

CorrectCoxVramp – a python function to correct for space-clamp errors in voltage-ramp experiments

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Introduction

The voltage-ramp technique is used to estimate the dependence of a stationary membrane current (I) on an applied voltage (V). As the name implies, V is linearly ramped while I is recorded. It is assumed that the ramp is sufficiently slow so that at each point I is effectively stationary, i.e. if the ramp were stopped at some point I would not change (an assumption that can, of course, be tested experimentally). Hence the V -ramp provides no information about kinetics. Nevertheless, it is still useful for estimating the V -dependence of a pharmacologically isolated specific conductance $g(V) = i(V)/(V-E)$, where i is the current density (e.g. mA cm^{-2}) and E is the reversal potential. However, a serious problem when applying the V -ramp technique to neurons is that V is clamped only at the recording site. This will often be the soma, or perhaps an axonal bleb or varicosity, although proximal dendrites can also be patched. Away from the recording site V will not be clamped at the desired values (“space-clamp error”), but the membrane current at those points will contribute to the current measured at the recording site. Hence the interpretation of the recorded values of I and V is not straightforward; rather one must in some way correct for this space-clamp error. Various approaches have been tried (reviewed briefly by Murphy *et al.*, 2023). Here we take as our starting point the method described by Cox (2008), which provides an initial estimate of $i(V)$. This is then improved upon iteratively. Full details of the method are given in Murphy *et al.* (2023). Here I describe the use of a Python function `CorrectCoxVramp`, which operates in conjunction with the simulator NEURON (Carnevale and Hines, 2009) to correct for space-clamp errors in V -ramp data and so return an estimate of $i(V)$. Only depolarising ramps (positive slopes) are supported at present.

Using the function `CorrectCoxVramp`

Create a folder (which we will call the “input folder”) and put your NEURON files into it, together with a text file containing the V -ramp data (or include a path using “/” in the data filename). An example input folder (`CorrectCoxVrampExample`) is provided. The example ramp-data file is `NaP_Mean_IV.txt`; your data must conform to the data in that file (although the unit of current can be nA rather than pA; see below). Copy the file `CorrectCoxVramp.py` to your input folder. Next create a parameter file and save it to the input folder; you can use the provided `parameters.txt` as a template. The meaning of the

parameters is given in the Table 1. Put your own Python script(s) into the input folder and import `CorrectCoxVramp` by putting a line like the following near the start of your script:

```
import CorrectCoxVramp as cox
```

Calling the function from your script is simple; `result` is a dictionary:

```
result = cox.CorrectCoxVramp('parameters.txt')
```

An example script is provided (`CorrectCoxVrampExample.py`), together with an example NEURON model (the `.hoc` and `.mod` files in `CorrectCoxVrampExample`; remember to compile the latter). You can use any parameter file name you like, but parameter names and the colons in the parameter file must not be changed. As some parameters are needed by the NEURON model, these can be loaded from the parameter file by your hoc script (see `mossy_fiber_run.hoc`). You can also add your own text lines, but these must conform to the format in `parameters.txt` (e.g. “`neurite_id: 3`”). The name of the parameter file can be loaded by your NEURON model from `parameter_file.txt`. You may never need to use `result`, but in case you do its entries are given in Table 2.

Table 1. Definition of parameters.

Parameter	Example	Description
<code>neuron_path</code>	<code>C:/nrn/bin</code>	Omit this line if you want your system to find <code>neuron.exe</code> .
<code>neuron_file</code>	<code>model.hoc</code>	NEURON model file.
<code>maxit</code>	9	Maximum number of iterations.
DV (mV)	0.1	See ΔV and Eq. (17) in Murphy <i>et al.</i> (2023).
Iunit	nA	Unit of current in <code>tVIfile</code> (pA or nA; the latter will be converted to the former).
Optimise_Cm	yes	yes = optimise C_m and $i(V)$; otherwise C_m is fixed.
Interpolation	modified	Type of interpolation (see Technical Notes).
<code>maxIerror_tol</code> (pA)	0.1	Maximum allowed error on I .
<code>Icap_error_tol</code> (pA)	0.1	Maximum allowed error on the capacitive current (I_c) if <code>Optimise_Cm</code> = yes.

V_LJP_corrected	no	Is V corrected for the liquid junction potential?
tVifile	Vramp.txt	V-ramp data (t , V , I), e.g. NaP_Mean_IV.txt.
coxdir	tempCox	Temporary folder for intermediate data.
outputdir	output	Output folder (absolute or relative; use “/”, not “\”); will be deleted if it already exists.
Area (um ²)	100	Membrane area of isopotential compartment (e.g. soma, bleb, dendritic section); nseg = 1.
diam (um)	0.4 0.4	List of neurite diameters (minimum 2).
Ra (Ohm.cm)	100	Axial resistivity.
Raccess (MOhm)	10	Patch access resistance.
Rseal (GOhm)	Inf	Patch seal resistance.
Cm (uF/cm ²)	1.0	Membrane capacitance (initial or fixed value).
LJP (mV)	2.0	Liquid junction potential ¹ .
gL_fraction	0.01	Use this fraction of $i(V)$ to estimate the leak conductance (g_L) and reversal potential (E_L) ² .
VRm (mV)	-85 -65	Estimate the specific membrane resistance (R_m) over this V range ² .
thold (ms)	200	Pre-ramp holding interval (V-ramp start time).
tstart (ms)	400	Start time for data analysis.
poly	2 3 -80	Specifies the polynomial(s) used to smooth I^3 .
do_plots	yes	yes = do plots for each iteration.

¹Used to calculate the leak current through the seal resistance, $(V + \text{LJP})/R_{\text{seal}}$.

²Not necessary but must be present; just ignore if don't want these results.

³Smoothing polynomial(s); `cox.test_smooth('parameters.txt')` plots the fit. See poly table on next page.

poly (example values are given; other values may be specified):

3	Fit a cubic polynomial to $I(V)$ and $I^*(V)$ (see Murphy <i>et al.</i> (2023) for the meaning of the latter).
4 4.0	Find the ‘best-fit’ polynomial of degree ≤ 4 using forward selection with an F -to-enter value (float) of 4.0 (Kutner <i>et al.</i> , 2004).
2 3 -80	Splice together polynomials of degrees 2 and 3 at $V \approx -80$ mV (initial guess).
	Don’t fit a polynomial; use linear interpolation (not recommended).

Table 2. Definition of entries in the `result` dictionary.

Key	Description
t (ms)	Sampling times for the V -ramp data.
V (mV)	Observed V values after correcting for R_{access} (and LJP if necessary).
I (pA)	Observed I values after correcting for R_{seal} and capacitive current.
predI (pA)	Predicted I values after correcting for R_{seal} and I_C . Pairs with V.
cd (mA/cm ²)	Estimated current density. Pairs with V.
Cm (uF/cm ²)	Estimated membrane specific capacitance.
Icap_error (pA)	Error on the predicted capacitive current (I_C).
maxIerror (pA)	Maximum error on the predicted injected current.
done	1 = done, 0 = not done.
Run time (s)	What it says.
Best iteration	Ditto.
output_folder	Ditto.

Results are also saved to the output folder; file names are given in Table 3. The parameter and V-ramp data files are also copied to the output folder. If you wish the temporary folder `coxdir` to be copied to the output folder, add an argument `saveCox = 'yes'` when calling `CorrectCoxVramp`. During the optimisation process, a number of temporary files are also created in the input folder. These files, which are described in Table 4, allow your NEURON program to interact with `CorrectCoxVramp`.

To run a series of optimisations using different parameter values (e.g. different R_a values or different fixed C_m values) put the call to `CorrectCoxVramp` in a loop, creating a new parameter file (containing a different output folder name) for each turn of the loop. E.g.

```
Ra = [110, 120, 130]; j = 0
file = open('parameters.txt','r')
paras = file.readlines(); file.close()
while j < len(paras):
    if 'Ra(Ohm.cm)' in paras[j]: jRa = j
    if 'outputdir' in paras[j]: jout = j
    = j + 1
i = 0
while i < len(Ra):
    print('')
    print('Ra(Ohm.cm): '+str(Ra[i]))
    outputdir = 'output_Ra='+str(Ra[i])
    paras[jRa] = 'Ra(Ohm.cm): '+str(Ra[i])+'\n'
    paras[jout] = 'outputdir: '+outputdir+'\n'
    parafile = 'parameters_Ra='+str(Ra[i])+'.txt'
    file = open(parafile,'w')
    file.writelines(paras); file.close()
    result = cox.CorrectCoxVramp(parafile,saveCox = 'yes')
    i = i + 1
```

In principle you could also use an optimiser to find the best value of R_a etc., but in practice I haven't been able to get this to work.

Technical notes

As discussed in Murphy *et al.* (2023), the method involves the solution of a nonlinear ODE in the current density, i (their Eq. 13). Specification of the ODE requires estimation of a fictitious current (I^*), which is determined by linear interpolation (or extrapolation if this is not possible). Possible choices for the Interpolation method in the parameter file are simple, standard and modified, where the latter two are taken from Gerald and Wheatly (1984). In principle these should be more robust than simple. Also modified is faster than standard and so is the recommended method. The initial value $i = 0$ is taken at $V = V_{\text{rest}}$. In principle there can be multiple V_{rest} values but they must be stable equilibrium points (i.e. $dI/dV > 0$ for $I = 0$). If necessary such points are manufactured by linear extrapolation from the beginning and/or end of the $I(V)$ data. If an unstable equilibrium point is present ($dI/dV < 0$ for $I = 0$) it is excluded from the analysis. Eq. (13) is then solved for points to the left and right of the unstable point, followed by concatenation of the two solutions to obtain the final result for $i(V)$. Eq. (13) is solved for $i(V)$ using function `scipy.integrate.solve_ivp` from the *SciPy* Python package. Depending on the setting of `poly`, $I(V)$ and $I^*(V)$ are smoothed using the *SciPy* function `optimize.least_squares`, or the *NUMPY* function `polyfit`, or linearly interpolated using the *SciPy* function `interpolate.interpld`. Values of V_{rest} are estimated as the roots of the fitted functions, obtained with the function `numpy.roots` for the polynomials or by linear interpolation. All analyses are performed on the smoothed or interpolated data. To check the fit of the polynomial(s) to the raw ramp current, call `cox.test_smooth('parameters.txt')` and if necessary adjust `poly` in the parameters file before calling `CorrectCoxVramp`.

Table 3. Output files names. # is the best iteration number.

File name	Description
cd_#.txt	Estimated $i(V)$ in two columns (V , i).
CmRmL_#.txt	Estimates of C_m , R_m , g_L and E_L .
IterationTimeErrors_#.txt	Run time and errors (I and I_C).
printout.txt	Run time, errors and C_m for each iteration.
Ierror_#.txt	Prediction errors for I at each V .
IcapIholdVholdVrest.txt	Estimate of I_C , I_{hold} , V_{hold} and V_{rest} .
PredIcapIholdVholdVrest_#.txt	Predicted values of I_C , I_{hold} , V_{hold} and V_{rest} .
Raw_tVI.txt	Raw observed t , V , I (excluding pre-ramp data).
tVI.txt	Corrected* observed t , V , I (excluding pre-ramp).
Raw_tVpredI_#.txt	Raw predicted t , V , I (excluding pre-ramp).
tVpredI_#.txt	Corrected* predicted t , V , I (excluding pre-ramp).
Pred_fn_#.txt	Raw predicted t , V , I (including pre-ramp), where fn is the name of the V -ramp data file (tVIfile in the parameter file, excluding the “.txt”).

* V is corrected for R_{access} and I is corrected for R_{seal} and C_m . Note that I will not be corrected for C_m if you set C_m to zero in the parameter file (in which case you should also set Optimise_Cm to “no”). The image files Current_density.png, Raw_I_and_I_corrected_for_Rseal_and_Cm.png and Effect_of_an_access_resistance_on_V.png contain what their names suggest.

Table 4. Temporary files in the input folder.

File name	Description
tVpredI.txt	Input for CorrectCoxVramp. Save your NEURON-model predictions (t , V , I), including pre-clamp holding data, to this file. The format must conform to that of tVpredI.txt in CorrectCoxVrampExample.
flag.txt	<p>Input for CorrectCoxVramp. Create this file with the following hoc code (or equivalent) when your NEURON program has finished running.</p> <pre>objref file proc finish() { file = new File() file.wopen("flag.txt") file.printf("Done") file.close() quit() }</pre> <p>Anything other than "Done" will cause CorrectCoxVramp to terminate.</p>
cd.txt	Input for your NEURON model. The current best estimate of the current density as a function of V , $i(V)$, in two columns (V , i). Pass these data as a FUNCTION_TABLE to your .mod file (see cd.txt and the .hoc and .mod files in folder CorrectCoxVrampExample). Note that $i(V)$ includes the leak current density, $g_L(V - E_L)$.
CmRmL.txt	<p>Input for your NEURON model. The current best estimate of C_m ($\mu\text{F cm}^{-2}$). This will not change from the value set in the parameter file if Optimise_Cm = no. Import it with something like:</p> <pre>objref file strdef s { file = new File() file.ropen("CmRmL.txt") } { Cm = file.scanvar() file.close() }</pre> <p>Additional lines in CmRmL.txt contain estimates of R_m, g_L and E_L.</p>

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References

- Carnevale, N. T. and Hines M. L. (2009). *The NEURON Book*, Cambridge University Press.
- Cox S. J. (2008). Direct correction of non-space-clamped currents via Cole's theorem. *Journal of Neuroscience Methods* **169**(2): 366-373.
- Gerald C.F. and Wheatly P.O. (1984). *Applied Numerical Analysis*. Addison-Wesley.
- Kutner M.H., Nachtsheim C.J., Newman E.L. and Li W. (2004). *Applied Linear Statistical Models*. McGraw-Hill/Irwin
- Murphy R., Alle H., Geiger J. and Storm J. (2023). Estimation of persistent sodium-current density in rat hippocampal mossy fiber boutons: correction of space-clamp errors. *Journal of Physiology*. Submitted.