Mathematical modelling of the action potential of human embryonic stem cell derived cardiomyocytes

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Abstract

BACKGROUND: Human embryonic stem cell derived cardiomyocytes (hESC-CMs) hold high potential for basic and applied cardiovascular research. The development of a reliable simulation platform able to mimic the functional properties of hESC-CMs would be of considerable value to perform preliminary test complementing in vitro experimentations.

METHODS: We developed the first computational model of hESC-CM action potential by integrating our original electrophysiological recordings of transient-outward, funny, and sodium-calcium exchanger currents and data derived from literature on sodium, calcium and potassium currents in hESC-CMs. RESULTS: The model is able to reproduce basal electrophysiological properties of hESC-CMs at 15-40 days of differentiation (Early stage). Moreover, the model reproduces the modifications occurring through the transition from Early to Late developmental stage (50-110, days of differentiation). After simulated blockade of ionic channels and pumps of the sarcoplasmic reticulum, Ca2+ transient amplitude was decreased by 12% and 33% in Early and Late stage, respectively, suggesting a growing [...]
Mathematical Modelling of Electrotonic Interaction between Stem Cell-Derived Cardiomyocytes and Fibroblasts

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Abstract

Human embryonic stem cell-derived cardiomyocytes (hES-CM) represent a promising tool for cell therapy and drug screening. We developed a hES-CM mathematical model based on data acquired with electrophysiological and RT-PCR techniques. Coupling with modelled fibroblasts was assessed too. hES-CM model reproduced satisfactorily most of the action potential (AP) features. Coupling with fibroblasts shows an increment of slope of diastolic depolarization and beating frequency and reduction of the AP peak. These results suggest that our novel mathematical model can serve as a predictive approach to interpret and refine in-vitro experiments on hES-CM.

1. Introduction

Human embryonic stem cell-derived cardiomyocytes (hES-CM) represent an interesting and promising tool for regenerative medicine and drug screening. For these aims in vitro characterization of this lineage is mandatory and useful experimental approaches are represented by different electrophysiological and molecular techniques as current voltage mesurements on sigle cells and embryonic body and RT-PCR. A complementary approach to analyse hES-CM function resides in developing a mathematical model of their action potential. A better scenario would be also represented letting the single hES-CM interact with one or more human fibroblasts, conveniently modelled: this would allow studying the interaction between these two kinds of cells in terms of electrotonic coupling and modifications of the hES-CM AP shape. This approach has been extensively used for human [2,3] and rat [4] adult cardiomyocytes. One of the newest aspects of this work is the development of specific AP model for hES evolving into cardiomyocytes, showing a spontaneous beating activity. According to this prospective AP properties of hES-CM model, eventually coupled with one or more in silico fibroblasts, were analysed.

2. Methods

2.1. Experimental data

The hES-CMs in their early developmental stage (15 - 40 days) were characterized with a combination of electrophysiological (single cell patch- clamp and multicellular recordings) and RT-PCR techniques. These experiments led to the characterization of transient outward current \( I_{to} \), delayed rectifier current \( I_{Kr} \), f-current \( I_f \), inward rectifier \( I_{K1} \) and L-type current \( I_{CaL} \). More information about the experimental protocol and the single currents characterization can be found in [5, 6]. Data about the other ionic currents were derived from [7–10].

2.2. Modelling the hES-CM

Experimental data were integrated into a modified version of the Ten Tusscher model of human cardiomyocyte (TT04) [1, 11]. Matching the model currents to the experimental data required a refined tuning of parameters since currents are not expressed as in a human adult cardiomyocytes till the development is not terminated. Moreover the hyperpolarization-activated \( I_f \), not present in adult ventricular cardiomyocytes, was incorporated following the Hodgking-Huxley formulation with a single activation gate \( x_f \), maximal conductance \( G_f \) and Nernst potential \( E_f \):

\[
I_f = G_f \cdot x_f \cdot (V - E_f)
\]

This led to an auto-oscillating cell model with no pacing required, whose AP is expressed by the classical equation:

\[
\frac{dV}{dt} = \frac{-I_{ion}(V, t)}{C}
\]

where \( I_{ion}(V, t) \) represents the sum of the \( K^+ \), \( Na^+ \) and \( Ca^+ \) currents flowing through the membrane and \( C \) the hES-CM capacity. Using this model several AP features were calculated as shown in table 2.
Table 1. Maximal conductances and currents incorporated in the model to simulate the action potential of the hES-CM.

<table>
<thead>
<tr>
<th>$G_{i,\text{max}} / I_{i,\text{max}}$</th>
<th>hES-CM</th>
<th>Adult</th>
</tr>
</thead>
<tbody>
<tr>
<td>$I_{to}$</td>
<td>49.19</td>
<td>294 S/F</td>
</tr>
<tr>
<td>$I_{Kr}$</td>
<td>384</td>
<td>96 S/F</td>
</tr>
<tr>
<td>$I_{f}$</td>
<td>33.6</td>
<td>– S/F</td>
</tr>
<tr>
<td>$I_{K1}$</td>
<td>678</td>
<td>5405 S/F</td>
</tr>
<tr>
<td>$I_{CaL}$</td>
<td>0.044</td>
<td>0.175 L/(F·s)</td>
</tr>
<tr>
<td>$I_{Na}$</td>
<td>979</td>
<td>14838 S/F</td>
</tr>
<tr>
<td>$I_{Ks}$</td>
<td>1.57</td>
<td>157 S/F</td>
</tr>
<tr>
<td>$I_{NaCa}$</td>
<td>6000</td>
<td>1000 A/F</td>
</tr>
<tr>
<td>$I_{NaK}$</td>
<td>0.409</td>
<td>1.362 A/F</td>
</tr>
<tr>
<td>$I_{pK}$</td>
<td>–</td>
<td>14.6 S/F</td>
</tr>
<tr>
<td>$I_{up}$</td>
<td>0.013</td>
<td>0.425 mM/s</td>
</tr>
<tr>
<td>$I_{rel}$</td>
<td>12.4</td>
<td>24.7 mM/s</td>
</tr>
<tr>
<td>$I_{leak}$</td>
<td>0.03</td>
<td>0.08 1/s</td>
</tr>
</tbody>
</table>

Figure 1. Electrical representation of passive fibroblasts and coupling with hES-CM.

2.3. Interaction with in silico Human Fibroblast

AP registrations were not performed on single cells but on embryoid bodies, aggregates containing different cell phenotypes among which hES-CM and fibroblasts. Therefore, an additional human fibroblast model, to couple resistively to the hES-CM, was developed following two different implementations. The aim is testing the interaction between these kinds of cells and trying to fit better the AP features. The electrical representation of the coupled model is shown in figure 1. Equation 2 was therefore modified as follows:

$$\frac{dV}{dt} = -\frac{1}{C} \cdot [I_{\text{ion}}(V, t) + N_f \cdot I_{\text{leak}}]$$ (3)

where

$$I_{\text{leak}} = G_{\text{gap}} \cdot (V - V_c)$$ (4)

$V_c$ is the fibroblast potential, $G_{\text{gap}}$ is the conductance of the hES-CM - fibroblast coupling and $N_f$ the number of coupled fibroblasts. The fibroblast AP evolves according to

$$\frac{dV_c}{dt} = -\frac{1}{C_c} \cdot [I_c(V_c) - I_{\text{leak}}]$$ (5)

where $C_c$ represents the fibroblast capacity and $I_c$ the transmembrane current. First, a model of passive fibroblast was developed according to [2–4] with MacCannell’s parameters: $G_{\text{gap}} = 3$ nS, $C_c = 6.3$ pF, $R_{fib} = 10.7$ GΩ and $E_f = -20$ mV. A second model of active fibroblast was implemented replacing $I_c(V_c)$ with the sum of the four time-voltage dependent currents identified by MacCannell and others ($K^+$ current $I_{Kv}$, Inward rectifying $K^+$ current $I_{K1}$, $Na^+$+$K^+$ pump current $I_{NaK}$, and Background $Na^+$ current $I_{b,Na}$) [2]. Equations and parameters are the same of the cited article, except for the Background $Na^+$ current conductance $G_{b,Na}$ changed from 0.0095 nS/pF to 0.0032 nS/pF. We set this parameter in order to equal the integrated $Na^+$ influx through the leak pathway to the $Na^+$ efflux through the $Na^+$+$K^+$ pump. We assume this discrepancy caused by differences in the cardiomyocyte model, since we used a modified version of Ten Tusscher model [11].

3. Results

3.1. hES-CM Model

Table 1 shows the results of hES-CM parameter identification compared to the adult cardiomyocyte ones. Using these parameters we found that AP mimic satisfactorily the recorded ones as shown in figure 2 so AP features were calculated as shown in table 2, column Exp.

The proposed model of hES-CM was able to reproduce the experimentally observed AP morphology as shown in figure 2. The AP features measured on the experimental data were recalculated on the hES-CM simulated AP and reported in table 2, column Simulations - Uncoupled. Most of the simulated features shows a satisfactory matching to the real ones but MDP, APA and DDR are not good enough. Since the experimental data were acquired from intracellular recordings on embryoid bodies where non excitable cells are present together with hES-CM [5], we decided to test our cardiomyocyte model coupled with some fibroblasts, as shown in the next section.

3.2. Coupling with Fibroblasts

Before assessing the results of our model in terms of AP features, some verifications were made in order to test its correctness. First we verified the electrotonic coupling
Table 2. Features of experimental (Exp) and simulated AP. Simulations have been performed using the model of one single hES-CM uncoupled and coupled both with passive and active fibroblasts. $N_f$, number of coupled fibroblasts; APD, action potential duration; MDP, maximum diastolic potential; APA, action potential amplitude; DDR, diastolic depolarization rate; F, frequency; bpm: beats/min. Bold font reports simulated results not matching the experimental data.

<table>
<thead>
<tr>
<th></th>
<th>Exp</th>
<th>Uncoupled</th>
<th>Passive Fibroblast</th>
<th>Active Fibroblast</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$N_f = 0$</td>
<td>$N_f = 1$</td>
<td>$N_f = 2$</td>
</tr>
<tr>
<td>$APD_{30%}$ (ms)</td>
<td>115±7</td>
<td>110</td>
<td>111</td>
<td>115</td>
</tr>
<tr>
<td>$APD_{50%}$ (ms)</td>
<td>167±10</td>
<td>166</td>
<td>168</td>
<td>175</td>
</tr>
<tr>
<td>$APD_{70%}$ (ms)</td>
<td>199±11</td>
<td>202</td>
<td>207</td>
<td>213</td>
</tr>
<tr>
<td>$APD_{90%}$ (ms)</td>
<td>228±11</td>
<td>231</td>
<td>237</td>
<td>246</td>
</tr>
<tr>
<td>$V_{max}$ (mV/s)</td>
<td>4216±611</td>
<td>4778</td>
<td>4965</td>
<td>4825</td>
</tr>
<tr>
<td>$MDP$ (mV)</td>
<td>-47±7</td>
<td>-79</td>
<td>-79</td>
<td>-78</td>
</tr>
<tr>
<td>$APA$ (mV)</td>
<td>63±5</td>
<td>92</td>
<td>91</td>
<td>90</td>
</tr>
<tr>
<td>$DDR$ (mV)</td>
<td>22.8±5.8</td>
<td>13</td>
<td>20</td>
<td>28</td>
</tr>
<tr>
<td>$F$ (bpm)</td>
<td>36±6</td>
<td>35</td>
<td>51</td>
<td>61</td>
</tr>
</tbody>
</table>

Figure 2. Experimental (left panel) and simulated (right panel) uncoupled hES-CM AP.

between hES-CM and fibroblasts as reported in literature [12]. In figure 3 two different APs arisen in a fibroblast coupled to the cardiomyocyte are shown. Increasing the coupling conductance $G_{gap}$, the fibroblast AP mimics the cardiomyocyte one in a more refined way, as reported in [2, 3]. A second check concerned about the $I_{leak}$ flowing between cardiomyocyte and fibroblast. As shown in figure 4 it is negative (flowing from fibroblast to cardiomyocyte) during diastolic phase, increasing the cardiomyocyte AP slope, while it is positive (from cardiomyocyte to fibrob- last) during the sistolic phase so representing a new repolarizing term. This caused on one side a more steep diastolic phase and an increase of the frequency, on the other a slightly reduced amplitude of the AP peak. After these tests, we proceeded assessing the effect of the passive fibroblast model on the cardiomyocyte AP increasing the $N_f$ term. As shown in figure 5 and table 2 the main effects are: increased $F$ and DDR, reduced MDP, APA and $V_{max}$. Comparing the coupled system results with the electrophysiological data we found that the passive model perform a rude modulation of DDR and frequency. In or-

Figure 3. Simulation with different coupling conductance between hES-CM and one single fibroblast: left panel $G_{gap} = 30$ pS, right panel $G_{gap} = 3$ nS. Increasing $G_{gap}$ value means a better mimicking of hES-CM AP by fibrob-

Figure 4. $I_{leak}$ current acts modulating the hES-CM AP.
der to test further improvements in MDP, APA, and DDR we used the MacCannel’s active fibroblast model, whose results are shown in figure 6 and table 2. Coupling with a small number of fibroblasts, we are able to gain a DDR in good agreement with experimental data, without losing other correct features. Two features (MDP and APA) don’t closely match the experimental data yet, but it is interesting to note that increasing $N_f$ they slowly approach the recorded values. In particular with $N_f = 10$ MDP increases of 2.3 mV while APA reduces of 10.5 mV, even if the AP shape is extremely warped (data not shown).

4. Discussion and conclusions

Our mathematical model offers a tool that can serve as a predictive approach to interpret and refine in vitro experiments on hES-CM. In particular it predicts the effects of electrotonic coupling with fibroblasts detected in the embryoid bodies used for our recordings. A leakage current flows between hES-CM and fibroblasts, representing a depolarizing term during diastole (F and DDR increase) and a repolarizing term during systole (MDP and APA reduction). Our work shows that few fibroblasts can affect DDR while their influence on MDP and APA is relatively small. These model predictions could be validated by comparison with further AP recordings on single hES-CM.

References


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