left pane (the Heart-pane) may be used for displaying the distribution over the heart surface of the

EDL parameters, such as the timing of local depolarization, or the instantaneous potential distribution generated.

The lower-left pane (the TMP-pane) displays the wave form of the EDL source strength assigned to any node selected on the Heart-pane. The waveform can be varied by changing any of the seven parameters, induced by dragging the corresponding double arrow handle. In addition, the local electrogram at the surface node may be viewed. The parameter changes induced in this way are applied to a region, indicated by the white circles around the selected node in the Heart-pane. The region affected may be restricted to the surface section carrying the selected node (say, the epicardium), or extended to the surface section facing it (say, the endocardium). The spatial extent of the induced parameter change as well as its decay across its border may be specified by setting the slope of a transition function (Figure 2). A separate option is included for inducing global changes to any of the parameters.

The signals on the body surface (ECGs or VCGs) generated by any set of source parameters may be viewed on the right-lower pane (the ECGs-pane). These

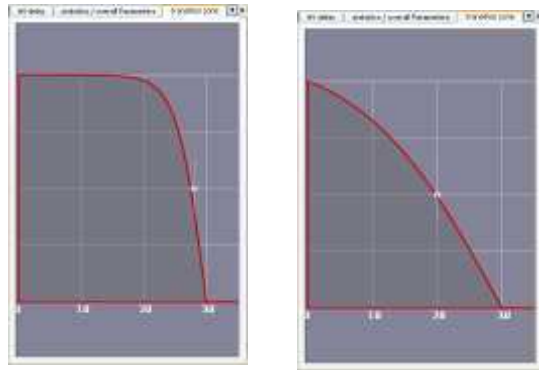


Figure 2 Two examples of the function scaling the decay of an imposed parameter change as a function of the distance to the node to which the change is applied.

may be compared to any set of recorded signals, by superimposing these to the simulated ones.

The simulated body surface potential distributions corresponding to the source parameters, or the measured ones, may be viewed on the right-upper panel (the Thorax-panel).

The distributions may be viewed either as a “map” at the time indicated selected in the ECGs-pane (yellow bar) or animated as “movies”.

The views on geometries shown in the upper panes may be changed interactively.

4. Some examples

As mentioned, any of the 7 source parameters can be displayed on the heart surface in the heart pane. An example of this of is presented in Figure 3. It depicts the MRI-derived geometries of the atria and the ventricles of the healthy subject studied, a 22 year old male, both shown in the natural, anterior view, albeit on a different scale.

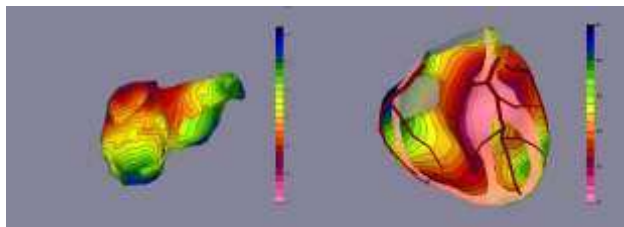


Figure 3 Image copied from the Heart-pane. The timing of depolarization on the atrial (left) and ventricular (right) surface used in simulating the normal ECG. The ventricle is partly shown in a cross-section to enable the endocardial view. The 3 major coronary arteries, displayed in dark red, are included for keeping track of the orientation while rotating the geometries.

The function shown is the timing of depolarization of the surfaces, both with reference to the separate onsets of activation of both heart sections.

The traces shown on the ECGs-pane of Figure 4 depict the simulated 12-lead ECG of this subject. The timing of depolarization and repolarization of the atria and the ventricles were obtained by means of dedicated inverse procedures [7]. In addition, for the sake of evaluating the realism of the simulation, traces in blue are depicted, which represent the measured ECGs.

In Figure 4, another representation of the same cardiac electric activity is presented: the vectorcardiogram (VCG).



Figure 4 Image copied from the ECGs-pane. In red: the 12-lead ECG as simulated; in blue: the 12-lead ECG as measured on the healthy subject studied.

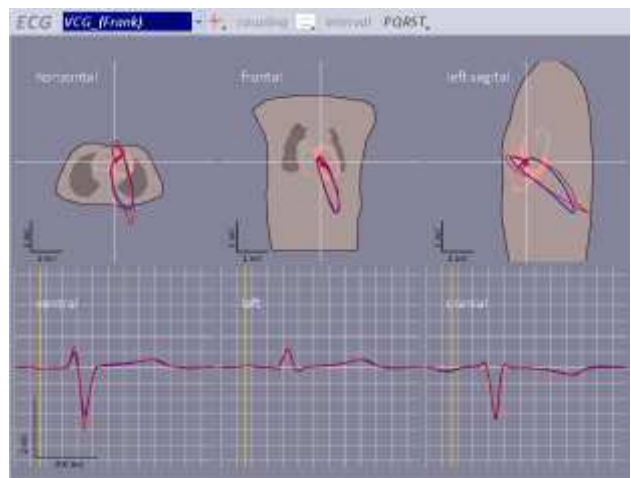


Figure 5 Image copied from the ECGs-pane. Vector cardiographic representation of the same data: vector loops projected on the horizontal, frontal and left sagittal planes, as well as their projections on the three orthogonal axes, usually referred to as the X, Y, and Z lead signals. Color coding of the signals as in Figure 4. The VCG loops are shown on the corresponding cross-sectional planes.

Note the close correspondence between the measured data and those based on the data simulated by means of the EDL model (Figures 4 and 5).

As a special option, each node selected on the heart surface may be given the status of a “focus” of electric activity. After setting the timing of the local initiation of focal activity, the activation sequence generated from this focus, spreads out over the entire myocardium at a selectable propagation velocity. This sequence may be studied as such, or merged with an activation sequence arising from a different origin. An example of a simulated ectopic beat is shown in Figure 6. Here, a focus has been placed on the left atrium near one of the left pulmonary veins. Note the effect on P wave morphology.

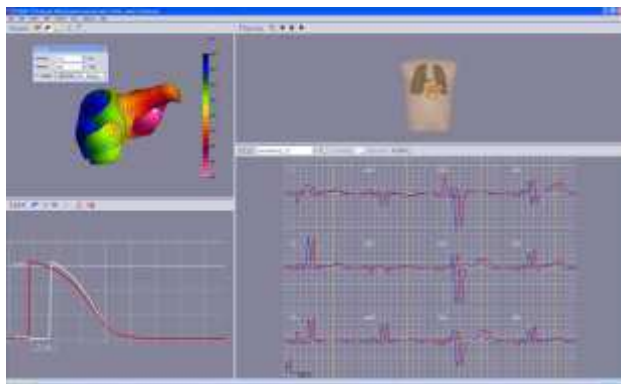


Figure 5 Image copied from the ECGSIM window. The timing of depolarization on the atrial originating from a single focus near the one of the pulmonary veins. Distinct differences are visible between the normal (blue) and simulated (red) ECGs.

5. Discussion

The close correspondence between the measured data and those based on the data simulated by means of the EDL model (Figures 4 and 5) is a necessary, but not sufficient, indication of the general validity of the EDL in this particular application. It depends more critically on the realism of the major default parameters used: those setting the timing of local depolarization and repolarization. The timing of depolarization of both atria and ventricles (timing of maximal upstroke velocity of the upstroke of the TMP) are in qualitative agreement with those reported in the literature. For the timing repolarization, taken to be the inflection point of the TMP during the final part of repolarization, no complete

data are available. However, starting from a setting in which simulated and recorded body surface potentials are in close agreement, the effect of subsequently induced change in the setting of any of the source parameters is highly reliable.

An alpha-version of ECGSIM(2.0) is currently available on the website indicated above. The official release will follow this year (2010). All of the (approx. 5000) groups that have downloaded the previous release will be notified of the new release.

Acknowledgements

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