ReScience

[Re] Chemical Signalling in the Neurovascular Unit

Alexandra K. Diem[1]

1 Computational Engineering and Design, Faculty of Engineering and the Environment, University of Southampton, Southampton, UK

alexandra.diem@gmail.com

Editor
Name Surname

Reviewers
Name Surname
Name Surname

Received Sep, 1, 2015
Accepted Sep, 1, 2015
Published Sep, 1, 2015

Competing Interests:
The authors have declared that no competing interests exist.

Article repository

Code repository

Data repository

A reference implementation of

→ Witthoft A, Karniadakis GE (2012) A bidirectional model for communication in the neurovascular unit. *Journal of Theoretical Biology* 311: 80-93.

Introduction

Witthoft and Karniadakis [1] introduced a bidirectional model for communication via chemical signalling within the neurovascular unit (NVU), which comprises a neuron, astrocyte and small artery. Functional hyperemia is an important mechanism in the brain, by which an increased neuronal metabolism leads to an increase of blood flow in surrounding arteries in order to maintain adequate oxygen and nutrient supply to the active neurons. This process works via a cascade of chemical signalling processes from neurons to astrocytes to arteries. The unidirectional vascular response to increased neuronal demands has previously been modelled [2,3], however, there is evidence that vascular activity also has an effect on neurons [4]. This bidirectional response is implemented in [1]. The paper contains the differential equations that are being modelled, however no code repository is provided. The model is useful for the investigation of the effect of cerebrovascular diseases on the brain and thus an openly available code repository reproducing the results of this paper will be helpful to other researchers.

Methods

The paper indicates that the original code was written in Matlab, while the reproduction presented here is written in Python 3.5. The model is given as a series of ordinary differential equations (ODE), which are implemented as a function nvu(). This function is solved using the scipy.integrate library. Initial attempts to solve the system of ODE using the standard function odeint() failed. Instead, the equations can be solved using the function ode() with the integration method set to "lsoda", which automatically selects between the Adams method for non-stiff and BDF for stiff problems. The ODE system described in [1] is a stiff system. Values for absolute and relative tolerance have to be set in order for the simulation to finish successfully. These are given in the results section as they differ for different simulations.

The code was implemented following the descriptions of the equations in [1], but upon cross-checking equations against their equivalents in [2,3,4] it became evident that some of the equations contain typographical errors. This was confirmed after contacting the authors of [1]. Changes to the equations are as follows:

- $I_{\Sigma K}$ in (20) should be defined as $I_{\Sigma K} = -J_{\Sigma K} C_{astr} \gamma$

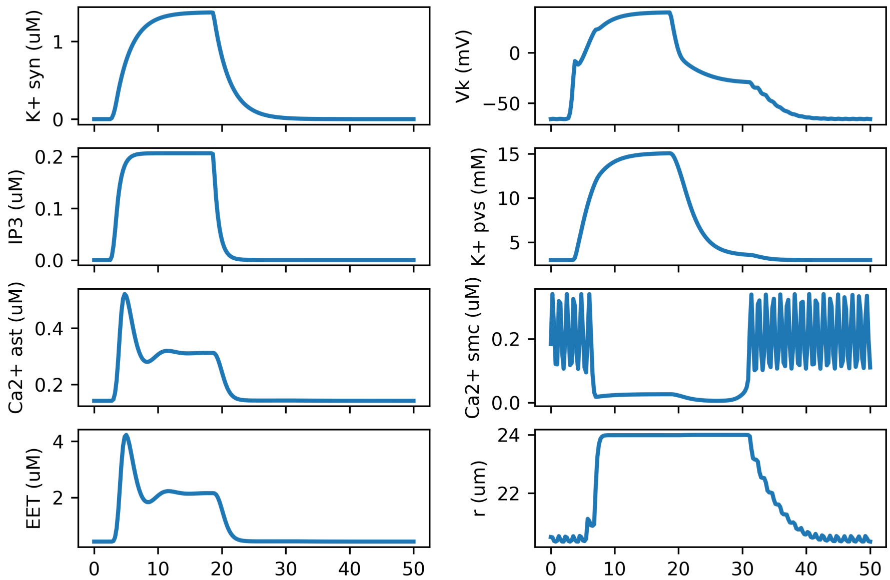

Figure 1: Astrocyte and arterial response during neuronal stimulation. This figure is a reproduction of Figure 5 in the original publication using the code in this repository. Potassium (K^+)) in both the synaptic and perivascular space match their corresponding plots in the original publication, as do calcium (Ca^{2+}) in the smooth muscle cell and the arterial radius. Differences can be seen for Ca^{2+} in the astrocyte, EET and the astrocyte membrane potential V_k. In the case of astrocytic Ca^{2+} and EET the first peak overshoots compared to the results in the original publication, while the remainder of the plots match the original publication. Most interesting is the shape of V_k, which in the first half looks very different from the reproduced figure. Additionally, V_k overshoots into positive values, which is not given in the original publication. Simulation tolerance values atol=1e-7, rtol=1e-7.

- (31) $I_K = g_K n(V_m - v_K)$
- (A.1) Term $\frac{1}{2\alpha} I_{Ca}$ should be αI_{Ca}
- (A.6) The brackets around the exponential function are set incorrectly, it should read $\exp\left(\frac{-(y'-y'_0)^2}{2\left[y'_1/(y'+y'_2)\right]^{2y'_4}}\right) - y'_3$ [4]
- Decimal of parameter a in Table B2 is in the wrong place, it should read $a = 502.65\ \mu m^2$
- The value for $[\mathrm{Ca}^{2+}]_{\mathrm{ER}}$ is not given, but can be found in [2] as $[\mathrm{Ca}^{2+}]_{\mathrm{ER}} = 400 \mu m$

Furthermore, upon correspondence with the original authors, an equilibration phase ($t = -20 - -0s$) without stimulus presentation had to be implemented. This step is not mentioned in the original publication, but is vital to obtain the correct results.

Results

Results from the code presented in this repository aim at reproducing Figure 5 in the original application, which shows ion and voltage dynamics over a simulation period of 50 s.

Figure 1 shows the results obtained from the code in this repository. Potassium (K^+)) in both the synaptic and perivascular space match their corresponding plots

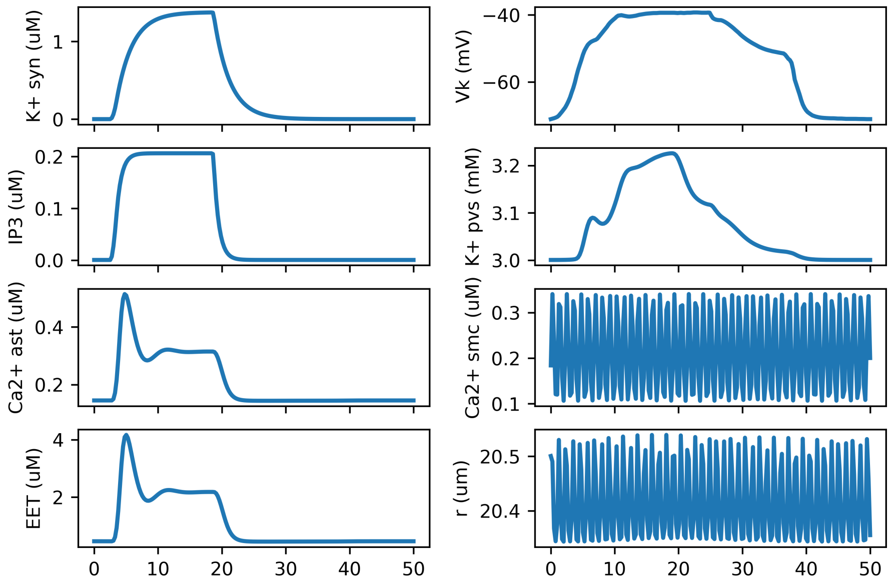

Figure 2: Astrocyte and arterial response during neuronal stimulation whilst V_k is fixed to match the original publication. The difference in results for K^+ in the perivascular space, Ca^{2+} in the smooth muscle cell and arterial radius suggest that possible further errors in the equations exist in the original publication. Simulation tolerance values atol=1e-7, rtol=1e-7.

in the original publication, as do calcium (Ca^{2+}) in the smooth muscle cell and the arterial radius. Differences can be seen for Ca^{2+} in the astrocyte, EET and the astrocyte membrane potential V_k. In the case of astrocytic Ca^{2+} and EET the first peak overshoots compared to the results in the original publication, while the remainder of the plots match the original publication. Most interesting is the shape of V_k, which in the first half looks very different from the reproduced figure. Additionally, V_k overshoots into positive values, which is not given in the original publication. Simulation tolerance values were atol=1e-7 and rtol=1e-7.

The large difference in V_k between the two simulations is surprising, especially because this does not lead to incorrect results in the other plots, apart from an overshoot of the values for Ca^{2+} and EET in the astrocyte. The key results, which are the response of Ca^{2+} and subsequently the arterial radius match the original publication. A newer publication by the same authors exists [6], which does contain the same spike for Ca^{2+} and EET as the simulation results presented here. It is unclear, where this difference comes from as [6] does not indicate that any of the equations affecting Ca^{2+} or EET have been altered. It is also unclear why V_k shows such a large difference.

One possible explanation could be that some components of $\partial V_k/\partial t$ are wrongly implemented, but the results are mostly affected by the mere fact that V_k increases in response to the stimulus instead of the exact value of V_k. To test this, V_k was obtained from the original publcation and hard-coded into the simulation instead of being calculated from its ODE. This is shown in Figure 2. Simulation tolerance values were atol=1e-7 and rtol=1e-7. Here, the results for K^+ in the perivascular space, Ca^{2+} in the smooth muscle cells and the arterial radius differ largely from the results in the original publication or indeed 1. Because of this discrepancy between results the authors of the original publication were contacted to request the code for this publication. However, they could only provide the Matlab code for [6], from which it was not possible to revert back to the code to implement [1].

Conclusion

To a large degree the results from [1] were replicated. However, distinct differences in the results remain, which could not be explained. It should be emphasised that the number of errors found in the original publication may indicate that more errors may remain to be found, however, because no version of the code to implement [1] appears to exist anymore, it will be very difficult at best to find these additional errors.

References

[1] Witthoft A, Karniadakis GE (2012) A bidirectional model for communication in the neurovascular unit. *Journal of Theoretical Biology* 311: 80-93. http://dx.doi.org/10.1016/j.jtbi.2

[2] Bennett MR, Farnell L, Gibson W (2008) Origins of blood volume change due to glutamatergic synaptic activity at astrocytes abutting on arteriolar smooth muscle cells. *Journal of Theoretical Biology* 250: 172-185. https://doi.org/10.1016/j.jtbi.2007.08.024

[3] Farr H, David T (2011) Models of neurovascular coupling via potassium and EET signalling. *Journal of Theoretical Biology* 286: 13-23. https://doi.org/10.1016/j.jtbi.2011.07

[4] Gonzalez-Fernandez JM, Ermentrout B (1994) On the origin and dynamics of the vasomotion of small arteries. *Mathematical Biosciences* 119: 127-167. https://doi.org/10.101 5564(94)90074-4

[5] Moore CI, Cao R (2008) The hemo-neural hypothesis: on the role of blood flow in information processing. *Journal of Neurophysiology* 99: 2035-2047. https://doi.org/10.1152/jn

[6] Witthoft A, Filosa J, Karniadakis GE (2013) Potassium Buffering in the Neurovascular Unit: Models and Sensitivity Analysis. *Biophysical Journal* 105 (9): 2046-2054. http://dx.doi.org/10.1016/j.bpj.2013.09.012