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Hysteresis and bi-stability in a realistic cell-model for calcium oscillations and action potential firing

J.M.A.M. Kusters,1 J.M. Cortes,1,2 W.P.M. van Meerwijk,3 D.L.Ypey,3 A.P.R. Theuvenet,3 and C.C.A.M. Gielen1

1Dept. of Biophysics, Radboud University Nijmegen, 6525 EZ Nijmegen, The Netherlands
2Institute for Adaptive and Neural Computation, School of Informatics, University of Edinburgh, EH1 2QL, UK
3Dept. of Cell Biology, Radboud University Nijmegen, 6525 ED Nijmegen, The Netherlands

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Many cells reveal oscillatory behavior. Some cells reveal action potential firing corresponding to Hodgkin-Huxley (HH) type dynamics of ion-channels in the cell membrane. Another type of oscillation relates to periodic IP3-mediated calcium transients in the cytosol. In this study we present a bifurcation analysis of a cell with an excitable membrane and an IP3-mediated intracellular calcium oscillator. With IP3 concentration as a control parameter the model reveals a complex, rich spectrum of both stable and unstable solutions with hysteresis corresponding to experimental data. The range of hysteresis is largest for realistic parameter values of the model, illustrating the functional importance of hysteresis.

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Complexity and transitions among stable and unstable states are ubiquitous in biological systems [1, 2]. In physics instabilities in emerging collective properties have been studied since many years [3–6]. Recently the phenomenon of multi-stability with hysteresis has also awakened a large interest in biology [7]. Instabilities, for instance, have been shown to be responsible for genetic alterations in tumor development [8, 9] and for efficient information processing in the brain, such as in odor encoding [10, 11]. Multistable systems allow changes among different stable states. These transitions can be due to external input or due to instabilities which may serve as an alternative to switch between different branches of stable states [7]. Bistability is advantageous to prevent the system from reaching intermediate states. In addition, hysteresis may help to keep the system in a particular stable state, preventing it from sliding back to another state [12]. This is useful, for instance, in cell mitosis. Once initiated, it should not be terminated before completion [13].

At the network level, multistability plays an important role in cell signaling as well [14, 15]. Communication between cells takes place at synaptic contacts, where an action potential arrival releases a neurotransmitter, thus affecting the post-synaptic potential of the target cell. This information at the cell membrane is transferred to the cell nucleus by second messengers, causing gene expression. Calcium is one such second messenger and calcium transients have been observed over a wide range of frequencies, with a chaotic or deterministic oscillating pattern [16].

Oscillatory behavior of cells is typically the result of two mechanisms. The first mechanism is located at the cell membrane and is related to periodic action-potential firing, usually triggered by input from other cells in the network. The other mechanism relates to oscillations in the concentration of free intracellular calcium by calcium release from the endoplasmic reticulum (ER) store. In this study we show how coupling of these two simple systems leads to a rich behavior with multiple stable and unstable states with hysteresis, in agreement with experimental observations. We present a simplified model, which captures the basic characteristics of normal rat kidney (NRK) fibroblasts reported in [17], and which reproduces, on the basis of single-cell and single-channel data [18], the kinetics for both the membrane ionic currents and the intracellular calcium oscillator.

The dynamics of the NRK membrane potential depends on the sum of ion currents through the membrane:

$$\frac{dV_m}{dt} = -\frac{1}{C_m} \sum I_i$$

where $V_m$ is the membrane potential and $C_m=20 \text{ pF}$ is the capacitance of the membrane. The most relevant currents are those through the inward rectifier potassium channel ($I_{K_i}$), the L-type Ca-channels ($I_{CaL}$), Ca-dependent chloride channels ($I_{Cl(Ca)}$), leak channels ($I_{L_k}$), and SOC-channel ($I_{SOC}$). The dynamics of the L-type Ca-channel is given by $I_{CaL} = m \cdot h \cdot G_{CaL} (V_m - E_{CaL})$ with an activation ($m$) and inactivation ($h$) variable. The dynamics of $m$ and $h$ are described by first order differential equations of the type

$$\frac{dx}{dt} = \frac{x_\infty (V) - x}{\tau_x (V)}$$

where $x_\infty$ and $\tau_x$ correspond to the steady-state (membrane potential and conductance-dependent) (in)activation and time constant, respectively.

The Ca-dependent Cl-current $I_{Cl(Ca)}$ is given by

$$I_{Cl(Ca)} = \frac{[Ca^{2+}]_{cyt}}{[Ca^{2+}]_{cyt,eq} + K_{Cl(Ca)}} G_{Cl(Ca)} (V_m - E_{Cl(Ca)})$$

The Cl-current increases with cytosolic calcium concentration $[Ca^{2+}]_{cyt}$, causing a depolarization to the Nernst
potential of Cl ions $E_{Cl(Ca)}$ near -20 mV. For the definition of the other currents, see [19]; for details, see [17].

The flux of calcium through the membrane is the sum of the fluxes of Ca$^{2+}$ ions through the L-type Ca-channel and the SOC-channel and by extrusion by the PMCA-pump $J_{PM} = -\frac{V_{cl}}{V_{m}}(I_{CaL} + I_{SOC}) - J_{MCA}$.

Calcium in the cytosol is buffered by proteins in the cytosol. Buffering is described by first order interactions between $[Ca_{cys}]$ and the concentration of the buffer $\frac{d[BCa]}{dt} = k_{on}([T] - [BCa])([Ca^{2+}]_c) - k_{off}[BCa]$ (4)

where $[BCa]$ represents the total buffer concentration and $[BCa]$ represents the concentration of buffered calcium.

The dynamics for the calcium concentration in the ER depends on the sum of fluxes through the IP3-receptor (J$_{IP3}$), leak through the ER-membrane (J$_{kER}$) and by uptake by the SERCA pump (J$_{SERCA}$) $\frac{d(Ca^{2+})_ER}{dt} = \frac{A_{ER}}{Vol_{ER}}(-J_{IP3} - J_{kER} + J_{SERCA})$ (5)

where the ratio of the surface $A_{ER}$ and the volume $Vol_{ER}$ of the ER transforms the flux of Ca$^{2+}$ ions through the ER-membrane into changes of $[Ca^{2+}]_ER$-concentration. The flux through the IP3-receptor is described by

$J_{IP3} = f_s w^{3} K_{IP3} ([Ca^{2+}]_ER - [Ca^{2+}]_ER)$ (6)

where $[Ca^{2+}]_ER - [Ca^{2+}]_ER$ is the concentration difference between calcium in the ER and in the cytosol. $K_{IP3}$ is the rate constant per unit area of IP3-receptor mediated release. $f_s$ and $w$ represent the fraction of open activation and inactivation gates, respectively. The dynamics of $f$ and $w$ is given by Eq. 2, but since the time constant for $f$ is fast, we use $f_s$ instead of $f$. $f_s$ and $w_s$ depend both on the cytosolic calcium concentration $f_s = \frac{[Ca^{2+}]_ER}{K_{fIP3} + [Ca^{2+}]_ER}$ (7)

$w_s = \frac{K_{IP3}}{K_w[IP3]} + K_{w}[Ca^{2+}]_ER$ (8)

The excitable membrane and the IP3-oscillator are coupled by $[Ca^{2+}]_c$. During an action potential opening of the L-type calcium channel causes a large inward current of Ca-ions in the plasma membrane. After an action potential or Ca-oscillation the reduction of cytosolic calcium by the activity of the SERCA and PMCA pump reduces $E_{Cl(Ca)}$, such that the membrane repolarizes to the rest potential near -70 mV.

The dynamics of the complete single-cell model depends on the time evolution of the 7-dimensional vector $\hat{x}(t) = (m, h, w, [BCa], V_n, [Ca^{2+}]_c, [Ca^{2+}]_ER)^T$. Using Eqs. 1, 2, 4 and 5 and keeping in mind the dependence of $[Ca^{2+}]_c$ on the Ca-fluxes through cell membrane and ER-membrane, this can be written as

$\frac{d}{dt}\hat{x}(t) = J(x(t))\hat{y}(t)$

In order to find the stable states of $\hat{x}(t)$ it is important to notice that the cell behavior corresponds to an autonomous nonlinear dynamical system with periodic oscillatory behavior. To find its stable periodic solutions we assume that $\hat{x}(t)$ is the periodic solution of the system in Eq. 9. For any perturbation $\hat{y}(t)$ around the stable periodic solution $\hat{x}(t)$ substitution of the solution $\hat{x}(t) = \hat{x}(t) + \hat{y}(t)$, Taylor expansion around the period solution $\hat{x}(t)$ and retaining only linear terms, gives

$\hat{y}(t) = J(\hat{x}(t))\hat{y}(t)$

where $J(\hat{x}(t))$ is the Jacobian matrix $\nabla_x f(\hat{x}(t))$ at the point $\hat{x}(t)$ on the periodic solution. The eigenvectors $\hat{\lambda}(t)$ of $J$ form the fundamental matrix $\Phi(t) = [\hat{\lambda}(t), \hat{\mu}(t), \ldots, \hat{\eta}(t)]$. Any fundamental solution to the periodic system $\Phi(t)$ has the form $Y(t) = Z(t)e^{\Phi}$, where $Y, Z$ and $\Phi$ are $n \times n$ matrices ([20]) with $Z(t) = Z(t + T)$. In particular we can choose $Y(0) = Z(0) = I$, so that $Y(t) = Z(T)e^{\Phi}$. It then follows that the behavior of the solutions in the neighborhood of $\hat{x}(t)$ is determined by the eigenvalues of the matrix $e^{\Phi}$. The (complex) eigenvalues $\lambda_i$ of this matrix (the Floquet multipliers ([20])) provide a measure of the local orbital divergence $|\lambda_i| > 1$ or convergence $|\lambda_i| < 1$ along a particular direction over one period of the periodic motion.

We will explore the bifurcation behavior and local stability of the electrically excitable membrane and intracellular calcium oscillator, separately, and then compare the results for a complete model, where the membrane oscillator and intracellular calcium oscillator are coupled, using the software packages AUTO [21] and XPP [21].

The excitable membrane can be studied in isolation by setting the IP3 concentration to zero to eliminate persistent intracellular calcium oscillations. The dynamics of the membrane is studied as a function of the leakage parameter $K_{kER}$ to produce variations in $[Ca^{2+}]_c$. Fig. 1 shows the hysteresis diagram for the membrane with the steady states of $[Ca^{2+}]_c$ ($A$) and the membrane potential $V_m$ ($B$). $[Ca^{2+}]_c$ and $V_m$ increase gradually until $K_{kER} \approx 58.0 \times 10^{-3} dm/s$. Then the increased calcium concentration opens the Cl($Ca$)-channels and
the membrane potential depolarizes to the Nernst potential of the $\text{Cl}(\text{Ca})$-channels close to $-20 \text{ mV}$ (see Fig. 1B). This sudden depolarisation opens the $L$-type $\text{Ca}$-channels causing a calcium inflow through the membrane into the cytosol, which explains the sudden increase of $[\text{Ca}^{2+}]_{\text{cyt}}$ until $2.3 \mu M$. When $K_{\text{K}_{\text{ER}}}$ is decreased, the $L$-type $\text{Ca}$-channels are open, causing an increased $[\text{Ca}^{2+}]_{\text{cyt}}$. This explains why the $\text{Cl}(\text{Ca})$-channels are open and why the membrane potential remains near $-20 \text{ mV}$. Only when $[\text{Ca}^{2+}]_{\text{cyt}}$ decreases to low concentrations, the $\text{Cl}(\text{Ca})$-channels close and the membrane potential repolarizes to $-70 \text{ mV}$.

The dynamics of the intracellular calcium oscillator as a function of the $IP_3$ concentration can be studied by blocking the $L$-type $\text{Ca}$-channels ($G_{\text{Ca,L}}=0$). The bifurcation diagram shows a stable state at low $IP_3$-concentrations, followed by a subcritical Hopf-bifurcation, where the IP3-receptor shows periodic oscillations (open/closed) and large calcium transients in the cytosol. The oscillation frequency increases with $IP_3$-concentration until a subcritical Hopf-bifurcation brings the system into a stable state where the IP3-receptor is continuously open with a constant leak of calcium into the cytosol, see [22, 23]. The bifurcation diagram looks very similar to the top panel in Fig. 3.

The bifurcation diagram for the complete single-cell model is illustrated in Fig. 2, which shows cytosolic calcium concentration ($A$) and membrane potential ($B$) as a function of $IP_3$. The solid and dashed lines represent stable and unstable states, respectively. For small $IP_3$ values the cell has a single stable steady state. For $IP_3 > 0.15 \mu M$ the stable fixed point becomes unstable in a subcritical Hopf bifurcation. Calcium oscillations with action potentials ($B$) occur for $IP_3 \in (0.15, 1.75) \mu M$. In this regime, a rapid calcium inflow from the ER into the cytosol opens the $Ca(Cl)I$-channel, causing an inward current towards the $Cl\text{-Nernst}$ potential at $-20 \text{ mV}$. After closure of the $IP_3$-receptor, calcium is removed from the cytosol by Ca-pumps in the cell membrane and ER, leading to repolarisation to $-70 \text{ mV}$. For $IP_3 > 1.75 \mu M$, the fixed point ($Ca_{\text{cyt}}, V_m \approx (3.00 \mu M, -20 \text{ mV})$) becomes stable in a subcritical Hopf bifurcation. When $IP_3$ is high, the IP3-receptor acts as a constant leak of calcium into the cytosol which opens the $Ca(Cl)I$-channels, causing a depolarization to the $Cl\text{-Nernst}$ potential near $-20 \text{ mV}$ ($B$).

If $IP_3$ decreases, the cell reveals a complex hysteresis pattern. For decreasing $IP_3$ concentrations, the system stays in a single stable steady state with an elevated $Ca_{\text{cyt}}$ near $3 \mu M$ and a membrane potential near $-20 \text{ mV}$ until $IP_3 \approx 0.85 \mu M$. Then, crossing through a Hopf bifurcation causes instability (dashed line) forcing the system to behave as a stable oscillator with calcium oscillations (amplitude $\approx 6 \mu M$) and small membrane potential oscillations around $-20 \text{ mV}$. These oscillations are due to interaction between the $L$-type $\text{Ca}$-channel and the IP3-receptor at elevated cytosolic calcium concentrations. At $IP_3 \approx 0.45 \mu M$ the stable oscillator becomes unstable (dashed line), returning the system to the stable oscillations with large $Ca$-transients and action potentials. Finally, for $IP_3$ values smaller than $0.15 \mu M$ the system returns to a single stable state.

Since the $SOC$ channel in the plasma membrane plays a crucial role in stabilization of the calcium dynamics [17], we studied the dynamics of the cell as a function of the conductance of the SOC channel. Figure 3 shows the hysteresis diagrams for increasing values of $G_{SOC}$. As explained in [17], the cell behavior is unstable for $G_{SOC} = 0.00 \text{nS}$ with either depletion or accumulation of calcium in the ER. For small values of $G_{SOC}$ bist-
FIG. 3: Bifurcation diagrams for different values of $G_{SOC}$. Variations in $[Ca^{2+}]_{c}$ are due to both IP3-mediated calcium oscillations and action potentials for all $G_{SOC}$-values except for $G_{SOC} = 0.20 \text{ nS}$, where the action potentials disappear. For values of $G_{SOC}$ near 0.04 nS the IP3-range of hysteresis has a maximum.

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bility and hysteresis appears. The range of IP3-values with hysteresis is largest for $G_{SOC}$ near 0.04 nS (see Fig. 3). For higher values of $G_{SOC}$, the range of hysteresis decreases until only the typical Hopf-bifurcation for the IP3-mediated calcium oscillations remains for $G_{SOC} = 0.20 \text{ nS}$.

The $SOC$ conductance, which gives the largest hysteresis loop, corresponds to the observed $SOC$-conductance in the literature ([24] and [25]) with values in the range from 0.04 to 0.05 nS. For hepatocytes $SOC$ conductances are between (0.08,0.14) nS [26], but taking into account that the density of ionic channels in hepatocytes is twice as high as in fibroblasts [27, 28], the range of $SOC$-conductances which produce the largest amount of hysteresis is in agreement with values reported by [24, 25] and with our simulation results.

Summarizing, we have presented a model reproducing experimental data on calcium oscillations and action potential generation. A bifurcation analysis reveals hysteresis and a complex spectrum of stable and unstable states. Stability of the cell behavior is dominated by the homeostatic function of the $SOC$ channel. The conductance, which provides the largest range of hysteresis, coincides with the measured values for $G_{SOC}$.

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