A mathematical model of action potentials of mouse sinoatrial node cells with molecular bases

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1Biological Physics Group, School of Physics and Astronomy; 2Cardiovascular Research Group, School of Biomedicine, University of Manchester, Manchester, United Kingdom; and 3School of Computer Science and Technology, Harbin Institute of Technology, Harbin, China

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Kharche S, Yu J, Lei M, Zhang H. A mathematical model of action potentials of mouse sinoatrial node cells with molecular bases. Am J Physiol Heart Circ Physiol 301: H945–H963, 2011. First published July 1, 2011; doi:10.1152/ajpheart.00143.2010.—Genetically modified mice are popular experimental models for studying the molecular bases and mechanisms of cardiac arrhythmia. A postgenome challenge is to classify the functional roles of genes in cardiac function. To unveil the functional role of various genetic isoforms of ion channels in generating cardiac pacemaking action potentials (APs), a mathematical model for spontaneous APs of mouse sinoatrial node (SAN) cells was developed. The model takes into account the biophysical properties of membrane ionic currents and intracellular mechanisms contributing to spontaneous mouse SAN APs. The model was validated by its ability to reproduce the physiological exceptionally short APs and high pacing rates of mouse SAN cells. The functional roles of individual membrane currents were evaluated by blocking their coding channels. The roles of intracellular Ca2+ handling mechanisms on cardiac pacemaking were also investigated in the model. The robustness of model pacemaking behavior was evaluated by means of one- and two-parameter analyses in wide parameter value ranges. This model provides a predictive tool for cellular level outcomes of electrophysiological experiments. It forms the basis for future model development and further studies into complex pacemaking mechanisms as more quantitative experimental data become available.

computer modeling; cardiac action potential; genetic isoforms; pacemaking mechanisms

The cardiac excitation sequence is initiated by the cardiac pacemaker, the sinoatrial node (SAN), and spreads throughout the heart. The function of the SAN is therefore understandably vital in cardiac physiology. The SAN produces spontaneous rhythmic action potentials (APs) via an emergent action of many interacting membrane ionic currents and intracellular processes (8). Experimental cell membrane ion channel patch-clamp data were first incorporated into a predictive mathematical model by Noble in 1962 (63), leading to the seminal “theory leading experiment.” It resulted in decades of extensive experimental discovery of a large number of cell membrane ion channels (2, 6, 15, 17, 18) and the study of pacemaking mechanisms in several mammalian species (9, 10, 20, 44, 81). These experimental data have been incorporated into increasingly complex mathematical models of SAN automaticity to simulate species-specific SAN AP waveforms (83) and have also been used to investigate the roles of ionic currents and Ca2+ handling in cardiac pacemaking mechanisms (50, 78, 88, 90).

Despite these extensive electrophysiological studies, understanding of the underlying molecular basis of cardiac arrhythmogenesis remains limited. Pore-forming transmembrane proteins facilitating ionic currents are encoded by specific ion channel genes (54, 68). Tissue-specific expression of these ion channel genes and their functional impact on the tissue’s physiological (e.g., SAN pacemaking) and pathological (e.g., bradycardia) states are important issues to be addressed. In recent times, genetically modified mouse models have gained popularity in the study of clinical SAN dysfunction (39, 42).

The mouse heart rate (~294 beats/min [10]), however, is much higher than that in larger mammals [rabbit: ~189 beats/min (14) to ~214 beats/min (74); human: ~73 beats/min (81)]. To fully appreciate such observations, the biophysical properties of ion channels and their genetic bases that regulate mouse SAN APs need further investigation.

A biophysically detailed mathematical model of mouse SAN APs will complement experimentation in underpinning the correlation between ion channel function and their genetic bases. However, most contemporary SAN models (13, 16, 36, 67, 89) do not consider isofrom-specific channel gating and kinetics. A recent membrane delimited mouse SAN cell model (56) partially reproduced some experimental data of the mouse SAN but has fundamental limitations in simulating the functional roles of ion currents on mouse cardiac pacemaking (31). The present study aimed to further develop a biophysically detailed model of mouse SAN isolated cell APs with biophysically distinct ion channel isoforms and a detailed dynamic intracellular ionic mechanism.

GLOSSARY

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
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<tbody>
<tr>
<td>α</td>
<td>Voltage-dependent opening rate constant</td>
</tr>
<tr>
<td>β</td>
<td>Voltage-dependent closing rate constant</td>
</tr>
<tr>
<td>τ</td>
<td>Time constant</td>
</tr>
<tr>
<td>4-AP</td>
<td>4-Aminopyridine</td>
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<tr>
<td>AP</td>
<td>Action potential</td>
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<tr>
<td>APA</td>
<td>AP amplitude</td>
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<tr>
<td>APD</td>
<td>AP duration</td>
</tr>
<tr>
<td>APD50</td>
<td>APD at 50% repolarization</td>
</tr>
<tr>
<td>APD90</td>
<td>APD at 90% repolarization</td>
</tr>
<tr>
<td>[Ca2+]i</td>
<td>Intracellular Ca2+ concentration</td>
</tr>
<tr>
<td>[Ca2+]o</td>
<td>Extracellular Ca2+ concentration</td>
</tr>
<tr>
<td>[Ca2+]JSR</td>
<td>Ca2+ concentration in the JSR</td>
</tr>
<tr>
<td>[Ca2+]NSR</td>
<td>Ca2+ concentration in the NSR</td>
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Mathematical Model of Mouse Sinoatrial Node Cells

Conductance of HCN channels

Hyperpolarization-activated cyclic nucleotide-gated channels

**EC50_SR**
EC50 for Ca2+-dependent activation of SR Ca2+ release

**f_c**
Ca2+-dependent inactivation gating variable for I_CaL.1.2 and I_CaL.1.3

**f_cm**
Fractional occupancy of calmodulin by [Ca2+]i

**f_cM**
Fractional occupancy of calmodulin by [Ca2+]s

**f_CaL,1.2**
Activation gate for I_CaL.1.2

**f_CaL,1.3**
Activation gate for I_CaL.1.3

**f_T**
Activation gate of I_CaT

**f_Tc**
Fractional occupancy of the troponin Ca2+ site by [Ca2+]o

**f_TmC**
Fractional occupancy of the troponin Mg2+ site by [Ca2+]i

**f_TMM**
Fractional occupancy of the troponin Mg2+ site by Mg2+

**F**
Faraday’s constant

**F_Na**
Fraction of I_Na inactivating slowly

**g**
Gating variable; conductance

**g_0**
Steady-state voltage-dependent value of gate g

**g_b,K**
Conductance of I_K

**g_b,Ca**
Conductance of I_Ca

**g_CaL1.2**
Conductance of I_CaL.1.2

**g_CaL1.3**
Conductance of I_CaL.1.3

**g_CaT**
Conductance of I_CaT

**g_i**
Conductance of I_i

**g_K**
Conductance of I_K

**g_o**
Conductance of I_o

**h_1.1**
Fast inactivation gating variable of Na,1.1

**h_1.5**
Fast inactivation gating variable of Na,1.5

**h_3.1**
Inactivating gating variable of Na,1.1

**h_5.5**
Inactivating gating variable of Na,1.5

**HCN channels**

Hyperpolarization-activated cyclic nucleotide-gated channels

**HSR**
Parameter for Ca2+-dependent activation of SR Ca2+ release

**I**
Current

**I_CaNa**
Background Na+ current

**I_CaL**
L-type Ca2+ current

**I_CaL.1.2**
L-type Ca2+ channel isoform Ca,1.2 current

**I_CaL.1.3**
L-type Ca2+ channel isoform Ca,1.3 current

**I_CaT**
T-type Ca2+ current

**I_CaT.3.1**
T-type Ca2+ channel isoform Ca,3.1 current

**I_f**
Hyperpolarization-activated current

**I_HCN4**
HCN4 channel current

**I_K**
K+ component of I_i

**I_Na**
Na+ component of I_i

**I_K1**
Time-independent K+ current

**I_Kr**
Rapid delayed rectifying K+ current

**I_Na**
Slow delayed rectifying K+ current

**I_Na**
Fast Na+ current

**I_Na,1.1**
Na+ channel soform Na,1.1 current

**I_Na,1.5**
Na+ channel isoform Na,1.5 current

**I_NaCa**
Na+/Ca2+ exchanger current

**I_Nak**
Na+-K+ pump current

**I_NAK**
Maximum I_Nak

**I_n**
Sustained inward Na+ current

**I_nar**
Sustained component of 4-AP-sensitive currents

**I_o**
Transient component of 4-AP-sensitive currents

**I_so**
Inactive fraction of RyR channels

**I_iso**
Isoproterenol

**j_1.1**
Slow inactivation gating variable of Na,1.1

**j_1.5**
Slow inactivation gating variable of Na,1.5

**j_Ca,dif**
Ca2+ diffusion flux from the subspace to the myoplasm

**j_Ca,rel**
Ca2+ release flux from the SR to the subspace

**j_T**
Ca2+ transfer flux from the NSR to the JSR

**j_Ca,up**
Ca2+ uptake flux from the myoplasm to the NSR

**JSR**
Junctional SR

**k_CaQ**
Ca2+ dissociation constant of calsequestrin

**k_CaM**
Ca2+ dissociation constant of calmodulin

**k_CaT**
Ca2+ dissociation constant of the troponin Ca2+ site

**k_CaT_d**
Ca2+ dissociation constant of the troponin Mg2+ site

**k_CaT_d**
Ca2+ dissociation constant of the troponin Mg2+ site

**k_CaSR**
SR Ca2+-dependent RyR activation coefficient

**k_CaQ**
Ca2+ association constant of calsequestrin

**k_CaM**
Ca2+ association constant of calmodulin

**k_CaT**
Ca2+ association constant of troponin

**k_CaT**
Ca2+ association constant of the troponin Mg2+ site

**k_CaT**
Ca2+ association constant of the troponin Mg2+ site

**k_Ca**
Baseline non-SR-dependent transition rate constant for the RyR

**k_o**
Rate transition constant for RyR

**k_o,Ca**
Ca2+-dependent RyR rate constant not limited by diffusion

**k_o,Ca**
Scaling factor for I_Ca

**k_o,Ca**
Baseline non-SR-dependent transition rate constant for the RyR

**k_o**
Rate transition constant for RyR

**k_o,Ca**
Ca2+-dependent RyR rate constant not limited by diffusion

**k_o,Ca**
Release rate parameter

**K_1**
Dissociation constant for [Na+]o, binding to the first site on the I_Ca

**K_1**
Dissociation constant for [Na+]o, binding to the first site on the I_Ca

**K_2**
Dissociation constant for [Na+]o, binding to the second site on the I_Ca

**K_2**
Dissociation constant for [Na+]o, binding to the second site on the I_Ca

**k_6k**
Rate transition constant for RyR
### Glossary

- **K** _i_ — Dissociation constant for [Na⁺]ᵢ, binding to the third site on the Na<sub>Ca</sub> transporter
- **K** _NaO_ — Dissociation constant for [Na⁺]₀, binding to the third site on the Na<sub>Ca</sub> transporter
- **K** _Ci_ — Dissociation constant for [Ca<sup>2+</sup>]ᵢ sub binding to the Na<sub>Ca</sub> transporter
- **K** _emi_ — Dissociation constant for [Na⁺], and [Ca<sup>2+</sup>]ᵢ sub simultaneous binding to the Na<sub>Ca</sub> transporter
- **K** _co_ — Dissociation constant for [Ca<sup>2+</sup>]ᵢ sub binding to the Na<sub>Ca</sub> transporter
- **K** _RyCa_ — RyR Ca<sup>2+</sup>—dependent inactivation rate
- **K** _Rym_ — RyR repriming rate
- **K** _mfCa_ — Dissociation constant for Ca<sup>2+</sup>—dependent inactivation of the I<sub>Ca,1.2</sub> and I<sub>Ca,1.3</sub>
- **K** _m,K_ — Dissociation constant of K⁺ affinity of the Na<sub>Ca</sub> pump
- **K** _mKp_ — Half-maximal [K⁺]ᵢ, for the Na<sub>Ca</sub> pump
- **K** _mNa_ — Dissociation constant of Na⁺ activation of the Na<sub>Ca</sub> pump
- **K** _mNap_ — Half-maximal [Na⁺]ᵢ, for the Na<sub>Ca</sub> pump
- **K** _r,Ry_ — Reverse-mode Ca<sup>2+</sup> affinity of the SERCA pump
- **K** _Ry,Ca_ — RyR Ca<sup>2+</sup> activation rate
- **K** _Rym_ — RyR deactivation rate
- **K** _rel,Ry_ — Half-maximal [Ca<sup>2+</sup>]ᵢ sub of Ca<sup>2+</sup> release from the JSR
- **K** — Ca<sup>2+</sup> release constant
- **K** _up,Ry_ — Half-maximal [Ca<sup>2+</sup>]ᵢ sub of Ca<sup>2+</sup> uptake by j<sub>up</sub> in the NSF

- **K** _K_ — Intracellular K⁺ concentration
- **K** _K_ — Extracellular K⁺ concentration
- **m<sub>1.1</sub>_i_ — Activation gating variable of Na<sub>1.1</sub>
- **m<sub>1.5</sub>_i_ — Activation gating variable of Na<sub>1.5</sub>
- **mERG1** — Mouse ether-a-go-go-related gene 1
- **MaxSR** — Ca<sup>2+</sup> modeling parameter
- **MDP** — Maximum diastolic potential
- **[Mg<sup>2+</sup>]_i_ — Intracellular Mg<sup>2+</sup> concentration
- **MaxSR** — Ca<sup>2+</sup> modeling parameter
- **MinSR** — Ca<sup>2+</sup> modeling parameter
- **n<sub>up</sub>_i_ — SR Ca<sup>2+</sup> uptake and Hill coefficient
- **K** _N_ — Intracellular Na⁺ concentration
- **K** _Na_ — Extracellular Na⁺ concentration
- **NSR** — Network SR
- **O** — Open fraction of RyR channels
- **ODE** — Ordinary differential equation
- **OS** — Overshoot of the AP
- **p<sub>Na</sub>_i_ — Activation gating variable of I<sub>Na</sub>
- **p<sub>n</sub>_i_ — Inactivation gating variable of I<sub>Na</sub>
- **P<sub>up</sub>_i_ — Rate constant of Ca<sup>2+</sup> uptake by j<sub>up</sub> in the NSF
- **q<sub>i</sub>_i_ — Inactivation gating variable of I<sub>Na</sub>
- **q<sub>n</sub>_i_ — Activation gating variable of I<sub>Na</sub>
- **q<sub>i</sub>_i_ — Inactivation gating variable of I<sub>Na</sub>
- **P<sub>10</sub>_i_ — Functional change in a variable with a 10-K increase in temperature
- **Q<sub>inc</sub>_i_ — Fractional charge movement during the [Ca<sup>2+</sup>]ᵢ sub occlusion reaction of the Na<sub>Ca</sub> transporter
- **Q<sub>co</sub>_i_ — Fractional charge movement during the [Ca<sup>2+</sup>]ᵢ sub occlusion reaction of the Na<sub>Ca</sub> transporter
- **Q<sub>n</sub>_i_ — Fractional charge movement during Na⁺ occlusion reactions of the Na<sub>Ca</sub> transporter
- **r<sub>i</sub>_i_ — Activation gating variable of I<sub>Na</sub> and I<sub>Na</sub>
- **R** — Universal gas constant
- **R** — Fraction of reactivated (closed) RyR channels
- **RI** — Fraction of RyR inactivated channels
- **RyR** — Ryanodine receptor
- **SAN** — Sinoatrial node
- **SERCA** — Sarco(endo)plasmic reticulum Ca<sup>2+</sup>—ATPase
- **SR** — Sarcoplasmic reticle
- **T** — Absolute temperature (in K)
- **TC<sub>tot</sub>_i_ — Total concentration of the troponin Ca<sup>2+</sup> site
- **TM<sub>Ca</sub>_i_ — Total concentration of the troponin Mg<sup>2+</sup> site
- **TOP** — Take off potential
- **V** — Voltage
- **V<sub>1/2</sub>_i_ — Voltage of half-activation or half-inactivation of ion channel gates
- **V<sub>mem</sub>_i_ — Membrane potential
- **V<sub>cell</sub>_i_ — Cell volume
- **V<sub>i</sub>_i_ — Myoplasmic volume available for Ca<sup>2+</sup> diffusion
- **V<sub>vol</sub>_i_ — Volume of the NSF
- **V<sub>sub</sub>_i_ — Subspace volume
- **x<sub>i</sub>_i_ — Volume of the NSR
- **x<sub>i</sub>_i_ — Activation gating variable of I<sub>Na</sub>
- **y<sub>i</sub>_i_ — Activation gating variable of I<sub>Na</sub>
of experimental and modeling data is shown in Supplemental Material in Table S1.

$I_{Na}$ (I_{Na,1.1} and I_{Na,1.5}). The Na_{1.1} and Na_{1.5} isoforms predominantly compose mouse SAN $I_{Na}$ (41). Na_{1.1} is uniform across the SAN. Na_{1.5} is spatially heterogeneous, with its channel current density increasing from the center toward the periphery (39). Both activate during the pacemaker potentials; Na_{1.1} activates at more positive potentials than Na_{1.5}.

The models for the steady-state gating variables of $I_{Na}$ were based on our experimental studies on isolated mouse SAN cells (Fig. S1, A and B) (39, 41). $I_{Na}$ time kinetics in the present model were based on parent SAN models (36, 89). Maximum ionic current conductances for Na_{1.1} and Na_{1.5} isoforms were computed by comparing simulated $I_{Na}$ I-V relationships to experimental data (Fig. S1C) (39, 41). Current traces of both isoforms during the voltage-clamp simulation are shown in Fig. S1D.

$I_{CaT} (I_{CaT,1.2} and I_{CaT,1.3}).$ The two isoforms contributing to $I_{CaT}$ in the mouse SAN are the weakly expressed Cav1.2 isoform and the strongly expressed Cav1.3 isoform (52, 56).

In the model, the steady-state inactivation of Ca_{1.2} was based on experimental data (52), and the steady-state activation was adopted from a study by Mangoni et al. (56) (Fig. S2A). The steady states of activation and inactivation of Ca_{1.3} (Fig. S2B) were based on rabbit SAN experimental data as determined by Zhang et al. (89). Experimental data for mouse $I_{CaT}$ time kinetics are as yet unavailable. It was found that SAN AP profiles depend strongly on $I_{CaT}$ inactivation time kinetics at higher voltages (32). In the parent models, the inactivation time constant had a very large peak value (~310 ms at -40 mV) in the Kurata et al. (36) model and was kept almost constant at -45 ms (over -40 mV) in the Zhang et al. (89) model. Since such a slow voltage-dependent inactivation of $I_{CaT}$ produces a prolonged APD, the inactivation time kinetics of $I_{CaT}$ of the Zhang et al. (89) model were adapted in this study. The reversal potentials for Ca_{1.2} and Ca_{1.3} were set to +47 mV based on experimental I-V data (10, 52).

The ionic current models were validated by simulating experimental $I_{CaT}$ I-V relationships (52) for Ca_{1.2} and Ca_{1.3} isoforms (Fig. S2C). Current traces are shown in Fig. S2D. The maximum ionic current conductances so determined for both $I_{CaT}$ isoforms (52) were found to give current densities significantly lower than in other reports $|I_{CaT,1.2}|$: 3.1 pA/pF at +10 mV (56) and $I_{CaT,1.3}$: 10.4 pA/pF at -20 mV (56)). The conductances were therefore augmented to give appropriate current densities during model pacemaking APs.

$I_{CaT}$: $I_{CaT}$ is a voltage-dependent gated Ca^{2+} current with fast inactivation kinetics. $I_{CaT}$ is expressed in the SAN of most species (22, 56) with a predominant isoform of Ca_{3.1} (7). In the mouse SAN, $I_{CaT}$ has been shown to activate at approximately -65 mV, peak at approximately -30 mV, and have a reversal potential of +45 mV (10). The steady-state activation of $I_{CaT}$ was adopted from previous modeling studies (36, 89). The steady-state gating properties are shown in Fig. S3A, which shows a small window current at -45 mV, close to the late phase of mouse SAN AP diastolic depolarization. The time kinetics of $I_{CaT}$ were derived from experimental data (22) in previous models of $I_{CaT}$ in the rabbit SAN. The ionic current model was validated by quantitatively comparing the simulated $I_{CaT}$ I-V data with experimental data (10, 52, 56), as shown in Fig. S3B. The fast kinetics of $I_{CaT}$ are evident from the current traces shown in Fig. S3C.

$I_{F}$. In the mouse SAN, the isoforms contributing to the native $I_{F}$ are a heteromeric combination of HCN1, HCN2, and HCN4, with all being permeable to Na^{+} and K^{+} (3). It has been shown that the biophysical properties of individual isoforms coding $I_{F}$ channels are different from each other (2), and their tandems (e.g., HCN1–HCN4 tandem) have distinct kinetics to native $I_{F}$. In the mouse SAN, it has been shown that HCN1 and HCN2 activate 25 times faster than HCN4 (61), and HCN4 is the predominant isoform compared with HCN1 and HCN2 (45). Therefore, a single native $I_{F}$ was modeled in the present study. With experimental data showing a large range in the measured V_{1/2} of $I_{F}$ [-107 mV (10), -87.4 mV (55), -105 mV (26), -101 mV (1), and -106.8 mV (1)], a value of $V_{1/2} = -106.8$ mV was adopted in the present study (Fig. S4A). The slope of $I_{F}$ activation was also based on experimental data (10, 66) and was taken to be -16.1 mV in the basal model. $I_{F}$ time kinetics were based on experimental data of native $I_{F}$ from mouse SAN cells (10), as shown in Fig. S4B. The model for $I_{F}$ was validated by quantitatively comparing the simulated $I_{F}$ I-V data with experimental data (10, 55, 66) (Fig. S4C). Simulated current traces for $I_{F}$ are shown in Fig. S4D.

$I_{Le}$. A novel SAN Na^{+} current with $I_{CaT}$-like kinetics was first reported by Guo et al. (21) and has been observed in the SAN of several species (10, 41, 74). The voltage dependence of its gating kinetics are not available except for in the rat SAN. The gating kinetics of $I_{Le}$ were therefore based on experimental data obtained from the rat SAN (74). $I_{Le}$ in the mouse SAN activates around -80 mV and peaks at -60 mV (10). Both values are ~10 mV negative to those of the rat SAN. Therefore, a -10-mV shift was implemented in
Table 1. Model parameter values in the basal cell model

<table>
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<th>Parameter</th>
<th>Value</th>
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<tr>
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<td>$k_{m_{K},s}$, MS/mS</td>
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<tr>
<td>$K_{r}, s$, MS/mS</td>
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<td>$[Na^{+}]_{i}$, mM</td>
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<td>$P_{up}$, MS/mS</td>
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<td>$n_{up}$</td>
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<td>$K_{Na_{1,2}}$, MS/mS</td>
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<td>$K_{Na_{1,3}}$, MS/mS</td>
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<td>$R_{J}$, MS/mS</td>
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<td>$V_{p}$, pL</td>
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<td>$V_{ref}$, pL</td>
<td>0.0036</td>
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</table>

The model for parameter definitions, see the Glossary.

For model parameter definitions, see the Glossary.

The primary protein regulating mouse SAN $I_{K}$ is mERG1 (11). The model for $I_{K}$ steady-state activation was based on experimental data (10, 58), whereas the steady state of inactivation was adapted from a previous study (36) (Fig. S4A). The activation time kinetics were based on experimental data (11). Since the experimental data were acquired at 28°C, a $Q_{10}$ temperature correction of 1.4 (11, 60) was applied (Fig. S5B). $I_{K}$ inactivation kinetics were adapted from a previous rabbit model (36). The $I_{K}$ model was validated by simulating experimental I-V data (Fig. S5C) and current traces (Fig. SSD) (10, 55).

$I_{Ca}$. Maximum current conductance of the mouse SAN $I_{Ca}$ model was based on experimental data of Cho et al. (10) obtained from mouse SAN cells and included a dependence on $[K^{+}]_{o}$.

Miscellaneous membrane currents. The other currents that the model consists of are $I_{Kr}$, 4-AP-sensitive $I_{Na_{a}}$ and $I_{Na_{Ca}}$, $I_{Na_{K}}$, and $I_{o}$, each of which were either based on experimental data or inherited from parent models. For example, the steady-state activation and kinetics of $I_{Kr}$ were based on experimental data obtained from guinea pig SAN cells (24, 58). Equations for $I_{Na_{a}}$, $I_{Na_{Ca}}$ and $I_{Na_{K}}$ were based on parent rabbit SAN cell models (36, 89). The model for $I_{Na_{Ca}}$ was adopted from Kurata et al. (36) and simulated the saturation characteristics of $I_{Na_{Ca}}$ at large values of $[Ca^{2+}]_{i}$. The scaling parameter $K_{Na_{Ca}}$ was set to 220 pA/pF in the basal model to simulate physiological oscillations of $[Ca^{2+}]_{i}$ and $[Ca^{2+}]_{Sub}$ (Fig. S6) and to facilitate a strong coupling between the intracellular and membrane pacemaking mechanisms.

Ionic Homeostasis in Mouse SAN Cells

$Na^{+}$ and $K^{+}$ concentrations. The simultaneous direct measurement of APs and intracellular ion concentrations is a formidable task experimentally (59), providing limited data to facilitate a quantitative description of the dynamic intracellular variations of $[Na^{+}]_{i}$, and $[K^{+}]_{i}$, (see for, e.g., Refs. 16 and 28) in a mathematical model of cardiac cells. The present basal model incorporated the dynamics of $[Na^{+}]_{i}$, and $[K^{+}]_{i}$, based on an ionic material balance. $I_{Na_{a}}$ was optimized to simulate stable oscillations of the intracellular ion concentrations.

$Ca^{2+}$ homeostasis, buffers, and SR function. There is growing experimental evidence of the role of intracellular $Ca^{2+}$ in modulating pacemaking APs of the mouse SAN (57, 62) via $I_{Na_{Ca}}$, which contributes to the diastolic depolarization phase of the AP (9, 84). Intracellular $Ca^{2+}$ has also been shown to play an important role in the late diastolic depolarization phase of cat pacemaking APs (29, 44) via $I_{Ca_{L}}$. Depletion of $Ca^{2+}$ by challenging RyR function (i.e., reduced $Ca^{2+}$ release from the SR) has been shown to reduce pacemaking in

Continued
isolated mouse SAN cells (62). Mathematical modeling has also shown that a strong interaction between intracellular Ca\(^{2+}\) and membrane ionic processes regulates pacemaking APs (6, 50). In the present model, we started by incorporating the Ca\(^{2+}\) buffering formulations of Kurata et al. (36). Second, the SERCA Ca\(^{2+}\) uptake mechanism was based on the formulation by Shannon et al. (73), which models Ca\(^{2+}\) uptake from the cytosol to the NSR. The values of parameters for the SERCA pump vary widely among various modeling studies (69–71, 73). In this study, the Hill coefficient was set to 2 and the affinity of the forward mode of the pump to 0.246 \(\mu M\) to reflect measurements in rodents (69). The other parameters were optimized to maintain an \(~0.1\ \mu M\) peak free [Ca\(^{2+}\)] in the cytosol (36). Finally, the Ca\(^{2+}\) release mechanism to simulate RyR function was also based on the formulation of the Shannon et al. (73) multistate RyR “Ca\(^{2+}\) clock” model. The RyR Ca\(^{2+}\) release model was optimized by Mal'tsev and Lakatta (50) for rabbit SAN cell pacemaking APs with longer a CL of \(~315\ \text{ms}\). The CL of mouse SAN cell APs is much shorter \((~200\ \text{ms})\) and is regulated by several ionic channel currents with much larger densities, we therefore further modified the parameters of the Shannon et al. (73) model for modeling the Ca\(^{2+}\) clock in our mouse SAN cell model.

**Numerical Integration and Stability of Solutions**

*Integration method.* The presented mouse SAN cell model consists of a 38 variable coupled stiff nonlinear ODE system. A standard explicit Euler integration method with a constant time step \((dt = 10^{-3} \ \text{ms})\) was found to give stable solutions. Further reduction of the time step or implementation of a fourth-order Runge-Kutta integration method gave the same simulation results within 0.1% tolerance levels while increasing the computational time and effort. Simulations were carried out on a Sun Sparc with Solaris 9 using C programming.

*Free parameters values, stability of solution, and determination of initial conditions.* Biophysically detailed cardiac models consist of a large numbers of variables \((\sim 10–100)\) and parameters \((\text{in excess of} \ 100)\) (32). The basal model was primarily based on experimental data associating the majority of the modeling parameters to experimentally observed electrophysiological data. Biophysical parameters not available in experimental data were taken from the parent models (36, 37, 89) and adapted to give typical AP characteristics in mouse SAN cells. For details of all inherited features, see Table S1.

For the determination of stable intracellular ionic oscillations, mass balance based on the ionic conservation principle was applied (33, 77). During the time integration, the accumulation or depletion of all intracellular ions was monitored. Oscillations of all intracellular ionic concentrations were stabilized within a tolerance of 1% variation. For example, the concentrations of [Na\(^{+}\)], and [K\(^{+}\)], were stabilized around average physiological values of 8 and 140 mM, respectively, by minimally adjusting the maximum \(I_{\text{NaK}}\). It should be emphasized that the free parameters were estimated by minimal modifications to basal values. Consideration of dynamic variations in [Na\(^{+}\)] and [K\(^{+}\)], did not give rise to increased degeneracy and drift in the presented models (35), as seen predominantly in atrial and ventricular models (28, 46). This is due to the mass balance-based parametric fine tuning and the spontaneously beating SAN APs not requiring an extracellular stimulus. Such parametric fine tuning will nonetheless allow some drift and has been minimized in this study, as described above. The degeneracy and drift could be limited by maintaining constant [Na\(^{+}\)] and [K\(^{+}\)]. This would, however, have rendered the function of \(I_{\text{NaK}}\) to be basically a background current. It should be noted that model development is, essentially, an iterative process, with novel experimental data being incorporated into the models continually.

Once the free parameters were determined, the initial conditions and stability of the solutions were estimated. To determine the initial conditions, all 38 variables were set to values expected at MDP. Thus, the value of \(V_{m}\) was set to \(-65\ \text{mV}\). Initial values of 0 and 1 were assigned to the activation and inactivation gates, respectively. All ionic concentrations were set at anticipated physiological diastolic levels (e.g., [Ca\(^{2+}\)]\(\text{c}\), \(~0.1\ \mu M\), [Na\(^{+}\)], \(~8\ \text{mM}\), and [K\(^{+}\)], \(~140\ \text{mM}\)). The initial conditions for the RyR model four variables \((O, I, R, \text{and} \ RI)\) were set to suitable nonzero values. The dynamic spontaneously oscillating model was then integrated for 1,000 s. In the final 100 s of simulated activity, the beat-to-beat variation of all the 38 variables was monitored. When the variation was below tolerance values, the solution was deemed to be stable. Values of all variables at MDP were then noted as initial conditions, as shown in Table 2.

Typically found in gating kinetics and in ion current formulations, which are all functions of \(V_{m}\), division by small numbers close to machine precision makes the models unsuitable for numerical analysis. All above integrations were carried out by eliminating singularities in the modeling logical expressions (46) by performing a first-order Taylor expansion around all the relevant singularity values, and the approximations held valid with a range of 0.05 mV around the singularity.

**RESULTS**

Figure 2A shows the simulated time course of mouse SAN APs together with dynamic variation of the major ion

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**Table 2. Initial conditions for the basal cell model**

<table>
<thead>
<tr>
<th>Model Variables</th>
<th>Initial Values</th>
</tr>
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<tbody>
<tr>
<td>(V_{m}), mV</td>
<td>(-64.650005232)</td>
</tr>
<tr>
<td>(q_{ls})</td>
<td>(0.6185734202)</td>
</tr>
<tr>
<td>(q_{ds})</td>
<td>(0.4571851563)</td>
</tr>
<tr>
<td>(d_{f})</td>
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</tr>
<tr>
<td>(x_{d})</td>
<td>(0.4307985088)</td>
</tr>
<tr>
<td>(p_{j})</td>
<td>(0.4033930050)</td>
</tr>
<tr>
<td>(p_{h})</td>
<td>(0.0024742549)</td>
</tr>
<tr>
<td>(x_{e})</td>
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</tr>
<tr>
<td>(f_{l,1})</td>
<td>(0.996251824)</td>
</tr>
<tr>
<td>(d_{l,1})</td>
<td>(0.0000044417)</td>
</tr>
<tr>
<td>(f_{l,1,3})</td>
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<tr>
<td>(j_{1,1,3})</td>
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</tr>
<tr>
<td>(f_{s_{0}})</td>
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</tr>
<tr>
<td>(r)</td>
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</tr>
<tr>
<td>(q)</td>
<td>(0.6140717444)</td>
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<tr>
<td>(m_{1})</td>
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<tr>
<td>(m_{1,1})</td>
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<tr>
<td>(h_{1})</td>
<td>(0.4545040890)</td>
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<tr>
<td>(j_{1})</td>
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<td>(y)</td>
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<td>([\text{Ca}^{2+}]_{oc}), mM</td>
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<tr>
<td>([\text{Ca}^{2+}]_{oc}), mM</td>
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</tr>
<tr>
<td>(f_{RC})</td>
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<tr>
<td>(f_{MMC})</td>
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<td>(f_{MM})</td>
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<td>(f_{CM})</td>
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<td>([\text{Na}^{+}]_{oc}), mM</td>
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<td>([\text{K}^{+}]_{oc}), mM</td>
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<td>(R_{m})</td>
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For model variable definitions, see the *Glossary*. 
channel currents and intracellular ion concentrations. The simulated APs have a rapid depolarizing upstroke, short APD, and fast pacemaking rate, which agree with the unique features of isolated mouse SAN cell APs. Figure S6 shows details of the dynamic variations of intracellular Ca\(^{2+}\) variables. It can be seen that the model produces \([\text{Ca}^{2+}]_i\) oscillations with an amplitude of 0.1 µM, which is close to experimental data (36). \([\text{Ca}^{2+}]_i\) oscillations have systolic and diastolic values of 1,744 and 69.6 nM, respectively, which are comparable with experimental observations in rabbit SAN cells (51). To validate the model, simulated APs and ion channel blocking simulations were compared with experimental data as detailed below.

**Simulated APs and Experimental Recordings**

Simulated APs were validated against experimental recordings, as shown in Fig. 3. Simulated AP characteristics, i.e., CL, APD\(_{50}\), APD\(_{90}\), OS, MDP, dV/dt\(_{\text{max}}\), TOP, and DDR, agreed well with the experimental data, which further validated the use of parameters in the equations of individual ionic currents. Quantitative results are shown in Table 3 along with quantita-
Roles of Individual Ionic Channel Currents in the Genesis of Mouse SAN APs

The functional roles of ion channels were investigated by isoform-specific ion channel blocking simulations and comparison with experimental data.

Role of \( I_{Na} \). Simulation of block of \( I_{Na,1.1} \) and \( I_{Na,1.5} \) in the model is shown in Fig. 4. As shown in Fig. 4A, block of \( I_{Na,1.1} \) did not affect the model pacemaking (CL increased from 212.12 to 217.01 ms), but block of \( I_{Na,1.5} \) augmented CL by 32.5% (CL = 281.14 ms). Block of both isoforms simultaneously augmented CL by 38.2% (CL = 293.27 ms). The simulations are in agreement with our experimental results (41), where a 27% increase of CL was observed due to inhibition of \( I_{Na} \) using 30 µM TTX. A similar functional role of \( I_{Na} \) in the rabbit SAN has been observed by Kurata et al. (37). Although \( I_{Na} \) is not the main upstroke current in SAN cells and does not affect \( \frac{dV}{dt_{max}} \) (Fig. 4A, bottom), it contributes to pacemaking since both isoforms are active in the late diastolic depolarization pacemaker potential range (Fig. S1, A and B). This was reflected in the reduced DDR when \( I_{Na} \) was blocked in our basal model (Fig. 4B). Since \( I_{Na} \) acts predominantly in the late diastolic depolarization phase, block of \( I_{Na} \) did not affect APD and marginally reduced \( \frac{dV}{dt_{max}} \) in the model. Experimentally, however, we have observed that low (100 nM) or high (30 µM) concentrations of TTX used to block \( I_{Na,1.1} \) or \( I_{Na,1.5} \), respectively, caused a reduction of \( \frac{dV}{dt_{max}} \). This may be due to TTX affecting other depolarizing \( Ca^{2+} \) currents in SAN cells, as has been seen in experimental studies (75, 87).

Table 3. Experimental data and simulated mouse SAN AP characteristics from Mangoni et al. (56) and our basal models

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Experimental data range</th>
<th>Mangoni et al. model</th>
<th>Present cell model</th>
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<tr>
<td>CL, ms</td>
<td>106.1 to 255</td>
<td>212.31</td>
<td>212.21</td>
</tr>
<tr>
<td>APD(_{50}, ) ms</td>
<td>26.3 to 56.88</td>
<td>104.00</td>
<td>35.04</td>
</tr>
<tr>
<td>APD(_{90}, ) ms</td>
<td>45.8 to 107.14</td>
<td>121.1</td>
<td>62.00</td>
</tr>
<tr>
<td>OS, mV</td>
<td>22.7 to 42.0</td>
<td>24.6</td>
<td>22.60</td>
</tr>
<tr>
<td>MDP, mV</td>
<td>0 to 70</td>
<td>-66.87</td>
<td>-64.52</td>
</tr>
<tr>
<td>( \frac{dV}{dt_{max}}, ) V/s</td>
<td>8.2 to 32</td>
<td>5.31</td>
<td>9.20</td>
</tr>
<tr>
<td>TOP, mV</td>
<td>54.6 to 40</td>
<td>0.3701</td>
<td>-48.45</td>
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<tr>
<td>DDR, V/s</td>
<td>0.172 to 0.34</td>
<td>0.1786</td>
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</table>

Experimental data were obtained from quantitative results or from analysis of single cell AP profiles by Cho et al. (10), Lei et al. (39, 41), Mangoni et al. (52, 55), Clark et al. (11), Zhang et al. (91), Verheijck et al. (80), Alig et al. (1), Wu et al. (84), and Chen et al. (9). For definitions of the AP characteristics, see the Glossary.
To further investigate the functional role of $I_{Na,1.5}$ in mouse SAN pacemaking, the effects of alterations of $g_{Na,1.1}$ and $g_{Na,1.5}$ were simulated in the model (Fig. S7). Reduction of either isoform-specific conductance slowed down pacemaking, whereas increased conductance caused the expected progressive acceleration of pacemaking.

**Role of $I_{CaL,1.2}$** in the model (Fig. 5A) marginally increased CL by 0.2%, which was accompanied by reduced $dV/dt_{max}$, APA, and APD. Our simulations were similar to experimental data from rabbit SAN cells (34), where block of $I_{CaL}$ by nifedipine in small balls from central SAN tissue accelerated pacemaking, reduced $dV/dt_{max}$, and reduced APA. Since the activation potential of $I_{CaL,1.2}$ is higher than TOP, its functional role in pacemaking activity is primarily in the modulation of OS, rather than the pacemaking rates (Fig. S8). The limited role of $I_{CaL,1.2}$ on APs is due to its relatively small window current and small current density compared with $I_{CaL,1.3}$ (Fig. S2). The Mangoni et al. (56) model showed a small reduction of pacemaking rates upon inhibition of $I_{CaL,1.2}$.

The functional role of $Ca_{v,1.3}$ on mouse SAN pacemaker activity was studied by blocking $I_{CaL,1.3}$ (Fig. 5B). Experimentally, $Ca_{v,1.3}^{-/-}$ mice showed significantly slower pacemaking with prolonged CL or even an arrest in pacemaking activity (52). Such a negative chronotropic effect due to reduced $I_{CaL,1.3}$ on heart rates has also been observed in vivo, where $Ca_{v,1.3}$ knockout mice showed prolonged PR intervals with a high incidence of sinus bradycardia (91). In the present model, block of $I_{CaL,1.3}$ by 45% produced a 17.33% increase in CL. Complete block abolished autorhythmic APs, leading to a stable resting potential of $-40.47$ mV. The Mangoni et al. (56) model simulation data ($\times$).
model also showed a similar arrest of pacemaking upon \( I_{CaL,1.3} \) block (stable resting potential at \(-29.3\) mV). When both \( I_{CaL,1.2} \) and \( I_{CaL,1.3} \) were blocked in the model, pacemaking in the model was arrested with a stable resting potential of \(-40.4\) mV. Changes in CL are shown in Fig. 5C.

The effects of altered \( g_{CaL,1.3} \) on pacemaking were simulated in the model. \( I_{CaL,1.3} \) is a vital regulator of OS and APD, as shown in Fig. S8. A decrease in \( I_{CaL,1.3} \) slowed down pacemaking APs, resulting in increased CL along with dramatically reduced APAs. Augmenting \( I_{CaL,1.3} \) accelerated pacemaking APs, resulting in reduced CL along with increased APAs and \( dV/dt_{\text{max}} \).

**Role of \( I_{CaT} \).** Experiments using \( Ca_{3.1} \) knockout mice have shown a pacemaking rate reduction by 34% (56). Studies in cat atria by Huser et al. (29) and Zhou and Lipsius (92) have also shown that a Ni\(^{2+}\)-induced reduction of \( I_{CaT} \) causes a 35–230% prolongation of CL, indicating the critical importance of \( I_{CaT} \) in SAN pacemaking. In the model, complete \( I_{CaT} \) block dramatically slowed down the pacemaking, with CL increasing by 49.1% (Fig. 6A). As observed experimentally (29), \( I_{CaT} \) block revealed that the reduction of CL was directly related to the reduced level of diastolic \( Ca^{2+} \) (Fig. 6B). In model simulations, \( I_{CaT} \) block produced a 38% reduction of peak \( [Ca^{2+}] \), and a 42.79% reduction of \( [Ca^{2+}]_{\text{sub}} \) as well as reduced \( Ca^{2+} \) release during DDR. The simulated changes of \( [Ca] \), and \( [Ca]_{\text{sub}} \) in response to \( I_{CaT} \) block were greater than the experimental data of Huser et al. (29), who observed an initial reduction of the \( [Ca^{2+}]_{\text{sub}} \) pedestal during the diastolic depolarization phase but no remarkable change in peak \( [Ca^{2+}]_{\text{sub}} \) or \( [Ca^{2+}] \). This is possibly due to the fact that in the model, \( I_{CaT} \) is a major contributor to DDR and it plays an important role (secondary to \( I_{CaL} \)) in the early upstroke. Such a discrepancy between the model simulation and experimental data suggest a possible limitation of the model, which requires further improvements when more experimental data on the biophysical properties of mouse \( I_{CaT} \) become available. As \( I_{CaT} \) activates during the DDR phase, the increase in CL arising from \( I_{CaT} \) block is primarily due to a decrease in DDR (see Fig. S9). Our simulation results are quantitatively similar to the experimentally observed role of \( I_{CaT} \). \( I_{CaT} \) block produced a 6.2% increase of CL in the Mangoni et al. (56) model. Previous models of rabbit SAN cells have assumed a small maximal conductance of \( I_{CaT} \), limiting its role in pacemaking dynamics. However, \( I_{CaT} \) has been experimentally observed to play a significant role in mouse SAN pacemaking and an even greater role in cat SAN cell pacemaking, as observed by Huser et al. (29). In the present model, the important role of \( I_{CaT} \) is reflected in its effects on CL and DDR (Fig. S9, A and B). Furthermore, the role of \( I_{CaT} \) was investigated in a two-parameter analysis, where \( g_h \) and \( P_{up} \) (parameters regulating the diastolic depolarization, along with \( g_{CaT} \)) were simultaneously varied in the presence and absence of \( I_{CaT} \). As shown in Fig. S9C, the absence of \( I_{CaT} \) augmented the CL of stable pacemaking APs dramatically and reduced model robustness. Furthermore, the absence of \( I_{CaT} \) caused pacemaking arrest or aperiodic firing in a larger parametric range. The parameter analysis revealed the critical role of \( I_{CaT} \) in assuring the robustness of mouse SAN pacemaking activities.

**Role of \( I_{st} \).** \( I_{st} \) has been observed in pacemaking SAN cells of several species (10, 20, 21). \( I_{st} \) has been observed in the mouse (10) and was incorporated as a small maximum conductance current in the model. A larger conductance of \( I_{st} \) caused the model to become unstable. Block of \( I_{st} \) in the model (Fig. 7A) marginally slowed the pacemaking activity and increased CL.

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**Fig. 6.** Functional effects of \( I_{CaT} \) block. A: AP profiles under control (solid lines) and \( I_{CaT} \) blocked (dashed lines) conditions. B: \([Ca^{2+}] \) (top) and \([Ca^{2+}]_{\text{sub}} \) (bottom) profiles during APs under control (solid lines) and \( I_{CaT} \) blocked (dashed lines) conditions. C: CL (top) and DDR (bottom) under control and \( I_{CaT} \) blocked conditions. Shown are the model simulation (open bars), experimental data (●) (56), and Mangoni et al. (56) model simulation data (×).
by 2.1%. The alterations in CL due to \( I_{st} \) block are shown in Fig. 7B.

**Role of \( I_f \).** The role of \( I_f \) in cardiac pacemaking remains controversial. A recent study (50) has argued the important role of \( I_f \) in SAN pacemaking. However, HCN4 gene knockout experimental studies (4, 26) in the mouse SAN have shown that the role of \( I_f \) is significant, albeit not isolated from other mechanisms governing pacemaking. The functional role of \( I_f \) on mouse SAN pacemaking activity was determined by block of \( I_f \) (Fig. 8A). Complete block of \( I_f \) slowed down pacemaking, with CL being increased by 13.72% in the model. It produced a more hyperpolarized MDP to \(-69.4\) mV, a hyperpolarization of 5 mV. Since \( I_f \) modulates pacemaking by primarily acting during the DDR phase of the AP, it did not affect OS and APD. The measured CL and DDR under complete block conditions are shown in Fig. 8, B and C, respectively. Effects of alterations of \( g_h \) on model CL and DDR are shown in Fig. S10.

**Role of \( I_{Kr} \).** The role of \( I_{Kr} \) in the present model is to modulate APD and APA. Partial block of \( I_{Kr} \) by 48% prolonged APD\text{90} by 27.96% in the model. Accompanied with APD prolongation, block of \( I_{Kr} \) also elevated MDP by +4.2 mV in the model. Note that partial block of \( I_{Kr} \) only marginally reduced pacemaking (CL increased marginally by \(-0.7\%\); Fig. 9A,i). Such a response to \( I_{Kr} \) block has been observed experimentally in the rabbit SAN (8) and has also been reproduced in parent rabbit SAN models (37, 89). This is due to the primary function of \( I_{Kr} \) being modulation of APD and APA. As \( I_{Kr} \) was progressively blocked, APA reduced progressively (Fig. 9, A,ii, and Fig. S11). The reduction in APA is attributable to the elevated MDP, which results in incomplete activation of \( I_{Na} \) and \( I_{Cal} \) in the upstroke phase, giving reduced APA. Complete block of \( I_{Kr} \) abolished the pacemaking activity with \( V_m \) resting at \(-0.35\) mV. Upon block of \( I_{Kr} \) by 48%, pacemaking in the Mangoni et al. (56) model was abolished.

The present model showed a marginal reduction of CL due to \( I_{Kr} \) block, whereas our experimental data (62) showed that application of 1 \( \mu \)M E-4031 reduced CL by 68%. In isolated mouse hearts, Cho et al. (10) found that 1 \( \mu \)M E-4031 reduced CL by 36.5%. A low (0.2 \( \mu \)M) concentration of E-4031 was found to inhibit cellular \( I_{Kr} \) in the mouse SAN by 60% and increase CL by 51.5% in the experimental study by Clark et al. (11). In intact mouse hearts, the same study found an application of 1 \( \mu \)M E-4031 to increase CL in the range of 31–212%. E-4031 is presumed to be an \( I_{Kr} \)-selective drug. However, Verheijck et al. (79) showed that E-4031 not only inhibits \( I_{Kr} \) strongly but also reduces \( I_{Cal} \) by 30% in the rabbit SAN. Admittedly, the 30% block of \( I_{Cal} \) was observed at a high (10 \( \mu \)M) concentration of E-4031. In the present model, a substantial reduction of \( I_{Cal} \) (45%) was found to be necessary in the model to give a prolonged CL. Other major K+ currents (i.e., \( I_{K1}, I_{to}, I_{Kr}, \) and \( I_{sax} \)) may also be sensitive to E-4031 but were found to play insignificant roles in the model’s pacemaking behavior (Fig. S11). Therefore, the effects of E-4031 were simulated by reducing \( I_{Kr} \) density by 60% and reducing \( I_{Cal} \) density by 50%. As shown in Fig. 9, B,i and ii, such alterations reduced pacemaking by 30.5%. APD\text{90} was prolonged by 87.1%, and dV/dt\text{max} was reduced by 79.6%. The present model as well as previous models (36, 56, 89) cannot reproduce CL prolongation by means of \( I_{Kr} \) block alone, which is a possible model limitation. To reproduce E-4031-induced prolongation of CL, reductions of \( I_{Kr} \) as well as \( I_{Cal} \) are required in the present model. The full effect of E-4031 on mouse SAN ionic currents requires future experimental quantification.

**Role of \( I_{to} \).** It has been shown experimentally that \( I_{to} \) block causes an increase of APA and prolongs APD (40). Selective block of \( I_{to} \) in the model increased CL by 3.6% and prolonged APD\text{90} by 10.2% and APD\text{90} by 5.5% (Fig. 9, C,i and ii). Importantly, block of \( I_{to} \) caused OS to increase by 7 mV. The effect of \( I_{to} \) on OS reflects its role in regulating the early phase of repolarization. The small role of \( I_{to} \) in the present SAN cell model could be a model limitation (Fig. S11C). However, it should be noted that the role of \( I_{to} \) is greater in modulating repolarization in the ventricles compared with the atria (85, 86) and SAN (64, 65). To date, the biophysical properties of \( I_{to} \) in the mouse SAN have not been experimentally quantified. Furthermore, previous SAN modeling studies (36, 50, 89) have indicated that the role of \( I_{to} \) compared with \( I_{Kr} \), in regulating SAN AP characteristics is that of regulating OS and early repolarization. Further experimental quantification of \( I_{to} \) properties in mouse SAN cells will improve our understanding of K,4.2/K,4.3 \( I_{to} \) channels.

**Role of \( I_{NaCa} \).** \( I_{NaCa} \) strongly couples the AP to intracellular Ca\text{2+} and contributes to the DDR phase of the SAN AP.
Progressive reduction of $I_{NaCa}$ reduced APA and DDR, eventually giving rise to aperiodic or chaotic oscillations. When $I_{NaCa}$ was blocked by $70\%$, regular pacemaking activity was abolished. Complete block of $I_{NaCa}$ set $V_m$ to a resting value at $39.5\, mV$ (Fig. 10). The effects of various levels of $I_{NaCa}$ inhibition or augmentation on APA and DDR are shown in Fig. S12. With a decrease of $I_{NaCa}$, APA monotonically decreased. With severe block ($>70\%$), APs became aperiodic and eventually pacemaking was arrested. The $I_{NaCa}$ formulation in the Mangoni et al. (56) model was adopted from the Zhang et al. (89) model. Their formulation of $I_{NaCa}$ does not provide the strong coupling between membrane and intracellular processes. Therefore, although block of $I_{NaCa}$ in the Mangoni et al. (56) model produced a prolonged CL by $18.9\%$, it is not an essential component of the pacemaking mechanism in their model.

Role of intracellular Ca$^{2+}$. The role of intracellular Ca$^{2+}$ release and uptake mechanisms was investigated in the model. In the basal model, SR Ca$^{2+}$ SERCA uptake and RyR release mechanisms were based on the formulations by Shannon et al. (73). The isolated Ca$^{2+}$ clock model has been previously investigated in detail (50) and produces a wide range of pacing rates suitable for the rabbit SAN cell model. We further explored the two-parameter space of the uptake rate parameter $P_{up}$ and the release rate parameter $k_s$ to adapt the Ca$^{2+}$ clock to our membrane clock of the mouse SAN cell model. The integrated model was then able to reproduce a wide range of stable CL APs regulated by the intracellular Ca$^{2+}$-handling mechanism (Fig. 11A). By identifying appropriate values of $P_{up}$ and $k_s$ (shown by "x" in Fig. 11A), the model was able to generate stable pacemaking APs and intracellular Ca$^{2+}$ transients (Fig. 11B). Upon block of SR uptake ($P_{up} = 0$), pace-
making was dramatically slowed down (Fig. 11C). Ryanodine is known to slow down pacemaking in the mouse SAN (62) by means of challenging SR Ca\textsuperscript{2+} release (9). In the model, block of SR Ca\textsuperscript{2+} release ($k_\text{s} = 0$) also had a severe effect on the AP, making it aperiodic (Fig. 11D). Furthermore, when intracellular Ca\textsuperscript{2+} concentration ([Ca\textsuperscript{2+}]sub) was buffered to diastolic concentrations ([Ca\textsuperscript{2+}]i and [Ca\textsuperscript{2+}]sub set to 50 nM, simulating the effects of BAPTA), pacemaking was arrested (Fig. 11E).

Effects of Iso on mouse SAN pacemaking activity. The adrenergic response of the pacemaking mechanism in the mouse SAN has been studied using Iso experimentally. It has been shown that Iso causes a positive shift of the $V_{1/2}$ of $f_I$. Alig et al. (1) observed a shift from $-106$ to $-92$ mV (a positive shift of $+14$ mV). Barusco et al. (4) saw a similar $+7$-mV shift, whereas Liao et al. (43) saw a shift from $-128$ to $-110$ mV (shift of $+18$ mV). The slope factors in the steady-state of activation were unaffected. Upon shift of the $V_{1/2}$ from $-106$ to $-92$ mV in our model, CL was marginally reduced (CL = 208.1 ms). The effects of varied $V_{1/2}$ and $P_{up}$ on model pacemaking are shown in Fig. S13. As the simulated effect of shift of $V_{1/2}$ was substantially smaller than the experimentally observed effects of the 20–40% increase in pacemaking rates (1, 4, 84), it might imply a possible role of changes in the intracellular Ca\textsuperscript{2+} mechanism and other ionic currents affected by Iso. Experimentally, it has been found that $I_{CaL}$ is dramatically affected by Iso, resulting in augmented $I_{CaL}$ density (1) as well as a shift of the $I-V$ curve to more negative potentials (72). Similarly, Iso also augments $I_K$, density (12%) and shifts its steady state of activation to more negative potentials (82). Experimentally, it has also been observed that Iso increased $I_{NaK}$ activity by increasing its sensitivity to [Na\textsuperscript{+}] (5, 15, 23), i.e., a reduction of the half-maximal [Na\textsuperscript{+}] in $I_{NaK}$ ($K_{mNa}$). Iso also augmented SR uptake and release by stimulation of Ca\textsuperscript{2+}/calmodulin-dependent protein kinase II (50, 73). In simulations of Iso, we adopt the approach of Shannon et al. (72) and reduced the [Ca\textsuperscript{2+}] affinity of the forward model of the SERCA pump ($K_{na}$) and increased the baseline non-SR-dependent transition rate constant of RyR ($K_{off}$) in the Ca\textsuperscript{2+} release mechanism. Therefore, in accordance with experimental data, the effects of Iso were simulated by the following: 1) shift of $f_{V_{1/2}}$ to $-92$ mV (1); 2) increasing current densities of both $I_{CaL}$ isofoms by 45% (1); 3) shift of the $I_{CaL}$ $I-V$ curves toward more negative potentials by 5 mV (72); 4) reducing $K_{m,Na}$ from 14 to 11 mM (5, 15); 5) augmenting $g_K$, by 12% (82); 6) shift of the $I_{Kr}$ steady state of activation by 5 mV to more negative potentials (82); 7) reducing $K_{off}$ from 0.246 to 0.123 $\mu$m (72); and 8) increasing $K_{off}$ from 10 to 20 mM $^{-2}$/m (72). With these changes, simulated APs and Ca\textsuperscript{2+} transients under control and Iso conditions are shown in Fig. 12, A and B. Simulated actions of Iso produced a 23.21% reduction of CL (CL = 163.1 ms; Fig. 12C). Along with the reduced CL, there was an increase in the $[Ca^{2+}]_{sub}$ amplitude but a decrease in the amplitude of the cytosolic $[Ca^{2+}]_i$ oscillations. In previous ventricular cell modeling studies (17, 19, 72), $[Ca^{2+}]_i$ has been shown to be augmented due to Iso. $[Ca^{2+}]_i$ is important in the ventricles for tension-force generation (17, 73). In the SAN, however, $[Ca^{2+}]_{sub}$, rather than $[Ca^{2+}]_i$, has been identified to play a more critical role in regulating pacemaking activity (9, 50, 51). With the above-detailed Iso-induced electrophysiological alterations, the Maltsev and Lakatta (50) model also showed a reduction of cytosolic free $[Ca^{2+}]_i$, and an increase of $[Ca^{2+}]_{sub}$. The differences in intracellular compartments and major currents between ventricular and pacemaking cells may explain such a difference between the two cells’ responses of $[Ca^+]_i$ to Iso.

DISCUSSION

The presented model successfully reproduced physiological mouse SAN pacemaking APs with the atypically short APD.
offers limited possibilities of studying the regulatory effects advanced mechanisms, such as that of the Ca\(^{2+}\) clock (50), on pacemaking. We therefore believe the present biophysically detailed model to be one of the first to reproduce the mouse SAN AP along with the functional roles of ionic currents and intracellular Ca\(^{2+}\) handling.

**Comparison With Previous Models of Other Species**

In recent decades, several mathematical models of the SAN AP have been developed for the rabbit (13, 16, 36, 89) and guinea pig (67). These models are based on a single channel voltage-clamp experimental data representing generic-type ion channels, without considering the species-specific and isoform-specific properties of the ion channels. Although these models provide useful tools to study the functional roles of a certain generic-type ion channel current, they are not suitable to evaluate the functional roles of isoform-specific channels on cardiac pacemaking. The present models have a similar structure to previous SAN models (13, 16, 36, 89) but incorporate the following major difference and important advances.

A major difference between the previous rabbit SAN models and the present mouse model is that the mouse AP has much faster pacemaking rates, a higher OS, and a larger \(dV/dt_{max}\) which are attributable to the emergent interactions of ion channel properties specific to the mouse SAN, e.g., a substantially larger \(I_{CaL}\) density in the model and a greater \(I_{CaT}\) density than that of \(I_{CaL}\), as found by Mangoni et al. (53).

A major advance in the present model is the introduction of isoform-specific models for the major ionic channel currents present in the SAN, which include \(I_{Na}\) (consisting of \(I_{Na1,1}\) and \(I_{Na1,5}\)), \(I_{CaL}\) (consisting of \(I_{CaL,1,2}\) and \(I_{CaL,1,3}\)), \(I_{CaT}\) (consisting of \(I_{CaT,1,1}\)). Model equations and related parameters for these isoform-specified ionic channel currents were based on experimental data measured from mouse SAN cells (2, 10, 11, 26, 41, 52, 55, 56, 66). Another advance is its ability to reproduce the experimentally observed effects of ion channel blockers or gene knockouts (\(I_{Na}\), \(I_{CaL}\), \(I_{CaT}\), \(I_{Kr}\), and \(I_{K}\)) on pacemaking APs of the mouse SAN (11, 39, 41, 52, 56).

**Key Achievements of the New Model**

A key achievement of the present model is that the simulated APs (Fig. 3) were comparable with those recorded from mouse SAN cells in terms of AP characteristics, including CL, APD\(_{50}\), APD\(_{90}\), OS, MDP, \(dV/dt_{max}\), TOP, and DDR (see Table 3). These models could reproduce experimental data of voltage clamp for some major currents (Figs. S1–S5) as well as the functional roles of isoform-specific channels of \(I_{Na}\) and \(I_{CaL}\), which were more accurate than those by the previous Mangoni et al. (56) model. The functional roles of \(I_{Kr}\) and \(I_{K}\) have been explored in the model and indicate future directions of experimental quantification of mouse SAN electrophysiology. The simulated functional roles of all other channels also matched experimental data (see Results and Figs. 3–11). The model also incorporated an intracellular Ca\(^{2+}\) handling mechanism including the Ca\(^{2+}\) clock, which, together with the membrane clock, allows the simulation of various experimentally observed findings regarding intracellular Ca\(^{2+}\). Therefore, the present model provides a basis for further simulating the initiation and conduction of cardiac pacemaking activity in the intact tissue of the mouse SAN and atrium in the future.

Fig. 12. Effects of Iso. A: solid lines denote control, whereas dashed lines denote Iso simulations. Shown are simulated control AP (top), \([\text{Ca}^{2+}]_{\text{iub}}\) (middle), and \([\text{Ca}^{2+}]_{\text{iub}}\) (bottom) profiles. B: CL under control (CL = 212.21 ms) and Iso (CL = 163.59 ms) simulations. C: DDR under control (DDR = 0.178 mV/ms) and Iso (DDR = 0.23 mV/ms) conditions.
Limitations of the Model

Limitations of model components. In the model, the functional effects of \(I_{Na,1.1}\) (Fig. 4) and \(I_{CaL,1.2}\) (Fig. 5) were limited. This is partly due to the window currents of both these isoforms being small compared with other dominant isoforms (Figs. S1 and S2). Furthermore, these window currents line in the diastolic depolarization phase of the AP, where \(I_{NaCa}, I_{f}\), and intracellular \(Ca^{2+}\) mechanisms play a predominant role. The biophysical properties of these isoforms will be improved as experimental data become available. A second limitation of the model is that \(I_{Kr}\) block did not affect pacemaking rates, in contrast to our experimental observations. In most contemporary models of the SAN, \(I_{Kr}\) block causes increased pacemaking along with a reduction of APA. This limitation may be due to the inadequate modeling of \(I_{Kr}\) using a Hodgkin-Huxley formulation (36), as stated below. The modeling of \(I_{Kr}\) and \(I_{CaT}\) can also be further improved when more experimental data on their biophysical properties become available. Finally, the intracellular \(Ca^{2+}\) mechanism did not modulate pacemaking as strongly in the present model compared with the study of Maltev and Lakatta (50). Although block of SR uptake or release showed the experimentally observed alterations in pacemaking, the augmentation of \(P_{up}\) in the present model had a smaller effect compared with the rabbit model (50). This is a consequence of the large current densities of \(I_{CaL}, I_{CaT}\), and \(I_{f}\). Furthermore, the present model consisted of ionic currents \(I_{Na}\) and \(I_{Kr}\), which are absent in the model of Maltev and Lakatta (50), which also contributes the differences in the functional roles of \(Ca^{2+}\) clocks between the two models. The role of the \(Ca^{2+}\) clock in SAN pacemaking is still under debate (27), and further experimental quantification of SAN cellular intracellular mechanisms is definitely required.

Lack of complete experimental data. There is a lack of a complete data set on ion channel gating and kinetics, especially the intracellular \(Ca^{2+}\) handling mechanisms from the mouse SAN. In model development, we considered mouse SAN-specific biophysical data for some major currents but implemented generic current models for other channel currents (Table S1), which either have a small effect (e.g., \(I_{ks}\)) or are primarily fine tuning tools for the model development (e.g., \(I_{NaK} \) and background currents). Although the mouse is a widely used animal model in the study of SAN and atrial arrhythmias, the quantification of the biophysical properties of mouse membrane electrophysiology is still limited. In some instances, we need to use data obtained either at low temperature or from different species. Uncertainty about the accuracy of the experimental data further limited model functionality. The models also do not include some currents known to play important roles in the mouse SAN, for example, Akt-activated \(K^{+}\) current (18, 47), ATP-sensitive \(K^{+}\) current (18), a \(Ca^{2+}\)-activated nonselective cationic current (12), and store-activated \(Ca^{2+}\) channel currents (30).

Model limitations due to Hodgkin-Huxley ion currents and lack of the \(Ca^{2+}\) spark. Hodgkin-Huxley formulation as basis of ion channel currents and passive diffusion of intracellular \(Ca^{2+}\) have already been shown to be limiting factors for mathematical models of cardiac APs (50). For the ion channel currents, two-state Hodgkin-Huxley formulation cannot faithfully simulate the activation, inactivation, and deactivation process as a multisite Markovian chain formulation does. However, the Markovian chain formulation requires extensive experimental data obtained at various protocols for validating model parameters. Otherwise, the parameter set may not be unique. To our best knowledge, such experimental data necessary for developing a well-validated Markovian chain model for mouse SAN ion channels are not yet available. Therefore, two-state Hodgkin-Huxley formulation was implemented in the present models.

\(Ca^{2+}\) diffusion from the subspace to the myoplasm, \(Ca^{2+}\) release and uptake by the SR, and \(Ca^{2+}\) buffering mechanisms were adopted from the parent Kurata et al. (37) model and from Shannon et al. (73). It allowed simulation of the experimentally observed effects of \(Ca^{2+}\)/calmodulin-dependent protein kinase II, cyclopiazonic acid, and RyRs (38, 48–50). Investigating the role of \(Ca^{2+}\) sparks in driving SAN cell pacemaking due to the lack of spatially extended considerations of \(Ca^{2+}\) dynamics, as done in our recent study (76), would be the next modeling challenge.

Despite these limitations, the models presented here represent a significant progress in developing biophysically detailed mathematical models for mouse SAN cells and form a basis for further development with the advent of new experimental data.

Conclusions

In this study, a mathematical model for pacemaking APs of the mouse SAN cell has been developed. This model forms an important step leading toward a “virtual whole heart” of the mouse. Using the model, we analyzed the functional role of individual ion channel currents and intracellular \(Ca^{2+}\) handling on generating mouse pacemaking APs. Our simulation data have shown that the genesis of pacemaking APs is a coordinated action of all ion channel currents (including both depolarizing and repolarizing currents) and the intracellular \(Ca^{2+}\) clock, rather than being regulated by a single factor. For example, block of inward depolarizing currents, such as \(I_{Na}, I_{f}, I_{CaT}, I_{ks}, \) or \(I_{NaCa}\), slowed down pacemaking APs, highlighting their functional contributions to mouse SAN pacemaking APs. Block of outward repolarizing current, such as \(I_{Kr}\), abolished the pacemaking AP, indicating its important role as well. In the present model, intracellular \(Ca^{2+}\) handling has been shown to contribute to pacemaking APs (50) but does not underestimate the importance of HCN-related ionic pacemaking mechanisms (4).

APPENDIX: MODEL EQUATIONS

Membrane Potential

\[
\text{d}V/\text{d}t = -(I_{Na,1.1} + I_{NaL,1.5} + I_{CaL,1.2} + I_{CaL,1.3} + I_{CaT} + I_{Kr} + I_{ks} + I_{l} + I_{in} + I_{un} + I_{k1} + I_{a} + I_{NaK} + I_{NaCa} + I_{h,Na} + I_{H,K} + I_{H,Ca})/C_m
\]

Gating Variables

\[
\text{d}g/\text{d}t = (g_s - g)/\tau_s \quad \text{for any gating variable } g \text{ with steady-state value } g_s
\]

Reversal Potentials

\[
E_{K} = (RT/F)\ln([K^+]_o/[K^+]_i)
\]

\[
E_{Na} = (RT/F)\ln([Na^+]_o/[Na^+]_i)
\]

\[
E_{Ca} = (RT/2F)\ln([Ca^{2+}]_o/([Ca^{2+}]_{sub})
\]

\[
E_{Ks} = (RT/F)\ln([K^+]_o + 0.12[Na^+]_o)/([K^+]_i + 0.12[Na^+]_i)
\]
MATHEMATICAL MODEL OF MOUSE SINOATRIAL NODE CELLS

$I_{Na,1.1} \text{ and } I_{Na,1.5}$

$I_{Na,1.1} = g_{Na,1,1} m_{1,1} h_{1,1}[Na^+]_o V \left[ e^{(V-V_{Na})/FRT} - 1 \right] (e^{FRT} - 1) (V+35)/10.22$

$I_{Na,1.5} = g_{Na,1,5} m_{1,5} h_{1,5}[Na^+]_o V \left[ e^{(V-V_{Na})/FRT} - 1 \right] (e^{FRT} - 1) (V+35)/10.22$

$
\begin{align*}
    m_{1,1} &= \frac{1}{1 + e^{(V+35)/5}} \\
    h_{1,1} &= \frac{1}{1 + e^{(V+6)/3}} \\
    f_{1,1} &= \frac{1}{1 + e^{(V+35)/5}} \\
    m_{1,5} &= \frac{1}{1 + e^{(V+45)/7.22}} \\
    h_{1,5} &= \frac{1}{1 + e^{(V+62.578)/6.084}} \\
    f_{1,5} &= \frac{1}{1 + e^{(V+35)/5}}
\end{align*}
$

$F_{Na} = 0.0952 e^{-0.6247(V+34.4)/10.22} (1 + 0.66 e^{-0.225(V+63.7)}) + 0.0869$

$\begin{align*}
    h_{1,1} &= (1 - F_{Na}) h_{1,1} + F_{Na} f_{1,1} \\
    h_{1,5} &= (1 - F_{Na}) h_{1,5} + F_{Na} f_{1,5} \\
    \tau_m &= 0.6247 \left[ 0.832 e^{-(V+46.7)/2.985} + 0.627 e^{V+55.01/12.195} \right] + 0.04569
\end{align*}$

$\begin{align*}
    \tau_h &= 0.113 \left[ 1 + 13475.066 e^{-(V-59.398)/15.645} + 1 + 1.113 e^{-(V-86.768)/8.059} \right]^{-1} \\
    \tau_f &= 0.125 \left[ 1 + 140557.232 e^{-(V-59.455)/17.380} + 1 + 2.671 e^{-(V-68.931)/18.237} \right]^{-1}
\end{align*}$

$I_{Ca,1.2} \text{ and } I_{Ca,1.3}$

$I_{Ca,1.2} = g_{Ca,1,2} d_{1.2} f_{1.2} f_{Ca}(V-V_{Ca})$

$I_{Ca,1.3} = g_{Ca,1,3} d_{1.3} f_{1.3} f_{Ca}(V-V_{Ca})$

$d_{1.2} = \frac{1}{1 + e^{-(V+3)/5}}

f_{1.2} = \frac{1}{1 + e^{(V+36.4)/6}}$

$d_{1.3} = \frac{1}{1 + e^{(V+13.5)/6}}$

$f_{1.3} = \frac{1}{1 + e^{(V+35)/5}}$

$\alpha_{d_{1}} = -28.39(V+35)/e^{-(V+35)/2.5-1} - 84.95V/(e^{-0.208V-1})$

$\beta_{d_{1}} = 11.43(V-5)/e^{(0.4V-5)-1}$

$\tau_{d_{1}} = 2.000/(\alpha_{d_{1,1,2}} + \beta_{d_{1,1,2}})$

$\tau_{f_{1,1,2}} = 7.485 + 45.774 e^{-(V+24.753)/12.13}$

$\tau_{f_{1,1,3}} = 7.485 + 45.774 e^{-(V+28.753)/11.2}$

$\tau_{f_{Ca}} = \frac{K_{m_{Ca}}}{(K_{m_{Ca}} + [Ca^{2+}]_{sub})}$

$\tau_{f_{Ca}} = f_{Ca}/\alpha_{f_{Ca}}$

$I_{CaT}$

$I_{CaT} = g_{CaT} d_{1.2} f_{1.2} f_{t}(V-V_{Ca})$

$d_{t} = \frac{1}{1 + e^{V+36.4/6}}$

$f_{t} = \frac{1}{1 + e^{V+61.7/5.6}}$

$\tau_{f_{Ca}} = 0.0153 e^{-(V+61.7)/83.3 + 0.015 e^{V+61.7/15.38}}$

$I_{Kr}$

$I_{Kr} = g_{Kr} P_{Kr} P_{Kr}(V-V_{Kr})$

$P_{Kr} = 1 + e^{-(V+21.74)/9.757}$

$\tau_{P_{Kr}} = 0.7/(0.003596 e^{(V+15.33) + 0.00017 V^{125.868}})$

$P_{Kr} = 1/(1 + e^{V+28.6/17.1})$

$\tau_{C_{Kr}} = 0.2 + 0.9/(0.1 e^{V5.465} + 0.656 e^{V106.15})$

$I_{Ks}$

$I_{Ks} = g_{Ks} s(V-V_{Ks})$

$x_{s} = 1/[1 + e^{-(V+20.876)/11.85}]$

$\tau_{P_{Ks}} = 1.000/[1 + e^{-(V+48.911)/0.630}] + e^{-V35.317}$

$I_{f}$

$I_{f} = I_{Na} + I_{K}$

$I_{Na} = 0.383 g_{Na}(V-V_{Na})$

$I_{K} = 0.6617 g_{K}(V-V_{Na})$

$y_{1} = 1/(1 + e^{(V+106.8)/16.3})$

$\tau_{y} = 1.505/(e^{-0.011V+590.3} + e^{V+85.1}/17.2)$

$I_{a}$

$I_{a} = g_{a} q_{a}(V-V_{a})$

$q_{a} = 1/[1 + e^{V+6.7/5}]$

$\alpha_{q_{a}} = 1/[0.15 e^{(V-1)/10.22} + 0.2 e^{V/700}]$

$\beta_{q_{a}} = 1/[16 e^{V/18} + 15 e^{V/60}]$

$\tau_{q_{a}} = 1/(\alpha_{q_{a}} + \beta_{q_{a}})$

$I_{Kl}$

$I_{Kl} = g_{Kl}[K^{+}]_{o}(V-V_{Kl})/[1 + e^{V-0.07(V-E_{Kl})}][[K^{+}]_{o} + 0.229)]$

$I_{wo}$ and $I_{ws}$

$I_{wo} = g_{wo} q_{o}(V-V_{o})$

$I_{ws} = g_{ws} r(V-V_{w})$

$r_{w} = 1/[1 + e^{(V-19.3)/15}]$

$\tau_{r} = 9 + 47.52[1.037 e^{V/20.61} + 0.369 e^{12/(V+23.84)}]$

$q_{w} = 1/[1 + e^{(V+49)/13.1}]$

$\tau_{q} = 6.06 + 39.1/[0.57 e^{-(V+449.5)} + 0.065 e^{0.1V+45.3}]$

$I_{NaK}$

$I_{NaK} = \frac{1}{[K^{+}]_{o}}[1 + (K_{m_{NaK}}/([K^{+}]_{o})^{1.2})^{[1 + e^{(V-P_{Na}-E_{Na})/30}]^{-1}}$

$I_{NaCa}$

$I_{NaCa} = k_{NaCa}(s_{x} - s_{y}(x_{1} + x_{2} + x_{3} + x_{4}))$

$d_{1} = 1 + ([Ca_{2+}]_{sub}/K_{Ca}) + e^{-(V_{Ca})/FRT} + ([Na^{+}]_{o}/K_{Ca}) + ([Na^{+}]_{o}/K_{Ca})[1 + [Na^{+}]_{o}/K_{Ca}]_{o} + ([Na^{+}]_{o}/K_{Ca})[1 + [Na^{+}]_{o}/K_{Ca}]_{o}$

$k_{13} = ([Na^{+}]_{o}/K_{Ca})([Na^{+}]_{o}/K_{Ca})_{o}$

$k_{12} = ([Ca^{2+}]_{sub}/K_{Ca}) e^{-(V_{Ca})/FRT}/d_{1}$

$k_{14} = ([Na^{+}]_{o}/K_{Ca}) ([Na^{+}]_{o}/K_{Ca})_{o} (1 + [Na^{+}]_{o}/K_{Ca}) e^{-(V_{Ca})/FRT}/d_{1}$

$k_{44} = e_{-(V_{Ca})/FRT}$
Ca\textsuperscript{2+} Handling

\[ J_{up} = \frac{[Ca^{2+}]_{up}/K_{up} - ([Ca^{2+}]_{mem}/K_{mem})_{up}}{1 + ([Ca^{2+}]_{up}/K_{up} - ([Ca^{2+}]_{mem}/K_{mem})_{up})} \]

\[ J_{rel} = k_{O}([Ca^{2+}]_{rel} - ([Ca^{2+}]_{sub}) \]

\[ k_{CaSR} = k_{Ca}/k_{CaSR} \]

\[ dO/dt = (k_{sSRCA} \times [Ca^{2+}]_{sub} R - k_{Ca} \times Ca^{2+}) \]

\[ dI/dt = (k_{sSRCA} \times [Ca^{2+}]_{sub} O - k_{Ca} \times Ca^{2+}) \]

\[ dR/dt = (k_{Ca} \times R - k_{sSRCA} \times [Ca^{2+}]_{sub} R) \]

\[ dRI/dt = (k_{Ca} \times R - k_{sSRCA} \times [Ca^{2+}]_{sub} R) \]

\[ Ca^{2+} diffusion. \]

\[ J_{Ca,diff} = ([Ca^{2+}]_{sub} - [Ca^{2+}]_{i}) / \tau_{Ca,diff} \]

Intracellular ionic concentrations.

\[ d[Ca^{2+}]_{i}/dt = (J_{Ca,diff} \times V_{sub} - J_{up} \times V_{up} / V_{i} - ([CM]_{i} \times df_{CM}/dt + [TC]_{i} \times df_{TC}/dt + [TMC]_{i} \times df_{TMC}/dt) \]

\[ d[Ca^{2+}]_{sub}/dt = \left[ - (I_{Ca,1.2} + I_{Ca,1.3} + I_{Ca,1.4} + I_{Ca} - 2J_{NaCa}) / 2F \right] + J_{rel} \times V_{rel} / \left[ (V_{rel} - J_{Ca,rel} - [CM]_{i} \times df_{CM}/dt \right) \]

\[ d[Ca^{2+}]_{rel}/dt = J_{rel} - J_{rel} \times [CO] \times df_{CO}/dt \]

\[ d[Ca^{2+}]_{up}/dt = J_{up} - J_{Ca,up} \times V_{up} \]

\[ d[Na^{+}]_{i}/dt = - (I_{Na,i} + I_{Na,1.3} + I_{Na,1.5} + 3J_{Na} + 3J_{NaCa} + I_{Na} + I_{Na,Na}) \times F_{V} \]

\[ d[K^{+}]_{i}/dt = - (I_{K} + I_{Kr} + I_{Kt} + I_{K1}) \times F_{V} \]

\[ Ca^{2+} buffering. \]

\[ df_{TC}/dt = k_{TC}([Ca^{2+}]_{i} (1 - f_{TC}) - k_{TC} f_{TC} \]

\[ df_{TMC}/dt = k_{TMC}([Ca^{2+}]_{i} (1 - f_{TMC}) - k_{TMC} f_{TMC} \]

\[ df_{TM}/dt = k_{TMM}([Ca^{2+}]_{i} (1 - f_{TMM}) - k_{TMM} f_{TMM} \]

\[ df_{CM}/dt = k_{CM}([Ca^{2+}]_{i} (1 - f_{CM}) - k_{CM} f_{CM} \]

\[ df_{CO}/dt = k_{CO}([Ca^{2+}]_{rel} (1 - f_{CO}) - k_{CO} f_{CO} \]

GRANTS

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DISCLOSURES

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REFERENCES


