Supplementary Material

Journal name: Nonlinear Dynamics

Article title: Multi-Timescale Compound Oscillations in Pyramidal Neurons: Insights from a Three-Compartment Model

Feng Zhang[1], Meili Lu[2], Xile Wei[1]

[1]Tianjin Key Laboratory of Process Measurement and Control, School of Electrical and Information Engineering, Tianjin University, Tianjin, 300072, China

[2]School of Information Technology Engineering, Tianjin University of Technology and Education, Tianjin, 300222, China

Corresponding author: Xile Wei (xilewei@tju.edu.cn)

This PDF file includes:

Section S1. Compound oscillations in layer 5 pyramidal neuron.

To examine the effectiveness of the three-compartment model studied in this paper, we reconstruct the layer 5 pyramidal neuron model in NEURON platform (ModelDB) (Larkum et al., 2009), which is shown in Figure S1(a). The distribution of active ion channels in this model is illustrated in Figure S1(b), where Na^+ channels are located in soma, Ca^{2+} channels in proximal apical dendrite, and NMDA receptor-gated channels in basal dendrite and distal apical dendrite. All the parameter settings are consistent with the original literature. As shown in Figure S1(a), we select three recording locations for the transmembrane potentials in apical dendrite, basal dendrite, and soma, respectively.

The simulation result of this biophysical model is shown in Figure S1(c), where the stimulation current is set to 0.3 nA and is injected from 50 to 250 ms. The discharge behaviors can be summerized as follows:

1) The spikes in soma and basal dendrite are strongly coupled. Each spike in basal dendrite corresponds one-to-one with a spike in soma. In addition, there is spike frequency adaptation in the initial burst.
2) The discharge behavior in apical dendrite has a lower frequency compared to those in soma and basal dendrite. Its depolarization is faster, while the hyperpolarization is slower.
3) During the hyperpolarization phase in apical dendrite, the oscillation activities in soma and basal dendrite gradually terminate.

Thus, this biophysical model exhibits compounded oscillations, which are the focus of this study. Moreover, the three-compartment model we propose can largely reproduce the key behaviors observed in these oscillation activities. As shown in Figure S1(d), we appropriately adjust some parameters of the three-compartment model to simulate the above discharge patterns. Although there are slight differences in periods between the two models, they are qualitatively similar from the perspective of dynamics. Therefore, the dynamical analysis of the three-compartment model can helps us fully understand the mechanisms underlying compound oscillations in above biophysical model.

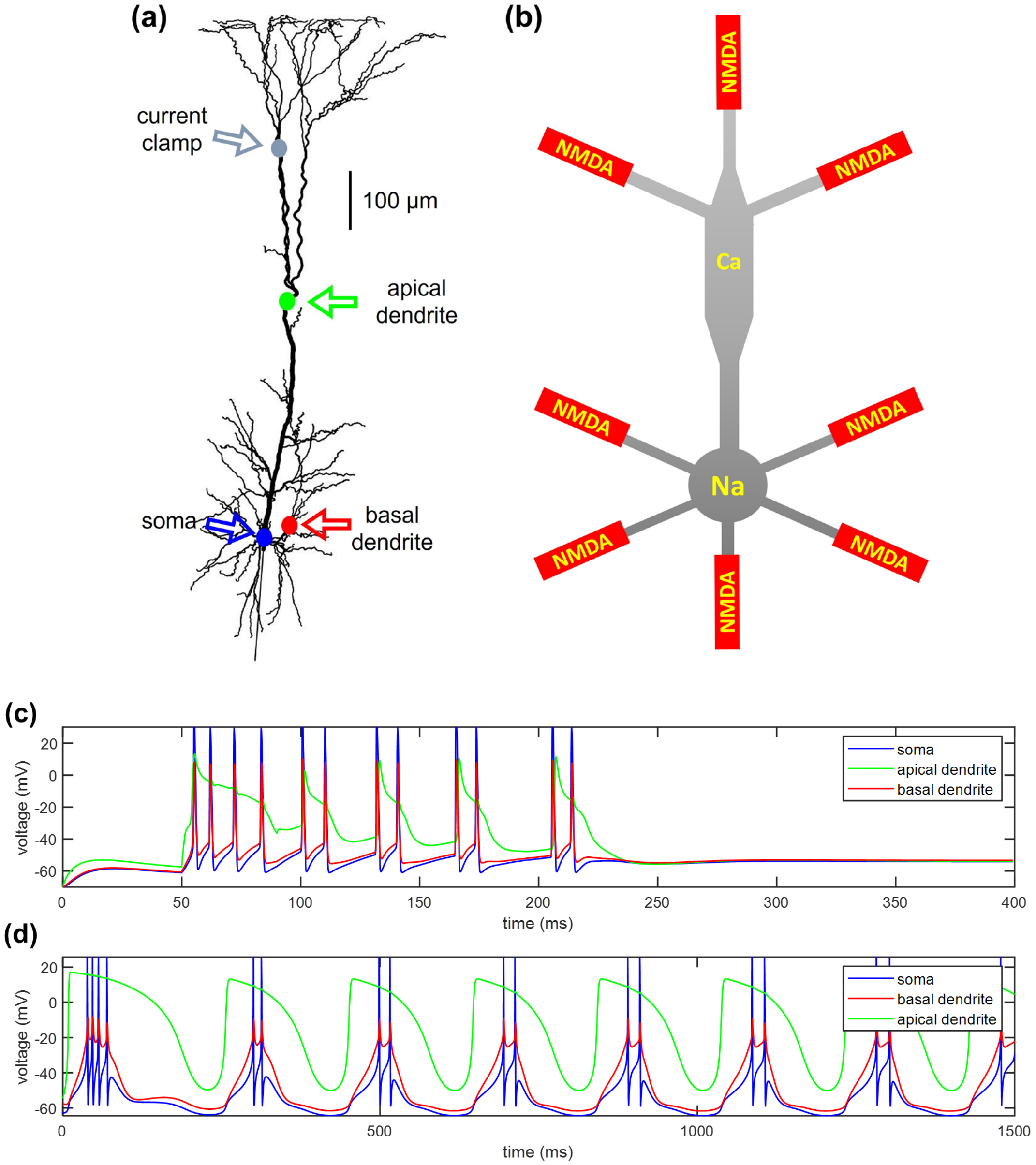

Figure S1. (a) Reconstruction of a layer 5 pyramidal neuron with realistic dendritic morphology. *Grey dot* in apical dendrite represents current clamp used to elicit discharge behaviors in this neuron model. *Green dot, red dot* and *blue dot* represent recording locations of the transmembrane potential in apical dendrite, basal dendrite, and soma, respectively. **(b)** Schematic representation showing the distribution of active ion channels in this biophysical model. **(c)** Numerical simulation of the biophysical model, which exhibits compound oscillations. **(d)** Numerical simulation of the three-compartment model we propose, in which we adjust some parameters of the three-compartment model to mimic the discharge patterns in (c). Specifically, we set $I_{\mathrm{ad}} = 0.05\ \mu\mathrm{A/cm^2}$, $g_{\mathrm{Ca}} = 8\ \mathrm{mS/cm^2}$, $g_{\mathrm{KAHP}} = 0.02\ \mathrm{mS/cm^2}$, $g_{\mathrm{NMDA}} = 1.58\ \mathrm{mS/cm^2}$, and $\tau_{h_{\mathrm{Ca}}} = 70$ ms.

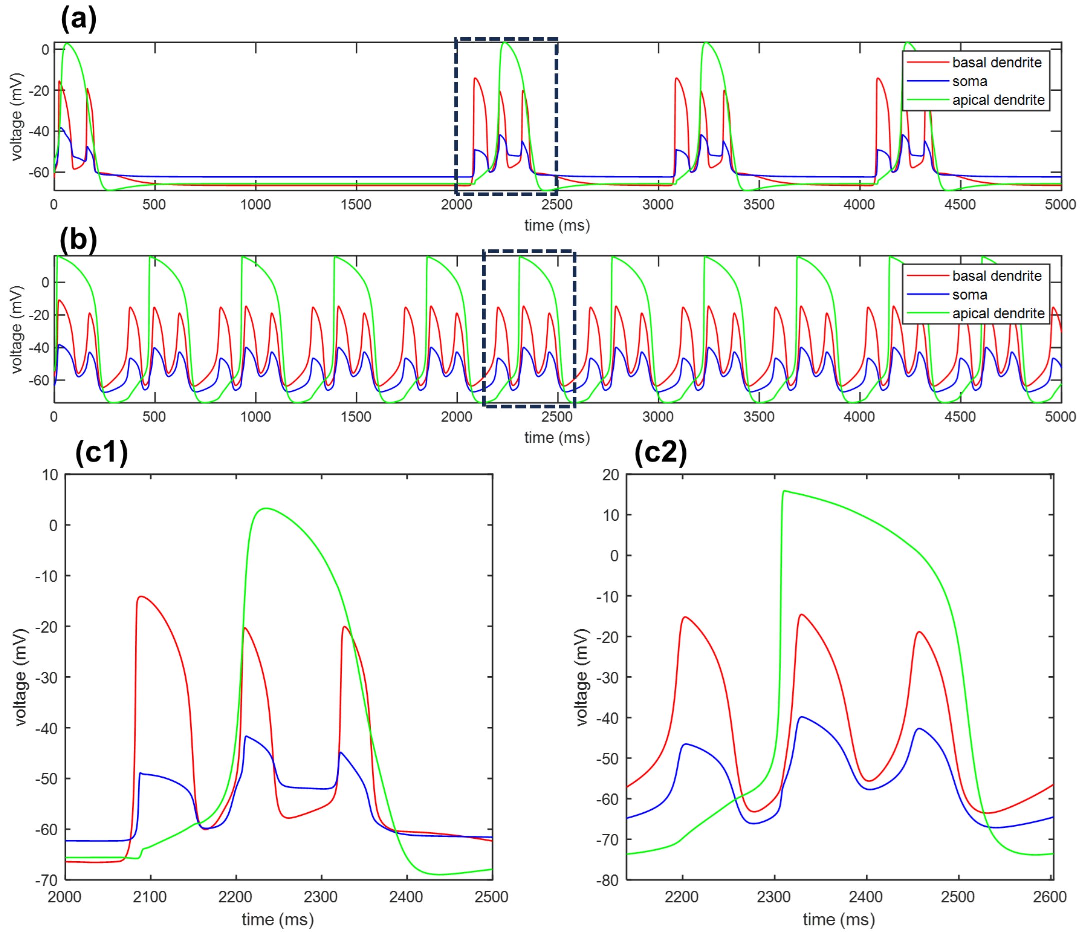

Figure S2. (a) Numerical simulation of the model (Chiang et al., 2018). This model is also a three-compartment model but features a passive soma, i.e., it cannot generate action potentials in soma. All the parameter settings are consistent with the original literature. To elicit discharge behaviors, a 30 ms stimulation current pulse of 15 $\mu A/cm^2$ is injected into the apical dendrite at 2000 ms, 3000 ms, and 4000 ms. **(b)** Numerical simulation of the three-compartment model we propose, in which we block Na^+ channels by setting $g_{\mathrm{Na}} = 0$. To accurately reproduce the firing behaviors, we also set $I_{\mathrm{ad}} = -0.5\ \mu\mathrm{A/cm}^2$, $\tau_{h_{\mathrm{Ca}}} = 100\ \mathrm{ms}$, and $g_{\mathrm{NMDA}} = 2\ \mathrm{mS/cm}^2$. **(c)** Enlarged view of blcak dotted box in (a) and (b) respectively. It can be observed that the firing patterns shown in (c1) are fully reproduced by our three-compartment model shown in (c2). Specifically, the apical dendrite exhibit Ca^{2+} oscillation, the basal dendrite exhibits NMDA oscillation, and the soma only exhibits subthreshold oscillation. The frequency of Ca^{2+} oscillation is slower than that of NMDA oscillation. Moreover, Ca^{2+} oscillation in apical dendrite acts as a source, regulating discharge behaviors in soma and basal dendrite.

Reference

Larkum, M.E., Nevian, T., Sandler, M., Polsky, A., Schiller, J.: Synaptic integration in tuft dendrites of layer 5 pyramidal neurons: a new unifying principle. Science 325(5941), 756–760 (2009). https://doi.org/10.1126/science.1171958

Chiang, C.C., Wei, X., Ananthakrishnan, A.K., Shivacharan, R.S., Gonzalez-Reyes, L.E., Zhang, M., Durand, D.M.: Slow moving neural source in the epileptic hippocampus can mimic progression of human seizures. Sci Rep 8(1), 1564 (2018) https://doi.org/10.1038/s41598-018-19925-7