Naud, Richard; **Marcille, Nicolas**; **Clopath, Claudia**; **Gerstner, Wulfram**
Firing patterns in the adaptive exponential integrate-and-fire model. (English) Zbl 1161.92012
Biol. Cybern. 99, No. 4-5, 335-347 (2008).

Summary: For simulations of large spiking neuron networks, an accurate, simple and versatile single-neuron modeling framework is required. We explore the versatility of a simple two-equation model: the adaptive exponential integrate-and-fire neuron. We show that this model generates multiple firing patterns depending on the choice of parameter values, and present a phase diagram describing the transition from one firing type to another.

We give an analytical criterion to distinguish between continuous adaption, initial bursting, regular bursting and two types of tonic spiking. Also, we report that the deterministic model is capable of producing irregular spiking when stimulated with constant current, indicating low-dimensional chaos. Lastly, the simple model is fitted to real experiments of cortical neurons under step current stimulation. The results provide support for the suitability of simple models such as the adaptive exponential integrate-and-fire neuron for large network simulations.

MSC:

92C20 Neural biology
92C05 Biophysics
37N25 Dynamical systems in biology

Keywords:

Simplified single-neuron models; Firing patterns; Chaos; Electrophysiological taxonomy

Full Text: DOI

References:

[1] Badel L, Lefort S, Brette R, Petersen C, Gerstner W, Richardson M (2007) Dynamic i curves are reliable predictors of naturalistic pyramidal-neuron voltage traces. J Neurophysiol. doi: 10.1152/jn.01107.2007

[2] Bean BP (2007) The action potential in mammalian central neurons. Nat Rev Neurosci 8(6): 451–465. doi: 10.1038/nrn2148 · doi:10.1038/nrn2148

[3] Beierlein M, Gibson JR, Connors BW (2003) Two dynamically distinct inhibitory networks in layer 4 of the neocortex. J Neurophysiol 90(5): 2987–3000. doi: 10.1152/jn.00283.2003 · doi:10.1152/jn.00283.2003

[4] Benda J, Herz AVM (2003) A universal model for spike-frequency adaptation. Neural Comput 15(11): 2523–2564. doi: 10.1162/089976603322385063 · Zbl 1052.92010 · doi:10.1162/089976603322385063

[5] Brette R, Gerstner W (2005) Adaptive exponential integrate-and-fire model as an effective description of neuronal activity. J Neurophysiol 94(5): 3637–3642. doi: 10.1152/jn.00686.2005 · doi:10.1152/jn.00686.2005

[6] Brumberg JC, Gutkin BS (2007) Cortical pyramidal cells as non-linear oscillators: experiment and spike-generation theory. Brain Res 1171: 122–137. doi: 10.1016/j.brainres.2007.07.028 · doi:10.1016/j.brainres.2007.07.028

[7] Chay TR, Rinzel J (1985) Bursting, beating, and chaos in an excitable membrane model. Biophys J 47(3): 357–366 · doi:10.1016/S0006-3495(85)83926-6

[8] Clopath C, Jolivet R, Rauch A, Luscher HR, Gerstner W (2007) Predicting neuronal activity with simple models of the threshold type: Adaptive exponential integrate-and-fire model with two compartments. Neurocomputing 70(10–2): 1668–1673 · doi:10.1016/j.neucom.2006.10.047

[9] Connors BW, Gutnick MJ (1990) Intrinsic firing patterns of diverse neocortical neurons. Trends Neurosci 13(3): 99–104 · doi:10.1016/0166-2236(90)90185-D

[10] Druckmann S, Bannitt Y, Gidon AA, Schuermann F, Segev I (2007) A novel multiple objective optimization framework for constraining conductance-based neuron models by experimental data. Front Neurosci 1(1)

[11] Fourcaud-Trocme N, Hansel D, van Vreeswijk C, BrunelN (2003) How spike generation mechanisms determine the neuronal response to fluctuating inputs. J Neurosci 23(37):11,628–1,640

[12] Gerstner W, Kistler WM (2002) Spiking neuron models : single neurons, populations, plasticity. Cambridge University Press, Cambridge, UK.URL http://www.loc.gov/catdir/samples/cam031/2002067657.html · Zbl 1100.92501

[13] Hill S, Tononi G (2005) Modeling sleep and wakefulness in the thalamocortical system. J Neurophysiol 93(3): 1671–1698. doi:

10.1152/jn.00915.2004 · doi:10.1152/jn.00915.2004

[14] Holden AV (1986) Chaos. Princeton University Press, Princeton, NJ

[15] Hutcheon B, Yarom Y (2000) Resonance, oscillation and the intrinsic frequency preferences of neurons. Trends Neurosci 23(5): 216–222 · doi:10.1016/S0166-2236(00)01547-2

[16] Izhikevich EM (2003) Simple model of spiking neurons. IEEE Trans Neural Netw 14(6): 1569–1572. doi: 10.1109/TNN.2003.820440 · doi:10.1109/TNN.2003.820440

[17] Izhikevich EM (2007) Dynamical systems in neuroscience : the geometry of excitability and bursting. MIT Press, Cambridge, MA

[18] Izhikevich EM, Edelman GM (2008) Large-scale model of mammalian thalamocortical systems. Proc Natl Acad Sci USA 105(9): 3593–3598. doi: 10.1073/pnas.0712231105 · doi:10.1073/pnas.0712231105

[19] Jolivet R, Kobayashi R, Rauch A, Naud R, Shinomoto S, Gerstner W (2007) A benchmark test for a quantitative assessment of simple neuron models. J Neurosci Methods. doi: 10.1016/j.jneumeth.2007.11.006

[20] Koch C (1999) Biophysics of computation : information processing in single neurons. Oxford University Press, New York. URL http://www.loc.gov/catdir/enhancements/fy0605/97051390-d.html

[21] Korn H, Faure P (2003) Is there chaos in the brain? II. Experimental evidence and related models. C R Biol 326(9): 787–840 · doi:10.1016/j.crvi.2003.09.011

[22] Latham PE, Richmond BJ, Nirenberg S, Nelson PG (2000) Intrinsic dynamics in neuronal networks. II. Experiment. J Neurophysiol 83(2): 828–835

[23] Mainen ZF, Sejnowski TJ (1996) Influence of dendritic structure on firing pattern in model neocortical neurons. Nature 382(6589): 363–366. doi: 10.1038/382363a0 · doi:10.1038/382363a0

[24] Markram H (2006) The blue brain project. Nat Rev Neurosci 7(2): 153–160. doi: 10.1038/nrn1848 · doi:10.1038/nrn1848

[25] Markram H, Toledo-Rodriguez M, Wang Y, Gupta A, Silberberg G, Wu C (2004) Interneurons of the neocortical inhibitory system. Nat Rev Neurosci 5(10): 793–807. doi: 10.1038/nrn1519 · doi:10.1038/nrn1519

[26] Mauro A, Conti F, Dodge F, Schor R (1970) Subthreshold behavior and phenomenological impedance of the squid giant axon. J Gen Physiol 55(4): 497–523 · doi:10.1085/jgp.55.4.497

[27] Richardson MJE, Brunel N, Hakim V (2003) From subthreshold to firing-rate resonance. J Neurophysiol 89(5): 2538–2554. doi: 10.1152/jn.00955.2002 · doi:10.1152/jn.00955.2002

[28] Rinzel J, Ermentrout GB (1998) Analysis of neural excitability and oscillations. In: Koch C, Segev I (eds) Methods in neuronal modeling, 2nd edn. MIT Press, Cambridge, pp 251–291

[29] Sabah NH, Leibovic KN (1969) Subthreshold oscillatory responses of the Hodgkin-Huxley cable model for the squid giant axon. Biophys J 9(10): 1206–1222 · doi:10.1016/S0006-3495(69)86446-5

[30] Strogatz SH (1994) Nonlinear dynamics and Chaos: with applications to physics, biology, chemistry, and engineering. Addison-Wesley Pub., Reading, MA. URL http://www.loc.gov/catdir/enhancements/fy0830/93006166-d.html

[31] Tateno T, Harsch A, Robinson HPC (2004) Threshold firing frequency–current relationships of neurons in rat somatosensory cortex: type 1 and type 2 dynamics. J Neurophysiol 92(4): 2283–2294. doi: 10.1152/jn.00109.2004 · doi:10.1152/jn.00109.2004

[32] Toledo-Rodriguez M, Blumenfeld B, Wu C, Luo J, Attali B, Goodman P, Markram H (2004) Correlation maps allow neuronal electrical properties to be predicted from single-cell gene expression profiles in rat neocortex. Cereb Cortex 14(12): 1310–1327. doi: 10.1093/cercor/bhh092 · doi:10.1093/cercor/bhh092

[33] Touboul J (2008) Bifurcation analysis of a general class of nonlinear integrate-and-fire neurons. SIAM J Appl Math 68(4): 1045–1079 · Zbl 1149.34027 · doi:10.1137/070687268

[34] Touboul J, Brette R (2008) Dynamics and bifurcations of the adaptive exponential integrate-and-fire model. Biol Cybernet. doi: 10.1007/s00422-008-0267-4 · Zbl 1161.92016

[35] Vanier MC, Bower JM (1999) A comparative survey of automated parameter-search methods for compartmental neural models. J Comput Neurosci 7(2): 149–171 · doi:10.1023/A:1008972005316

[36] Wang Y, Gupta A, Toledo-Rodriguez M, Wu CZ, Markram H (2002) Anatomical, physiological, molecular and circuit properties of nest basket cells in the developing somatosensory cortex. Cereb Cortex 12(4): 395–410 · doi:10.1093/cercor/12.4.395